Implications of Modern Non-Equilibrium Thermodynamics for Georgescu-Roegen's Macro-Economics: lessons from a comprehensive historical review.

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ABSTRACT

In the early 1970s, mathematician and economist Nicolas Georgescu-Roegen developed an alternative framework to macro-economics (his hourglass model) based on two principles of classical thermodynamics applied to the earth-system as a whole. The new model led him to the radical conclusion that "not only growth, but also a zero-growth state, nay, even a declining state which does not converge toward annihilation, cannot exist forever in a finite environment" (Georgescu-Roegen 1976, p.23). Georgescu-Roegen's novel approach long served as a devastating critique of standard neoclassical growth theories. It also helped establish the foundations for the new trans-disciplinary field of ecological economics. In recent decades however, it has remained unclear whether revolutionary developments in "modern non-equilibrium thermodynamics" (Kondepudi and Prigogine 1998) refute some of Georgescu-Roegen's initial conclusions and provide fundamentally new lessons for very long-term macro-economic analysis. Based on a broad historical review of literature from many fields (thermodynamics, cosmology, ecosystems ecology and economics), I argue that Georgescu-Roegen's hourglass model is largely based on old misconceptions and assumptions from 19th century thermodynamics (including an out-dated cosmology) which make it very misleading. Ironically, these assumptions (path independence and linearity of the entropy function in particular) replicate the *non-evolutionary* thinking he seemed to despise in his colleagues. In light of modern NET, I propose a different model. Contrary to Georgescu-Roegen's hourglass, I do not assume the path independence of the entropy function. In the new model, achieving critical free energy rate density thresholds can abruptly increase the level of complexity and maximum remaining lifespan of stock-based civilizations.

ABRÉGÉ

Au début des années 1970s, le mathématicien et économiste Nicolas Georgescu-Roegen développa une alternative radical au modèle de macro-économie standard de l'époque : son « sablier entropique ». Celui-ci fut fondé sur des principes de thermodynamique classique appliqués à l'ensemble du globe. La nouvelle approche thermodynamique de Georgescu-Roegen a longtemps servi de forte critique des théories de croissance économique conventionnelles, ainsi qu'au fondement d'une nouvelle science interdisciplinaire : l'économie écologique, ou aussi, la bioéconomie. Néanmoins, à travers ces dernières décennies, il est demeuré incertain si d'importantes découvertes en thermodynamique de systèmes hors d'équilibre (NET) (Prigogine 1980, 1984, 1998): 1) ne réfuteraient pas plusieurs prémices et conclusions de Georgescu-Roegen. C'est ce que j'ai ici tenté d'investiguer, à l'aide d'une recherche dans l'histoire de plusieurs sciences. Je conclue que le modèle initiale de Georgescu-Roegen (le « sablier entropique ») dépend de plusieurs conceptions et prémices scientifiques maintenant considérées comme dépassées. En guise de développements dans le domaine de la thermodynamique de systèmes hors d'équilibre, je propose un nouveau modèle, qui ne prend pas pour acquis que les limites (thermodynamique) d'évolution d'un système macro-économique soit indépendant de la trajectoire du système en question. En particulier, la capacité d'atteindre des seuils critiques de densité de flux énergétique peut changer de façon radicale non-seulement le niveau de complexité (structurel et fonctionnel) d'une civilisation, mais aussi les limites de longévité d'une civilisation (problème qui est centrale à l'approche de Georgescu-Roegen).

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Chapter 1

Introduction

In the early 1970s, mathematician and economist Nicolas Georgescu-Roegen developed an alternative framework to standard macro-economics (Georgescu-Roegen 1966, 1971, 1976, 1977, 1979). His framework was designed around the two principles of classical thermodynamics applied to the earth-system as a whole. The new model led Georgescu-Roegen to the radical conclusion that “not only growth, but also a zero-growth state, nay, even a declining state which does not converge toward *annihilation*, cannot exist forever in a finite environment” (Georgescu-Roegen 1976, p.23). His novel approach has long served as a devastating critique of standard neoclassical growth theories, and established the scientific foundations for the new trans-disciplinary field of ecological economics (Costanza et al. 2009, Daly and Farley 2004). However, revolutionary changes have occurred in thermodynamics since at least the early 1950s, especially with regards to open systems in far-from-equilibrium conditions (Nicolis and Prigogine 1977, Prigogine 1980). In recent decades, it has remained unclear in the ecological economics literature whether developments in “modern non-equilibrium thermodynamics” refute some of Georgescu-Roegen’s initial conclusions and provide fundamentally new lessons for very long-term macro-economic analysis.

In this thesis I first discuss the origins and characteristics of 19th century equilibrium thermodynamics, its historical ties to economics, as well as the cosmology ("heat death") that became associated with the second law (Chapter 2). Secondly, I introduce the trans-disciplinary field of ecological economics; discuss Georgescu-Roegen's thermodynamic-based macro-economics framework; and review academic literature that has critically assessed the validity and relevance of Georgescu-Roegen's ideas (Chapter 3). Next, I identify and discuss features of "modern non-equilibrium thermodynamics" that would contradict assumptions or expose weaknesses of Georgescu-Roegen's original framework (Chapter 4). Finally, I propose modifications to Georgescu-Roegen's framework, which integrate important lessons from "modern non-equilibrium thermodynamics"; and discuss how these new features still enable ecological economics to serve as an alternative to standard neoclassical growth theories (Chapter 5).

Research Context

In 1971, economist and mathematician Georgescu-Roegen published his anthology, *The Entropy Law and the Economic Process* (Georgescu-Roegen 1971). In it he argued for the need to reformulate economic analysis around irreversible energy and materials transformations inherent in the second law of thermodynamics. The entropic dissipation underlying all economic activity revealed the intrinsic biophysical limits of all energy-work transformations; food production systems; materials recovery and recycling capabilities; and pollution absorptive capacities on a finite planet.

Using thermodynamic principles, Georgescu-Roegen developed a new conceptual model, or *pre-analytic* vision (Daly and Farley 2004) for macro-economics to describe how the economy works and where it is situated. He expressed this in his "hourglass" diagram showing the economy as a subsystem of the Ecosphere (a materially closed thermodynamic system) that was open only to energy inputs from the sun.

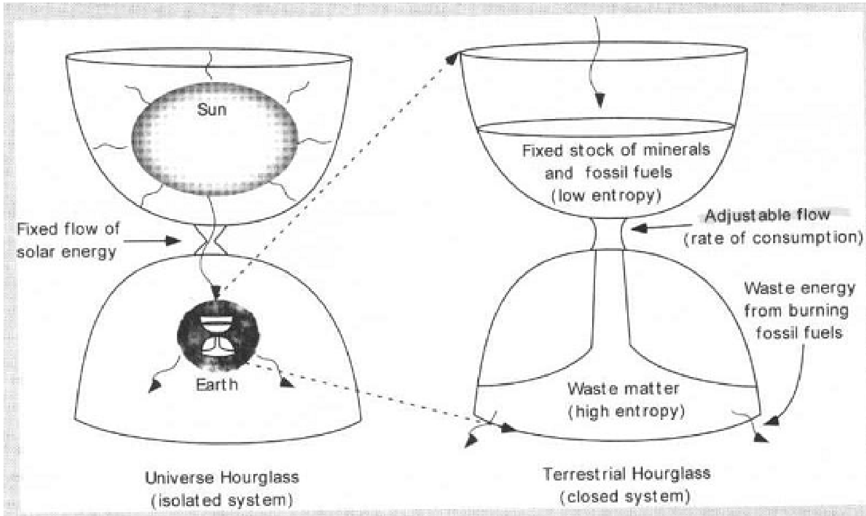

Figure 1: Georgescu-Roegen's hourglass (Daly and Farley 2004, p.30)

Georgescu-Roegen's *Entropy and the Economic Process* contained certain flaws, as I will argue in this thesis. But the general goal of inscribing economic processes in a biophysical framework is an essential ongoing research program. Since Georgescu-Roegen's initial work, Herman Daly, Robert Costanza and others founded a trans-disciplinary field called *ecological economics*. Inspired by Georgescu-Roegen and others (such as Odum and Bolding) ecological economics attempts to integrate the study of humans and nature as a basis for a sustainable future (Daly and Farley 2004).

Costanza summarizes currently active areas of research within ecological economics, including 1) multi-scale modeling of complex non-linear systems, 2) non-equilibrium thermodynamics of ecosystems and economies, and 3) theories of cultural and biological co-evolution (Costanza 2009). This thesis is firmly grounded on the second of the three main areas of ecological economics research.

Given the continuing crisis in the world financial-economic system and the parallel international food, energy and environmental crises (see Appendix 1), research is required to 1) reevaluate deep-seated assumptions in long-term economic growth and development theories, and 2) improve alternative models that account for the dependency of the economy on the larger biophysical system in which it is embedded.

Research Question

The general research questions I ask in the thesis are:

1. Do discoveries in modern non-equilibrium thermodynamics render Georgescu-Roegen's conclusions about the inevitable collapse of agro-industrial civilizations invalid? If so, why and how?
2. What are the implications of non-equilibrium thermodynamics for Georgescu-Roegen's macro-economics, and in particular for his thermodynamics-based hourglass conceptual model?

In the decades following Georgescu-Roegen's publication of his hourglass model and bio-economics framework, many have criticized his reasoning and use of the second law of thermodynamics. Valuable criticisms have focused on Georgescu-Roegen's assertion that the entropy law has as much relevance to *matter* as it does to energy (discussed in Chapter 3: materials entropy). In this thesis, I will reevaluate misconceptions and assumptions in the hourglass model in light of modern non-equilibrium thermodynamics. Such a reexamination should help provide *new constructive* criticism to Georgescu-Roegen's hourglass model, a model that remains an important foundational concept in ecological economics (Beard and Lozada 1999, Daly 1999, Daly and Farley 2004).

Specifically, there are two misconceptions and an implicit assumption introduced by Georgescu-Roegen. They are related to the growth and maintenance of complex economic structures and functions. I will reevaluate them in this thesis from the modern non-equilibrium thermodynamics viewpoint.

The two misconceptions are:

1) The role of irreversible processes as exclusively destructive of complex structure and function, and

2) The role of finite biogeophysical space as exclusively limiting (of complex structure and function)

The implicit assumption in Georgescu-Roegen's conceptual framework is that: *energy and spatial boundaries can be fixed once and for all in the analysis of coevolving economic and ecological systems, independent of evolutionary processes occurring both inside and outside the system of interest.* In other words, there is an assumption in Georgescu-Roegen's framework that his chosen, fixed, conceptual boundaries of macroeconomic *analysis* become the *actual* ultimate boundaries that constrain very long term economic growth and development.

These two misconceptions and implicit assumption necessarily result in some erroneous conclusions. Furthermore, they are not justified from the perspective of modern non-equilibrium thermodynamics. In contrast, I will emphasize the historically dynamic (as opposed to static or fixed) nature of these energy and spatial boundaries, in a manner more consistent with principles of modern non-equilibrium thermodynamics.

Methodology

> "It is easy to find a superficial analogy which really expresses nothing. But to discover some essential common features hidden beneath a surface of external differences, to form, on this basis, a new successful theory is important creative work."
>
> Einstein, referring to De Broglie's wave mechanics (Einstein and Hawking 2007, p.316-317)

The methods employed in this research are based on epistemology and the history of science (thermodynamics, ecology and economics): 1) tracking the co-evolution of ideas, shared or borrowed, amongst many disciplines (physics, the life-sciences and economics) and 2) identifying and correcting borrowed assumptions from physics and the life-sciences into economics that are no longer valid due to new scientific discoveries or a new scientific paradigm. This also happens to be the general method of reasoning that Georgescu-Roegen employed in formulating his original ideas; therefore, history of science and epistemology are appropriate for the research question at hand.

In Chapter 3, I have included a section of Georgescu-Roegen's own methodology: why he used thermodynamics in economics; and for what specific purpose and context. We will see that Georgescu-Roegen's hourglass model was not developed as a detailed dynamic process model. Thus, it cannot be tested or evaluated against time-series data on a short time scale. It does not fit that purpose. Ecological economist Herman Daly calls the model a "pre-analytic framework", a term borrowed from economist Joseph Schumpeter:

> "Schumpeter observes that 'analytic effort is of necessity preceded by a pre-analytic cognitive act that supplies the raw material for the analytic effort'. Schumpeter calls this pre-analytic cognitive act 'Vision'. […] Correcting the vision requires a new pre-analytic cognitive act, not further analysis of the old vision."
>
> (J. Schumpeter in Daly and Farley 2004; p.23)

Knowledge of the history of science and epistemology across a variety of disciplines is helpful to reevaluate deep-seated disciplinary assumptions. This is especially true in the case in economics, and particularly ecological economics. The history of economic thought is full of attempts to apply pseudo-scientific paradigms, analogies, world views and philosophical assumptions to the study of human *choices*, human *behavior*, and economic decisions (Mirowski 1991, Nadeau 2003, Polanyi 2001). Thus, it is necessary to have a clear understanding of historical exchanges between philosophy, physical science, biology/ecology and economic theory. Many important assumptions and methods introduced in economics find their distant origins in physics and ecology.

As mentioned above, I have selected key misconceptions and assumptions in the work of Georgescu-Roegen. These misconceptions and assumptions are revealed through detailed reexamination based on novel ideas in non-equilibrium thermodynamics. To identify specific misconceptions required a broad, comprehensive review of literature on non-equilibrium thermodynamics, the history and prehistory of thermodynamics, and other related fields of knowledge (economics, ecology, global biogeochemistry, and astrophysics).

Comprehensive literature review:

The literature I reviewed included paradigm-setting papers and books[1] within various fields relating to the topic, including:

1. In classical thermodynamics: (Carnot L 1803, Carnot S 1824, Clausius 1867, Einstein and Hawking 2007, Gibbs 1906, Planck 1989, Planck and Wills

[1] In the case of books, at least several chapters were read.

2009),

2. In non-equilibrium thermodynamics (Glansdorff et al. 1973, Kleidon and Lorenz 2005b, Nicolis and Prigogine 1971, 1977, 1989, Onsager 1931, Prigogine 1973, 1977, Prigogine 1980, Prigogine and Nicolis 1967, Prigogine and Stengers 1984, Schneider and Kay 1995, Schneider and Kay 1994)
3. In physical biology, evolutionary biology, physical geography, biochemistry, ecosystems ecology, global ecology and biogeochemistry (Holling 1973, Jørgensen 2004, Jorgensen and Svirezhev 2004, Jørgensen 2008b, Lindeman 1941, Lotka 1922, 1925, Lovelock and Margulis 1974, Margulis 1999, Odum EP and Barrett 1971, Schrodinger and Lewin 1968, Vernadski and McMenamin 1997, Vernadsky 2007, Von Humboldt and Otté 1859)
4. In modern cosmology: (Chaisson 2001, Chaisson 2005, Chaisson and McMillan 2002, Davies 1977, 1989, 2004, Dyson 1979, 2007, Egan 2010, Krauss and Starkman 2000, Lemaître 1931)
5. In classical economics and neoclassical economics (Edgeworth 1881, Jevons 1879, Malthus 1798, Marshall 2009, Smith 2000)
6. In ecological economics (Boulding 1993, Costanza et al. 1999, Costanza et al. 2009, Daly 1977, Daly and Farley 2004, Georgescu-Roegen 1966, 1971, 1976, Odum Howard T. 1971).

Focused Literature Review:

Chapter 3 contains a literature review of the critical reception of Georgescu-Roegen's thermodynamics model in macro-economics. The literature for this review was identified using an academic database, SCOPUS, with key words "Georgescu-

Roegen" or "thermodynamics". Searches were first restricted to the journal *Ecological Economics*, and then extended to all online journals.

Chapter 2

The Development of Equilibrium Thermodynamics

Thermodynamics is the study of *all* materials and energy transformations, in which *heat* and temperature are always involved. Though it is relevant to every branch of science, it is never complete on its own, and is always applied in conjunction with other fields of knowledge.

The modern concept of "energy" originated in the late 17th century as the key conserved quantity in Leibniz's *Dynamics*[2], as opposed to Newton's mechanics. Afterwards, potential and kinetic "energy" also became central to Bernoulli's hydrodynamics[3], and to Lagrange's reformulation of mechanics[4], in the 18th century.

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[2] The honor goes to Leibniz for both first postulating the energy conservation principle, and advising experimental work on the first steam engine and steam boat, already in the late 17th century. Leibniz developed this principle of energy conservation in collaboration with Christain Huygens, Jean Bernouilli and Denis Papin; they used the term "vis viva", for energy, and the formula: $E= mv^2$. In Newton's mechanics, momentum, "mv", is *the* important conserved quantity, and "force" is defined as the rate of rate of change of momentum. In Leibniz's *Dynamics*, the equivalent to "force" is "power": the time rate of change of energy. A great battle erupted between Leibniz and Newton over their different scientific method, mathematics, *and physics*, including Leibniz's insistence on the importance of "vis viva" as opposed to just momentum. These differences were not merely theoretical: they had very practical implications for the industrial revolution, and mechanical engineering in particular: in the design of machines, and steam engines.

[3] In his *Hydrodynamica*, Daniel Bernouilli used Leibniz's conservation of vis viva to develop a dynamic (kinetic) theory of gases and fluids in opposition to Newton's static theory of gases which prevailed at the time. Bernouilli's kinetic theory explains the relationship between the macroscopic variables of pressure, volume (Boyle-Mariotte law), and temperature (later the Ideal Gas law; $PV = NkT$) in terms of molecular collisions. Bernouilli's theory was rejected by most quarters for over 100 years, in favor of Newton's. It was finally revived in the late 19th century and formed the starting point for statistical thermodynamics.

[4] Louis-Joseph Lagrange reformulated Newton's mechanics around the concepts of potential energy, kinetic energy, and the principle of least action. The principle of least action, also initially developed by Leibniz, played a very important role 19th century physics in general, and had a great influence on physicists involved in the development of equilibrium thermodynamics, including Lazare Carnot, Sadi Carnot, Helmholtz, and all the way to Max Planck. It was thought that the second law of thermodynamics was closely related to the principle of least action. Planck considered this interesting, but reemphasized that at the time, the least action principle is only formulated for conservative, reversible, systems, and

Thermodynamics itself was developed in the early 19th Century by French engineer Sadi Carnot (1796 – 1832), in the attempt to understand the nature of heat, and elucidate the *economy* of heat engines (the limits of converting heat into useful mechanical work). Over the course of the next century (1820s-1920s), thermodynamics underwent a tremendous expansion in the *scope* of its applications, as the concept of *energy*, and energy transformations became a powerful unifying principle in all natural sciences[5].

In this chapter I will summarize key aspects of the *changing* nature of thermodynamics over the last three centuries as an introduction to the discussion in Chapter 3, on the use, or misuse, of thermodynamics in economics by Georgescu-Roegen.

In the first section, I recall the historical context in which thermodynamics initially emerged, at the intersection of three fields of knowledge: engineering, economics and physics, focusing particularly on the work of Sadi Carnot. The notion that thermodynamics was initially developed in close proximity to political economic considerations is underemphasized in monographs, yet quite important to this thesis. The second section provides a brief reminder of the "world view" implications and paradoxes which were often associated with the second law and 19th century equilibrium thermodynamics. In the third section, I end the chapter by explaining

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thus incompatible with irreversible processes (see Planck, 1908; Annila, 2008).

[5] After the initial insights by Carnot, thermodynamics was mathematically formalized by Claussius, Kelvin, Maxwell and Helmholtz into two laws (energy conservation and entropy increase), and functions of equilibrium states (the cornerstone of *equilibrium* thermodynamics). This process eventually culminated with J. W. Gibb's integration of chemistry with equilibrium thermodynamics in the late 19th century (Nelson and Cox, 2000), the development of statistical thermodynamics by Maxwell, Gibbs and Boltzman, and later in the early 20th century as statistical *quantum* thermodynamics (Gibbs, Planck, Einstein, Fermi, Bose).

briefly what is meant by 19th century equilibrium thermodynamics in contrast to "modern, non-equilibrium thermodynamics" (NET), and explain why this difference matters. This distinction is fundamental to the entire thesis.

Finally, the reader is referred to Appendix 1 for various formulations of the second law of thermodynamics, and Appendix 2 for a discussion of key assumptions of 19th century equilibrium thermodynamics, in particular: reversibility and path independence of the entropy function.

2.1 Early Beginnings and Historical Context

Thermodynamics was founded by the French engineer, physicist *and* economist Sadi Carnot in the early decades of the industrial revolution, with his paper *Reflections on the Motive Power of Fire* (Carnot S 1824). Carnot was trained at France's École Polytechnique as an engineer and physicist, but, as very few authors mention, he also studied and wrote on political economy[6]. The notion presented here that thermodynamics was initially developed in close proximity to political economy (in terms of production and growth theory) is greatly underemphasized in textbooks, yet quite important to this thesis. With adequate knowledge of historical context, we can speak confidently of thermodynamics as emerging from the intersection of 1) practical engineering, 2) theoretical physics, and 3) political economy and industrial economics. Some of the more important features of this historical context are as follows.

[6] Carnot died suddenly at a fairly young age (age 36, in 1830). His notes on economics were only published very recently (Fox, 1986).

2.1.1. Early limitations of low pressure steam engines

When the industrial revolution began in the 1770s, little was known about the physics of heat, or even the chemistry of combustion[7], nor how *ultimately* the steam engine actually "worked". The early steam engine model, developed and commercialized by James Watt (1770s-1790s), used the *condensation* of low-pressure steam to create a vacuum inside a piston chamber, and the weight of atmospheric pressure on the piston to operate a large mechanical "see-saw". Thus only the passive characteristics of steam (condensation under temperature reduction) were used, not its active or expansive nature. These early "atmospheric engines" were reliable, but very large and they consumed vast amounts of coal and were very inefficient. This particular mechanism also set an upper limit to the power[8] output of these early engines[9], and by the end of the 18th century, practical improvements in this model seemed to have reached a limit (Fox 1986, Hills 1993).

We can look at the consequences of such initial limitations in steam technology from the point of view of the complete *economic* production cycle: from the combined mining of iron and coal, through the primary transformation of iron ore into semi-finished and finished products (engine and machine parts) to the use of the machines and engines in the other manufacturing sectors. As the industrial revolution expanded, the demand for fuel and iron increased. Coal and iron mines

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[7] Lavoisier and Priestly's work on combustion came shortly after, in the 1780s.

[8] Power: the *rate* or speed of mechanical work. For example the amount of water or minerals which can be pumped-raised from a deep mine shaft per hour.

[9] Whether steam is used to displace air in a piston at a pressure of 1 atmosphere, or used to fill a vacuum chamber and raise the weight of a column of air to an equilibrium position of 1 atmosphere, the result is the same. The engine is thus limited to the work output of lifting the equivalent of one column of air per cycle. Only a change in the piston diameter can increase the weight of air displaced per stroke.

were either dug at increasing depths and needing increasingly powerful engines to pump out rain water; or were opened at greater distances from production centers with increased costs of transportation. Thus, at fixed steam technology levels, more and more coal (energy) was being consumed per ton of iron and coal energy extracted. The ratio of net profits to operating costs decreased as a function of the expansion of a factor of production (capital or labor), a problem that early economists such as Ricardo (1772-1823) and Malthus (1766-1834) called the problem of diminishing returns[10]. This problem is still relevant in economics today (Mankiw and Scarth 2001).

Had steam engine technology not been capable of improvements beyond this early point larger system-wide economic limitations would have quickly appeared as steam engine technology was a bottleneck in the economic production process as a whole (Fox 1986, Hills 1993). From a socio-political perspective, the hopes of improving the material or socio-economic conditions of the majority of the

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[10] Classical law of diminishing returns (Ricardo, 1800s-20s): for each additional increase, or extension/expansion, in a factor of production (capital or labor), the value of the end product decreases, thus decreasing the margin of profit until it no longer possible to break even. In classical economics, the typical example is farm land. The best farm land with the highest yields per laborer or capital is used first, giving the highest profits; following which any further expansion in the area of farmland under cultivation implies (according to the assumption) using land of less quality with lower yields per laborer or equivalent capital, and thus diminishing profits. At the break even or equilibrium point, the expansion must stop. In Ricardo's conception, land/soil quality was fixed, or static, in time, but it varied in space. In our special case, with **coal**, the ***irreversible*** combustion of coal adds an extra dimension to the classic problem of diminishing returns: *time*. For each additional increase, or extension, in a factor of production (capital or labor) in space *and* time, the value of the end-product decreases (according to the logic), giving diminishing profits. That is, the extension of the factors of production (capital and labor) can also be thought of as occurring in the dimension of *time*. Only, there is no obvious equivalent to a "break-even" point in this case, no smooth approach to equilibrium, where the extension of the factors of production comes to a stop, since we cannot easily stop irreversible processes from happening, nor the flow of time! What can happen is a contraction in the use of the factors of production, and thus quantity of end product output. This is a good example of Georegescu-Roegen's concerns about thermodynamic *irreversibility* in economics.

population largely rested on the possibility of improving early power technology of the industrial revolution[11].

2.1.2. High pressure steam engines and industrial economy

By the early 19th century, successful experiments were being conducted to use the direct expansion force of high pressure steam. Early models of high pressure steam engines demonstrated a remarkable improvement in the "economy of coal" (efficiency), as well as a potential for unprecedented raw horse-power outputs. The problem with these new engines however was that they were much more dangerous, due to their use of high pressure steam; they were susceptible to explosions, causing severe injuries, long periods of breakdown and substantial financial/capital losses and risk (Fox 1986, Hills 1993).

Meanwhile, extraordinary claims were being made by inventors (or charlatans), advocating radical designs. For example some advocated using air instead of steam as the working gas, dispensing entirely with standard components of an engine like an external boiler and condenser, and using a liquid fuel instead of coal as the combustion source (i.e. early proposals for internal combustion engines). Others claimed they could continuously recycle the heat from the exhaust, back into the engine, almost perpetually, thus achieving tremendous efficiencies[12]. Of course, all

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[11] Hydraulic power was also an important source of energy for early industrial-manufacturing processes. In the 18th century, British engineer John Smeaton conducted extensive experiments on water wheels. The energy efficiency of most water wheels in his time were typically only 20% (Smeaton, 1760). By the end of the 19th century, hydro-electric turbines already reached efficiencies of 80-90% thanks to parallel discoveries common to both heat engine design and hydraulic mechanics, particularly the high pressure steam turbine and hydroelectric turbine.

[12] A perpetual motion machine. Georgescu-Roegen argued, in his time, that the long term growth targets of the global economy were similar to a perpetual motion machine: physically

that these inventors needed were large sums of money to demonstrate their genius.

This created an important problem. By what means could one know beforehand which radical new design had merit and which ones were physically impossible? What *caused* the substantial differences in performance between high pressure and low pressure engine designs? How far could improvements in high pressure steam engines be extended, until new unsurpassable limits would be reached? This constitutes the general theoretical and practical problem that Sadi Carnot addressed, as an engineer, a physicist, and industrial *economist*.

2.1.3. Sadi Carnot and the birth of thermodynamics

Sadi Carnot's contributions to science and engineering were many[13]. He first

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impossible.

[13] We can trace the more immediate scientific origins of Sadi Carnot's work to two of his contemporaries, both of them geniuses in their time. First his father, Lazarre Carnot, the great republican scientist and general who founded France's famous Ecole Polytechnique, had long preceded his son Sadi with an important treatise entitled *On Machines* (1785). In this treatise, Lazare Carnot made the first systematic use of the principle conservation of energy and the principle of least action in engineering (Carnot, 1803, Carnot, 1825; Smil, 2005). He used the energy conservation principle first to define machines (or technology) in general as a means of *transforming*, energy into qualitatively more useful forms and concentrations (work) at a given rate (power). Then Lazare Carnot defined mechanical efficiency as the ratio of useful output work to input energy, and defined the *maximum* efficiency of a machine as that achieved under a reversible cycle. Using this ideal reversible cycle, he also established a proof of the impossibility of a perpetual motion machine for purely mechanical systems, much like his son would do for heat engines. He was also very interested in irreversible processes (friction, viscosity, inelastic collisions, shocks, etc), and developing new methods to calculate them. Taking these irreversible processes into account, he developed practical design principles of a general character to increase the efficiency or power output of machines in general, and hydraulic machines in particular.

Second, Joseph Fourier, a former colleague of Lazarre Carnot at the Ecole Polytechnique, had, after years of experiment, published a ground-breaking book on new analytical methods used to describe the propagation of heat in bodies (1822). Fourier developed an empirical law which relates the local rate of heat flow (conduction) in a substance (solid liquid, vapor), to the local temperature gradients in that substance, and a coefficient of heat conduction specific to every substance. Fourier's law of heat conduction was the first law describing of a truly *irreversible* process (Prigogine and Kondepudi, 1998), and is thus an early reference point for non-equilibrium thermodynamics. Fourier's work had a tremendous influence on the birth and development of thermodynamics (on Carnot in demonstrated that the benefit of high-pressure engines was not in the pressure itself, but the larger *temperature drop* they used between the hot reservoir and cold reservoir. Carnot showed that it was the total temperature gradient to which an engine was subject (from entry to exhaust) which was the ultimate *cause* of the machine's ability to do work, as well as the ultimate constraint limiting the theoretical efficiency of any heat engine.

In a heat engine, only a fraction of the incoming heat energy can ultimately be transformed into mechanical work. The rest of the incoming heat *must* flow out into a cold reservoir, even if all frictional losses are discounted. Carnot showed that regardless of the nature in the heat conducting substance, or any other internal details of the machine itself, the maximum efficiency any heat engine can achieve is determined by 1) the temperature gradient and 2) the distance of this temperature gradient from absolute zero.

Carnot's essay *Reflections on the motive power of fire* (Carnot 1824) is well-known in physics for introducing the key notion of an ideal "reversible thermodynamic cycle": the Carnot cycle. Carnot's *reversible* thermodynamic cycle gives us not only the expression for the maximum theoretical efficiency and maximal possible work output of a heat engine under given conditions, it also gives the condition for the transfer of energy in *any* process in the universe involving heat. In physics, the reversible Carnot cycle is important because:

1) It defines the minimal conditions required for *any process* in the universe which involves heat; it is a universal function, independent of substance, "a property of the world, not a property of a particular engine" (Feynman et al.

particular), as well as other closely related fields such as material science, mechanical engineering and chemistry.

196, p.44-6);

2) It helps identify the maximum work output and maximum efficiency of all energy conversions involving heat;
3) It is used to demonstrate the impossibility of perpetual motion heat engine;
4) It helps define the absolute temperature scale;
5) It defines with precision, by contrast, an *irreversible* cycle, or all irreversible processes in general;
6) It is used to derive an early formulation of the second law of thermodynamics, and define both entropy, and free energy with precision.

These concepts (reversible cycle, free energy, entropy and irreversibility) are discussed again in Chapter 3, in the context of economics. The concept of reversibility plays a fundamental role even in neoclassical economics. Correcting this deep flaw, with all its implications, was of particular concern to Georgescu-Roegen.

2.1.4. Implications of Carnot's discoveries for early industrial economy

Carnot's discoveries had a very practical significance. He demonstrated convincingly that there was ample room for further improvements in heat engine design at the time, what was called the "economy of power". Thus, *much* greater efficiencies, power outputs and *higher* performances were still possible, thus with great relevance to industrial economy. Carnot's ideas motivated the expansion of high-pressure steam engines in the second half of the 19th century, and led to the invention of the internal combustion engine and the particularly efficient diesel engine (Hills 1989).

Heat engines themselves had tremendous social and economic *impacts*, in terms of rapid industrialization and urbanization, division of labor, productivity increases and the creation of entirely new sectors of the economy. In fact, the sustained increases in production output and productivity in all sectors of the economy were so impressive; they seemed to fundamentally contradict many of the *famously pessimistic* economic doctrines which made early 19th century economics a "dismal science".

Such contradictions between practice (agro-industrial economy) and theory (Malthus and Ricardo's early limits to growth) begged the question: what *really* determines the wealth of nations? Many industrialists, politicians and economists, recognized the need to either rethink or completely overthrow the doctrines of their famous contemporaries (Malthus and Ricardo). For example the long assumed: 1) inevitability of diminishing returns in agriculture and industry; 2) inevitability of food shortages, famine and urban diseases associated with population growth; and 3) the inevitability of permanent subsistence wages and poverty for the masses. Much later, in the 20th century, the physical chemist Ilya Prigogine, one of the founders of modern non-equilibrium thermodynamics, highlighted in the introduction to his textbook on NET that "Adam Smith did not see in coal the hidden wealth of nations" (Kondepudi and Prigogine 1998, p.3).

As I mentioned above, Sadi Carnot, was also an economist of sorts. Unfortunately he only left sparse notes on economics behind (Fox 1986). Georgescu-Roegen sometimes used this unfinished and ambiguous aspect of Carnot's work to help justify the reintroduction of thermodynamic principles into economic analysis:

> "The early thermodynamics of Carnot, with its 'anthropomorphic' distinctions between useful work and waste heat, began as a *physics of*

> *economic value* and has remained so in spite of the numerous subsequent contributions of a more abstract nature" (Georgescu-Roegen 1993, p.78).

In summary, Carnot had asked general questions in the context of the early industrial revolution. These questions were: what was to the *ultimate* cause of a heat engine's ability to do work; what are the ultimate limits to the improvement of such engines; and how far are current technologies from those limits? In that context, he found an optimistic answer and useful guide: much progress lay ahead. A century and a half later, Georgescu-Roegen used similar methods (thermodynamics) to develop a macroscopic model of the global economy; however, Georgescu-Roegen sided with Malthus, and came to very pessimistic conclusion. Something had happened to thermodynamics in the meantime.

2.2 World View: the Paradox of Order and Disorder

As the 19^{th} century came to an end, many physicists, such as Lord Kelvin, Helmholtz and Claussius, helped popularize a view of the world in which the *universe as a whole* was inevitably headed towards total disorder: a universal heat death. They believed the second law of thermodynamics revealed, in accordance with religious doctrine, that the universe was not eternal, that is was indeed going to end (Kragh 2008). That is, since irreversible processes tend towards decay and complete thermodynamic equilibrium (thermal, mechanical, chemical, etc), and since the second law of thermodynamics which describes this process is universal, then, by extrapolation, the universe as a whole should eventually reach complete thermodynamic equilibrium. At this point, according to the logic, all processes in the universe would eventually stop[14], and all potential for order and structure would be annihilated.

Kelvin, who famously came up with a calculation of the age of the earth that was very short (20 million years), also estimated the remaining duration of conditions favorable to life and civilization on earth to be quite short (Kragh 2008). Thus, within this authoritative intellectual context, the evolutionary tendency towards increased order and complexity (for living organisms and human civilizations) seemed like a paradox; a series of statistical fluke events, of increasingly small probabilities, or a miraculous event requiring divine intervention (according to another bias).

This statement by Ilya Prigogine captures well the paradoxes of thermodynamics coming out of the 19th century:

> "It is a very interesting coincidence that the idea of evolution emerges in the science of the nineteenth century in two conflicting ways:
>
> a) In thermodynamics the second law is formulated. As is well known, according to this law the entropy increases in a closed system. Since Boltzmann we know that entropy is a measure of "disorder" or 'randomness'. Therefore the second law of thermodynamics is the law of progressive disorganization, of destruction of existing structures. […]
>
> b) On the contrary, in biology or in sociology the idea of evolution is closely associated with an increase of organization with the creation of more and more complex structures."
>
> (Grene and Prigogine 1971, p.1)

As a universal "force" of dispersal or diffusion, the second law of thermodynamics seemed particularly appropriate in describing fluids expanding in space, mixing with each other and *reducing* gradients of all sorts (chemical, thermal,

[14] Most importantly, they assumed the universe was a spatially *static* and *isolated* system. This proved to be wrong, with quite remarkable consequences.

pressure). However, in contrast, gravitational attraction acted universally, in the opposite direction, as a force which concentrated matter, and created and maintained pressure, chemical and temperature gradients (Prigogine and Stengers 1984). This too seemed paradoxical.

It is this early 19th century equilibrium thermodynamics, complete with its profound paradoxes and grim cosmology, which was most influential to Georgescu-Roegen's economic thinking, from the 1950s-70s onwards. Indeed, it is the *irreversible destruction of the potential for work,* within the confines of a finite, static space or environment, associated to the second law, which Georgescu-Roegen found most relevant for economics (Georgescu-Roegen 1971). This purely destructive aspect of 19th century thermodynamics and the second law in particular continue to carry a profound intellectual influence on ecological economists today, and long term macroeconomic growth theories (Beard and Lozada 1999, Daly and Farley 2004, Mayumi 2001, Mayumi and Gowdy 1999).

2.3 Non-Equilibrium Thermodynamics: a short introduction

What is the difference between "modern non-equilibrium thermodynamics" (NET) as opposed to "19th century equilibrium thermodynamics"? Is there really a difference? I rely here on a few authoritative statements by physicist Kondepudi (2008), which succinctly distinguish the two:

> "Classical [equilibrium] thermodynamics, as it was formulated in the nineteenth century by Carnot, Claussius, Joule, Helmholtz, Kelvin, Gibbs, and others, was a theory of initial and final states of a system, not a theory that included the irreversible processes that were responsible for the transformation of a state to another. It was a theory confined to systems in thermodynamic equilibrium. […] Time does not appear explicitly in this formalism: there are no expressions for the rate of

change of entropy, for instance.

> Modern [non-equilibrium—AP] thermodynamics, formulated in the twentieth century by Lars Onsanger, Theophile De Donder, Ilya Prigogine and others, is different. It is a theory of irreversible processes that very much includes time: it relates entropy, the central concept of thermodynamics, to irreversible processes. […] Irreversible processes, such as chemical reactions, diffusion and heat conduction that take place in non-equilibrium systems, are described as thermodynamic flows driven by thermodynamic forces and flows. […] In addition to all the thermodynamic variables, the student is also introduced to the concept of *rate of entropy production*, a quantity of much current interest in the study of non-equilibrium systems."
>
> (Kondepudi, 2008, p.1)

This characterization is supported textbooks on non-equilibrium thermodynamics by Jorgensen, (2004) Kleidon and Lorenz (2005), Kjelstrup et al. (Kjelstrup et al. 2006) and Kondepudi and Prigogine (1998).

By the early 20th century, many physicists, chemists, and life-scientists in particular, were dissatisfied with the limited conditions and predictions which equilibrium thermodynamics (*and* equilibrium statistical mechanics[15]) offered. It is not merely that a sub-set of interesting systems are open, involve irreversible processes and occur in non-equilibrium conditions, for which traditional thermodynamics is ill-equipped to handle. Rather, *all real processes* in our universe[16] *only* occur under non-equilibrium conditions and are *irreversible*. Living systems and human economic activity, for example, only typify this in a most extreme manner. As Planck explained:

---

[15] This is an important point: *equilibrium* statistical mechanics (developed by Maxwell and Boltzmann in particular) relates the macroscopic variables of thermodynamics to microscopic models of atomic phenomena under equilibrium conditions. *Quantum equilibrium* statistical mechanics (developed by Planck, Einstein, Gibbs, and *many* others) takes account of the *quantum* nature of such atomic and subatomic phenomena, at *equilibrium*. The issue is not macroscopic vs microscopic. The issue is equilibrium vs non-equilibrium, and reversible vs irreversible processes as Planck explains.

[16] Technically, even a purely mechanical process, if it involves change in momentum, necessarily only occurs under non-equilibrium conditions (an excess of force in a particular direction). Otherwise, it is static: either at "rest", or in uniform motion, with respect to a given reference frame.

> "… in actual nature *there is no such thing as a reversible process*. Every natural process involves in greater or less degree friction or conduction of heat. […] I hope the foregoing considerations have sufficed to make clear to you that the distinction between reversible and irreversible processes is much greater than that between mechanical and electrical processes […] and that it may eventually play in theoretical physics of the future the principle role."
>
> (Planck 2009, p.20)

Irreversible processes and non-equilibrium conditions represented a substantial challenge to scientists on many levels[17]. The scientific-mathematical methods required to handle far-from equilibrium conditions in thermodynamics took a longer time to develop, but are now widely available (Glansdorf and Prigogine 1968, Nicolis and Prigogine 1989, Strogratz 2000). These new physical-mathematical methods allow a better glimpse into the substantially more complex, fascinating and lively phenomena of our world. They confront us with a new picture of the universe, different from the one implied by both 19th century equilibrium thermodynamics and classical mechanics.

[17] Among these challenges are path dependence and non-conservation in dynamic equations for irreversible processes, and non-linear or chaotic dynamics for far-from equilibrium systems.

Chapter 3
Thermodynamics and Ecological Economics

The general research question I ask in the thesis is: do discoveries in modern non-equilibrium thermodynamics render invalid important elements of Georgescu-Roegen's hourglass macro-economics model?

In this chapter, I will first introduce the field of ecological economics and discuss why thermodynamics is relevant to it. Second, I briefly review the limitations of neoclassical economics, which Georgescu-Roegen and many others have attempted to overcome with a completely new approach. In the following section I will present in more detail Georgescu-Roegen's macro-economic framework the hourglass) and its thermodynamic content. I then summarize the academic literature which has critically assessed the validity and relevance of Georgescu-Roegen's ideas of ultimate constraints to long term macro-economic growth and longevity. Finally, I present two misconceptions and one important implicit assumption introduced by Georgescu-Roegen which I reevaluate in this thesis from the point of view of modern non-equilibrium thermodynamics.

3.1 Ecological Economics

Ecological economics is a trans-disciplinary field of academic research which seeks to integrate the study of human economics and global ecology as the basis for a sustainable and desirable future, and eventually supplant neoclassical economics as the dominant economic paradigm. It is distinguished from the mainstream environmental economics (a branch of neoclassical economics) in that it considers, from the point of view of energy and materials throughput, the human economy to be a *subsystem* of a larger ecosystem (Ecosphere) in which it is embedded. Ecological economics has its origins in the works of Alfred Lotka, Frederick Soddy, Kenneth E. Boulding, Nicholas Georgescu-Roegen, and HT Odum in the 1950s through 1970s. It was organized into an active field of research by Herman Daly, Robert Costanza, and others in the early 1990s (Costanza et al. 2009, Daly 1997a, 1999, Daly and Townsend 1993, Daly and Farley 2004, Daly et al. 1994).

One of the unique aspects of ecological economics is its particular focus on the laws of thermodynamics. Thermodynamics is used in ecological economics as a general framework to set the boundaries of macroeconomic *analysis*, and define ultimate boundary constraints on very long term economic growth. It also helps in understanding, from a biophysical point of view, irreversible material and energy transformations involved in *all* agro-industrial transformations, and hence all economic activity, and transactions (Daly and Farley 2004).

The general sector of ecological economics on which I concentrate on in this thesis is the problem of limits to long term economic growth, or limits to macroeconomic scale[18]. The problem of scale has two aspects: one of intensity of activity at any given time (carrying capacity); the other of longevity or life-span.

In ecological economics, the problem of maximum size/intensity is essentially the same problem addressed long ago by Malthus, and later by the authors of "Limits to Growth" (Meadows et al. 2004), or those of the "ecological footprint" (Wackernagel and Rees 1996). That is, there are biophysical constraints which human

[18] Two other policy problems addressed in ecological economics are: just distribution of incomes, and efficient allocation of resources.

economic systems cannot surpass in a finite global environment, especially in terms of continuous growth in size/intensity of energy and materials throughput, without risking inevitable economic, ecological and population crashes.

However, Georgescu-Roegen mainly emphasized the other facet of this problem: the tradeoff between high intensities of economic activity and the decreasing remaining lifespan of agro-industrial civilizations.

3.2 Georgescu-Roegen's Critique of Neoclassical Economics

First, it is important to mention that mathematician and economist Nicolas Georgescu-Roegen (1906-1994) was no outsider to the economics profession. As a young student, Georgescu-Roegen was recognized as mathematical prodigy of sorts, and given full scholarship to study under the famous statistician, Karl Pearson in London. Afterwards, he earned another scholarship to continue post-doctoral work in economics and mathematics at Harvard, where he quickly earned the respect of eminent members of the faculty (including Schumpeter and Samuelson) as well as that of many visiting scholars. In 1975, a book was published in his honor containing a collection of essays on Georgescu-Roegen's important contributions to neoclassical economics. The essays were written by some of his well-known colleagues who respected and admired his original work; four, Kuznets, Samuelson, Hicks, and Tinbergen, were Nobel Prize winners in economics (Tang et al. 1976).

After decades of very successful and accredited academic work, that Georgescu-Roegen published in 1971 his more controversial book-length essay *The Entropy Law and the Economic Process* (Georgescu-Roegen, 1971). To give an idea of its impact, a quick scroll on an academic search engine reveals that Georgescu-Roegen's book has been cited nearly three thousand times[19]. This work was followed several years later by a collection of papers published under the title *Energy and Economics Myths* (1976), as well as a series of other separate articles, on the subject of economics, economic evolution and energy/entropy principles. Together these writings contain the essential elements of Georgescu-Roegen's radical alternative framework for economics, which I attempt to summarize here.

3.2.1 On Neoclassical Economics

Neoclassical economics refers to a reformulation of classical economics[20], begun in the 1870s – 1890s. Three of the main features of neoclassical economics include: first, a new theory of economic value and prices called marginal utility[21], entirely based of human psychology; second, the introduction of infinitesimal calculus in economic analysis; and third, the claim that economics, following this reform, had now become a hard science, theoretical and empirical, on equal footing with physics or any other of the natural sciences. Strangely, the founders of neoclassical economics (Jevons, Walras, Edgworth, Pareto, Fisher) closely patterned their new science of economics[22] on 19th century theoretical physics, especially analytical mechanics[23] (Mirowski 1991, Nadeau 2003). From theoretical physics they

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[19] The count was 2996. I used Google Scholar after not finding the appropriate entry in Scopus.
[20] Adam Smith, Thomas Malthus, David Ricardo, and John Stuart Mill: period 1775-1870.
[21] Conceptually, utility is the term for the satisfaction of economic needs or desires. It is measured as price times the quantity of different types of goods purchased, and mathematically is a scalar, like energy. Marginal utility on the other hand is a rate of change in utility over quantity of products. It is a gradient. Marginal utility replaced the old labor theory of value from classical economics (Smith, Ricardo, Malthus).
[22] Marginal utility value and human behavior
[23] Analytical mechanics is founded upon the concepts of a potential energy field (position), kinetic energy or momentum (motion), depending on the specific equations (Hamilton's or Lagrange's) and least action or optimizing pathways.

borrowed from more than just the same idealized axiomatic thinking, analytical methods (infinitesimal calculus, calculus of variation), and perhaps distant analogies.

As Georgescu-Roegen pointed out:

> "There are several regrettable consequences of the adoption of the mechanistic epistemology by standard economics. The most important is the complete ignorance of the evolutionary nature of the economic process. Being erected as a sister science of mechanics, the standard theory has no room for irreversibility any more than mechanics has. The standard analysis of the market is all based on complete reversibility from one equilibrium to another." (Georgescu-Roegen 1977, p.267)

Neoclassical economics serves as the historical-intellectual background and target of Georgescu-Roegen's later work. A summary of the "world view" and methods which shaped neoclassical economic thinking is presented in appendix 3.

3.2.2 Neoclassical economics: the circular flow of exchange

Georgescu-Roegen's book *The Entropy Law and the Economic Process* (1971) begins with a short comment on the absurdity of the idealized *homo economicus*. This aspect of neoclassical economics attracted the most important and recurrent criticisms (even among the professional economists). According to Georgescu-Roegen, from a social-psychological point of view, the shortcomings of the mechanical individual were obvious, but already by then, sufficiently recognized.

However, Georgescu-Roegen wanted to draw attention to a very *different* aspect of neoclassical economics. According to him, the mathematical structure of economic theory imposed assumptions on economic systems which, from a *physical* perspective (not merely *psychological*, as in micro-economics), were untenable in the long run. To quote Georgescu-Roegen:

> "Mechanics knows only locomotion, and locomotion is quality-less.

> The same drawback was built into economics by its founders, who, on the testimony of Jevons and Walras, had no greater aspiration than to create an economic science after the exact pattern of mechanics. A most eloquent proof of how staunch the enthusiasm for mechanics was among the early architects is provided by Irving Fisher, who went to the trouble of building a very intricate apparatus just for demonstrating the purely mechanical nature of consumer behavior.
>
> And these architects succeeded so well with their grand plan that the conception of the economic process as a mechanical analogue has ever since dominated economic thought completely. In this representation, the economic process never induces any qualitative change nor is affected by the qualitative change of the environment into which it is anchored. It is an isolated, self-contained and a-historical process –a circular flow between production and consumption with no outlets and no inlets, as the elementary textbooks depict it."
>
> (Georgescu-Roegen 1971, p.2)

The following diagram, called the circular flow of exchange (or income), illustrates in its simplest form, what Georgescu-Roegen was referring to. It is the neoclassical conceptual diagram still included in most economics textbooks today. The diagram describes: 1) the reciprocal circulation of income between producers and consumers, and 2) the reciprocal flow of production factors (labor) and production outputs (goods and services). In its more detailed form (with more sectors), the circular flow exchange model is used to keep track of national income and national expenditures (GDP), and thus to calculate annual national economic growth, and make forecasts for the coming years. It is the ground work upon which all further macro-economic analysis is possible, at least within neoclassical economics.

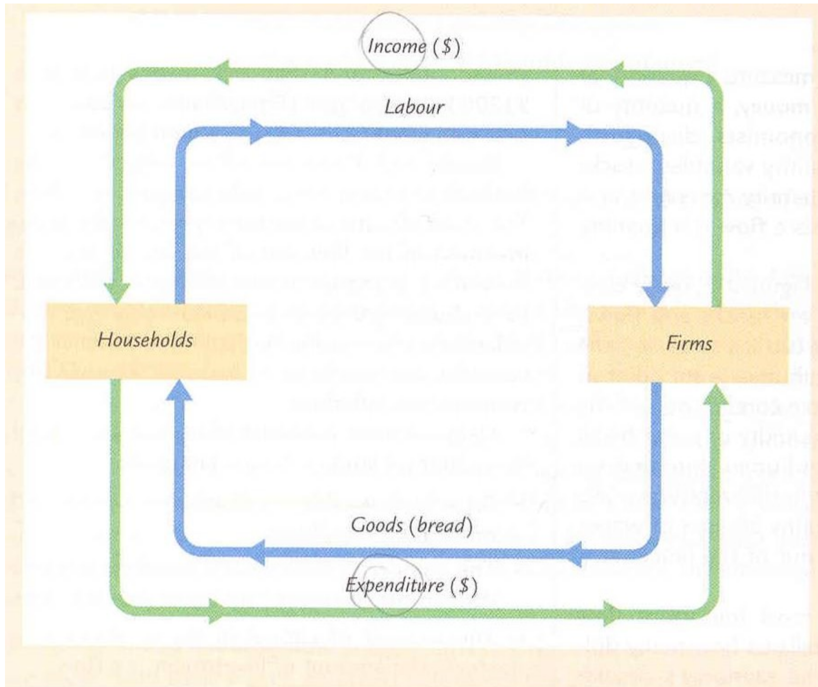

Figure 2. Neoclassical model: circular flow of exchange (Mankiw and Scarth 2001, p.19)

One can notice, as Georgescu-Roegen emphasized, the lack of "outlets and inlets" in the diagram. Where is the environment in this model? How do natural resources and waste products enter or exit the circular flow of exchanges? How large is the economy relative to the environment which supports it? If the circular flow of exchange accounts for business inventories being depleted or renewed during different economic phases, why not account for the Biosphere's geological and ecological resource "inventories", especially if they are being *irreversibly* depleted at increasingly rapid rates? Georgescu-Roegen wrote:

> "Economists do speak occasionally of natural resources. […] The contact some of these models have with the natural environment is confined to Ricardian Land, which is expressly defined as a factor immune from any qualitative change. We could very well refer to it simply as 'space'." (Georgescu-Roegen 1971, p.2)

Traditionally in neoclassical economics resources and sinks are considered as "given", or fixed in the short term, and are assumed to be unaffected by negligible changes in flow rates. The assumptions are that resource pools and pollution sinks are *external* to the process under study, and thus beyond the "boundaries of analysis" of economics[24].

Interestingly, the circular flow of exchange is also assumed to be perfectly reversible, just like the ideal reversible pendulum and Carnot cycle we discussed in chapter 2. From a physical point of view, this makes no sense at all:

> "There are several regrettable consequences of the adoption of the mechanistic epistemology by standard economics. The most important is the complete ignorance of the evolutionary nature of the economic process. Being erected as a sister science of mechanics, standard theory has no room for irreversibility any more than mechanics has. The standard analysis of the market is all based on complete reversibility from one equilibrium to another. […]
>
> The conception of the economic process as a merry-go-round between production and consumption *also* led to a second regrettable omission-that of the role of natural resources in that process."
>
> (Georgescu-Roegen 1977, p.267)

Georgescu-Roegen reasoned that an adequate macro-economic "framework" had to include, from the very beginning: first**,** irreversible processes fundamental to biophysical and real agro-industrial production processes; and second, finite absolute biophysical constraints which result from economic systems being embedded within a finite global biophysical system (earth system)[25].

Finally, to develop such a new "framework" and properly analyze the long term viability of human agro-industrial systems from this new perspective, Georgescu-

[24] In the long run, if "injections" into the circular flow exceed "leakages", measured in terms of monetary "value", the circular flow grows; if the contrary happens, it contracts. Because this type of growth and contraction is measured in terms of monetary value, it serves as the interpretation of recession periods and economic booms. Injections and leakages refer to money invested *within* the circular flow of exchange. Whatever this implies for the outside world is beyond the traditional boundaries of economic analysis.

[25] "The economic process is solidly anchored to a material base which is subject to definite constraints" (Georgescu-Roegen in Daly and Townsend 1993, p.81).

Roegen turned in part to the second law thermodynamics and a form of systems thinking, though he stayed away from detailed process descriptions, for reasons we will explain.

3.2.3 Georgescu-Roegen and methodology

Here, I describe why Georgescu-Roegen was interested in thermodynamic concepts to establish a new foundation for macro-economics; and explain for what specific methodological reason Georgescu-Roegen sought to use thermodynamics in economic science. To ensure accuracy of concepts and avoid misrepresentation, I quote Georgescu-Roegen at length in this and the following section. First:

> "From the epistemological viewpoint, the Entropy Law may be regarded as the greatest transformation ever suffered by physics. It marks the recognition by that science—the most trusted of all sciences of nature—that there is qualitative change in the universe.
>
> Still more important is the fact that the irrevocability proclaimed by that law sets on a solid footing the commonsense distinction between locomotion and true happening. According to this distinction, only that which cannot be brought back by reverse steps to a previous state represents true happening. […] …what happening this means is best exemplified by the life of an organism or the evolution of species…"
>
> (Georgescu-Roegen 1971, p.10)

Georgescu-Roegen was not alone in allocating a particular epistemological significance to thermodynamics, in contrast to that implied in reversible mechanics. In Chapter 2 we mentioned for example that Max Planck, at the turn of the 20th century, had forecast that the distinction between reversible and irreversible processes would "eventually play in theoretical physics of the future the principle role" (Planck, 2009, p.20). Georgescu-Roegen referenced other scientists, mathematicians or philosophers, such as Henri Bergson, Alfred N. Whitehead, Alfred Lotka[26] and Erwin Schrödinger[27], who had made remarkable breakthroughs in their own fields by applying principles of thermodynamics and irreversible processes in novel contexts[28]. Similarly, Georgescu-Roegen knew that thermodynamics was clearly relevant to human socio-economic systems; he even argued that the original thermodynamics of Carnot had in fact "*began* as a physics of economic value".

In reintroducing thermodynamic principles into economics, however, Georgescu-Roegen wanted to avoid two potential methodological errors: first, using thermodynamics merely as a kind of analogy, and second, modeling in detail that which could not be predicted (structural/qualitative changes). As he explains:

> "Instead of looking for a thermodynamic homology in the usual mathematical systems of economics, we may now try to represent the economic process by a new system of equations patterned after that of thermodynamics. In principle we can indeed write the equations of any given production or consumption process (if not in all technical details at least in a global form). Next, we may either assemble all these equations into a gigantic system or aggregate them into a more manageable one. But to write any set of initial equations, we must know the exact nature of the individual process to which it refers. And the rub is that in the long run or even in the not too long run the economic (as well as biological) process is inevitably dominated by a qualitative change which cannot be known in advance. Life must rely on novel mutations if it is to continue its existence in an environment which it changes continuously and irrevocably. So, no system of equations can describe the development of an evolutionary process."
>
> (Georgescu-Roegen 1971, p.17)

---

26 Alfred Lotka (1880-1949) was a famous demographer and mathematician, one of the founders of population biology and theoretical ecology. He used thermodynamics to advance a theory of evolution consistent with both natural selection, and physical science, and thus, a generalization of Darwinian evolution.

27 Famous quantum physics, Shroedinger also contributed to the foundation of biochemistry with his 1945 book "What is Life?".

28 Both Henri Bergson and Alfred North Whitehead discussed the primacy of change, becoming, evolution and irreversible processes in their writings on metaphysics and epistemology, in contrast to what they identified as an old Newtonian mechanical world view which had dominated western thought for two centuries. In the biological sciences, Alfred Lotka used thermodynamics and irreversible processes at the population and ecosystem level; while Erwin Schrödinger did the same at the organism and cellular level.

First he did not want to use thermodynamic equations, their form, and merely change the variables to fit human economic behavior, as had been done with micro-economics and analytical mechanics. Similarly, he did not expect that thermodynamics would unlock the mysteries of human psychology, complex social behavior and decision making. Second, because of a certain non-predictability of complex evolutionary processes, he did not believe that detailed models of individual agro-industrial processes could adequately depict macro-economic behavior in the very long run; even if the model's individual equations were supplemented with thermodynamic constraints. That is, Georgescu-Roegen explicitly did not choose to adopt system-dynamic modeling techniques as Forrester and Meadows employed (1971) for the global economy in the very long term, for specific methodological reasons.

Georgescu-Roegen never relinquished the use of mathematics and modeling to explain and evaluate ideas quantitatively for specific and tractable problems in economics. But he did warn against the traps and abuses associated to logical-deductive systems in general (see Whitehead 1928; Georgescu-Roegen 1971, p.16); especially since, according to him, they could not capture, by there very static structure, the novelty exemplified by long term evolutionary processes.

3.3 Georgescu-Roegen's Hourglass Model

Having now explained how Georgescu-Roegen was *not* going to use thermodynamics, I can now explain the use he *did* reserve for it. It is because of the very general method chosen by Georgescu-Roegen that I can re-evaluate his thinking in terms of analyzing assumptions which may no longer be valid today.

Georgescu-Roegen applied thermodynamic principles to the largest of scales, to redefine the boundaries of analysis of economics and encompass the economic system as a whole within the finite bounds of the earth-system. He thought thermodynamics could bring to light what he believed were the ultimate constraints and limits on global earth-bound agro-industrial systems in the very long run, *independent of changing internal processes, innovations, technologies, etc*. This was his most compelling and powerful argument. Even though one could not model radical evolutionary change, and the effect of innovations, resource substitution, technologies; nonetheless, in a finite environment, these innovations would be *bounded* by ultimate thermodynamic constraints (first and second law). Therefore, he argued, his analysis *was independent of path*, a most crucial aspect of 19th century thermodynamics.

First, he emphasized that all agro-industrial economic processes can be understood as transformations of energy and materials. Second, "free energy" itself (energy available to do work, or low entropy as he called it) is not a substitutable good, unlike specific materials or commodities (e.g. wheat vs rice and petroleum vs coal vs firewood); free energy is complimentary to every economic activity, regardless of its specific form. This non-substitutability of free energy in all agro-industrial economic processes then justified particular attention to the laws of thermodynamics, while taking a macroscopic, system-wide approach, typical of thermodynamics.

Georgescu-Roegen then separated energy resources into flows and stocks; solar flow was limited in intensity (energy per square meter), but practically unlimited in time; while energy stocks (such as fossil fuels) may have been unlimited in intensity, but definitely limited in time (being non-renewable, they were of finite duration).

The larger thermodynamic framework, governed by irreversible processes and the second law of thermodynamics, Georgescu-Roegen called the "hourglass":

> "[…] let the hourglass of Fig. 1 [see figure bellow—AP] represent an isolated system, i.e., that system exchanges neither energy nor matter with the outside. […]
>
> First, as the 'stuff' [matter-energy—AP] pours down, it changes its quality. The 'stuff' in the upper half represents available matter-energy, i.e., matter-energy in the form that can be used by us humans as well as by all other life-bearing structures of this planet. The 'stuff' in the lower half represents matter-energy which is unavailable in this sense. Second, the hourglass of the universe can never be turned upside down.
>
> These two special features are the essence of the Second Law of Thermodynamics, namely, that in an isolated system available matter-energy is continuously and irrevocably degraded into the unavailable state. […] If we now note that *entropy* is an index of the relative level of unavailable matter-energy, we may also say that the entropy of an isolated system continuously increases to a maximum."
>
> (Georgescu-Roegen 1977, p.267)

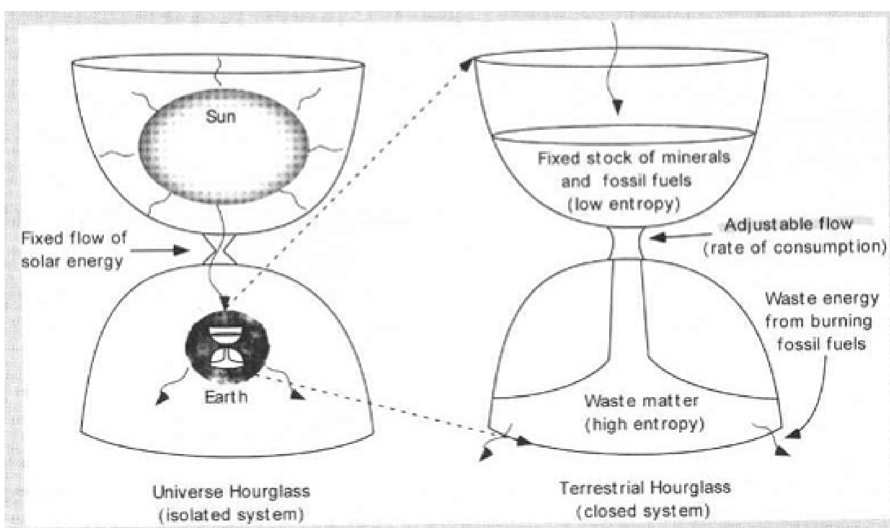

Figure 3. The Entropy hourglass conceptual model (Daly and Farley, 2004, p.30)

Rather than being bounded by an *isolated* system, Georgescu-Roegen then argued that the economy is bounded by a system which is closed, the earth system (the second hourglass on the right). It is closed to matter, and only exchanges energy with its environment, the solar system. The amount of matter in such a closed system remains constant at all times. In the case of the earth, the flux of energy coming from the sun is fixed in time. Because bulk matter too is subject to degradation due to mechanical friction, erosion, annual thermal shocks, chemical breakdown, and dispersal (chemical diffusion), Georgescu-Roegen argued that entropy also inevitably increases to a maximum in closed system. Even though "low entropy" (high quality)[29] energy is flowing in from the outside, and constantly replenishing degraded energy (high entropy, low quality), materials entropy, on the other hand, nonetheless constantly increases. His reasoning was that, even with the recycling by biological processes, some minerals, nutrients, and atomic elements would inevitably escape the biological cycle, and disperse widely, becoming of low quality, irreversibly and settle for eternity (low chemical oxidation-reduction potential and high dispersal).

Using the *first* law of thermodynamics in the context of a closed system, Georgescu-Roegen argued that the earth-system only contained a finite stock of "low entropy" (high-quality) energy-matter, "S", available to do work (to maintain human civilization and other living processes), and that this initial quantity S, was independent of scientific and technological discoveries, or any other internal evolutionary changes, that is path independent. According to the *second* law, the quantity of "S", low entropy energy-materials, was inevitably always being irreversibly depleted. There are *important* problems with this picture that will be discussed in the following sections.

The hourglass model implies the following regarding population growth,

[29] Georgescu-Roegen borrowed this language of low vs high entropy energy and matter from Schrödinger.

economic growth and the life-span of civilization, according to Georgescu-Roegen:

> "To see this, let S denote the present stock of terrestrial low entropy, and r be some average annual amount of depletion. If we abstract (as we can safely do here) from the slow degradation of S, the theoretical maximum number of years until complete exhaustion of that stock is S/r. This is also the number of years until the industrial phase in the evolution of mankind will forcibly come to an end. […]
>
> The fact remains that the higher the degree of economic development, the greater must be the annual depletion r and, hence, the shorter becomes the expected life of the human species."
>
> (Georgescu-Roegen in Daly and Townsend 1993; p.85)

Elsewhere, again using similar reasoning Georgescu-Roegen describes the following scenario:

> "To get to the core of the problem, let S denote the actual amount of accessible resources in the crust of the earth. Let P_i and s_i be the population and the amount of depleted resources per person in year *i*. Let the "amount of total life," measured in years of life, be defined by $L = \sum P_i$, from $i = 0$ to $i = \infty$. S sets an upper limit for L through the obvious constraint $\sum P_i s_i < S$.
>
> For although s_i , is a historical variable, it cannot be zero or even negligible (unless mankind reverts sometime to a berry-picking economy). Therefore, $P = 0$ for *i* greater than some finite n, and $P_i > 0$ otherwise. That value of *n* is the maximum duration of the human species."
>
> (Georgescu-Roegen 1976, p.23)

This seems rather simplistic. Nonetheless, his reasoning had merit. First, in comparison to the neoclassical economics model, this model extended the boundaries of analysis to include a changing environment upon which human economic systems depend. Second, even though many different types of resources can be *substituted* upon momentary scarcity or depletion, nonetheless, *there is no substitute to energy* itself in an agro-industrial production process, regardless of particular form; or as Georgescu-Roegen argued, there is no substitute for "low entropy" energy-matter itself. Third, rather then falsely assuming reversible processes, as was the habit in analytical mechanics and neoclassical economics, Georgescu-Roegen's model adopted a provocatively realistic approach, in making irreversible processes central to long term macro-economic thinking. Fourth, for the very reason, that there was no substitute to free energy itself (or low entropy), complex evolutionary processes, could nonetheless be understood, according to Georgescu-Roegen, as necessarily bounded by external thermodynamic conditions, in a changing environment. These changing environmental conditions were ultimately bounded by absolute thermodynamic limits ("S sets an upper limit for L", where L is life years, or longevity).

Contrary to many other authors who wrote on this subject (Daly 1977, 1997a, Meadows et al. 2004, Odum Howard T. 1971, Odum H. T. and Odum 1976), Georgescu-Roegen's thermodynamic thinking led him to conclude that even a perfectly steady state system were impossible in a finite environment for an indefinite period of time. This, he argued, was due to irreversible processes depleting stocks of high quality resources and increasing stocks of waste products in a finite space.

His thoughts about the steady state economy, currently the more commonly accepted macro-economic model within ecological economics, are reflected in the following comments:

> "The earth also has a so-called carrying capacity, which depends on a complex of factors, including the size of s_i. This capacity sets a limit on any single P_i. But this limit does not render the other limits, of L and n, superfluous. It is therefore inexact to argue—as the Meadows group seems to do—that the stationary state can go on forever as long as P_i does not exceed that capacity. The proponents of salvation through the stationary state must admit that such a state can have only finite duration—unless they are willing to join the 'No Limit' Club by maintaining that S is inexhaustible or almost so—as the Meadows group does in fact." (Georgescu-Roegen 1975. 23)

And

> "This vision of a blissful world in which both population and capital stock remain constant, once expounded with his usual skill by John Stuart Mill, was until recently in oblivion. […] The crucial error consists in not seeing that not only growth, but also a zero-growth state, nay, even a declining state which does not converge toward *annihilation*, cannot exist forever in a finite environment. […] (Georgescu-Roegen 1975, p.23)

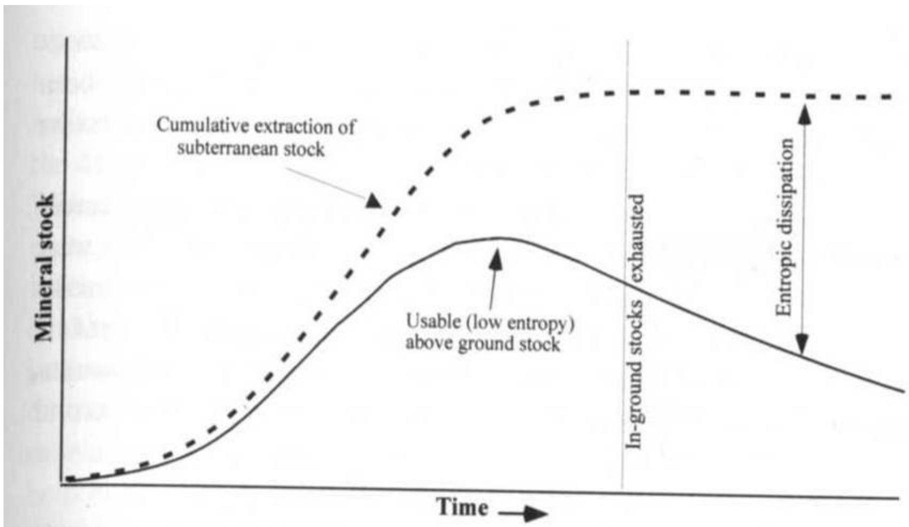

Figure 5.2 • The cumulative extraction of subterranean stock and aboveground stock of minerals over time. The distance between the two curves is a measure of entropic dissipation.

Figure 4. "Low entropy" resources being depleted (Daly and Farley 2004, p.85)

This dismal fate, the convergence toward *annihilation*, is the logical conclusion of Georgescu-Roegen's thermodynamic reasoning applied to population theory, agro-industrial pollution, natural resources depletion and very long term economic growth. We can notice the similarity with 19th century thermodynamic cosmology on Georgescu-Roegen's thinking: economic annihilation being the earthly equivalent of universal "heat death". Discounting some apparent errors, there are several reasons why Georgescu-Roegen's position is particularly interesting to reevaluate, both from a purely scientific and theoretical point of view, as well as one with very practical, with broad policy implications for long term macro-economic and environmental policy. Since he presented his arguments, scholars have weighed in both against and in support of Georgescu-Roegen.

3.4 Appraisal of Georgescu-Roegen's Hourglass

I now summarize an existing body of academic literature which has either criticized or praised the validity and relevance of Georgescu-Roegen's new macro-economic framework.

3.4.1. General comments and early response: 1970-1980s

In 1999, Herman Daly, one of the two founders of ecological economics, claimed that the orthodox neoclassical economics community had been silent towards Georgescu-Roegen's work on entropy and economics for over 20-years (Daly 1999). Yet, there is ample evidence which suggests that Georgescu-Roegen's work did not go unnoticed. On the contrary, as mentioned previously, Georgescu-Roegen's 1971 book, *The Entropy Law and the Economic Process*, has to this day been cited over 3000 times, second only in its genre to *Limits to Growth*. What Herman Daly means specifically by his comment is that key professional economists, the leading advocates of infinite exponential growth without constraints (particularly Nobel Prize winning economist Robert N. Solow, and Joseph Stieglitz), had not chosen to publicly respond to specific issues raised by Georgescu-Roegen, or modify their theories in accordance to his criticism (however see Daly 1999, where Solow and Stieglitz give short comments to long-lasting queries, and Mayumi, 1999, where Paul A. Samuelson contributes an essay in honor of Georgescu-Roegen).

It is very possible that both Georgescu-Roegen's general approach (using thermodynamics) and long term *apocalyptic* conclusions were too radical, and too sudden a departure from both the existing methods of practice within the profession, and the long term ideological expectations of progress widely promoted by professional economists and financial/political institutions. It is also possible that the multi-disciplinary arguments employed by Georgescu-Roegen (i.e. the mix of physics, philosophy and economics) caused a great deal of confusion among specialized economic colleagues. Furthermore, entropy in particular is intrinsically liable to confusion even among physicists themselves. In a 1986 "retrospect" article, looking back on his work on thermodynamics and economic processes, Georgescu-Roegen explains:

> "The reaction of my fellow economists to this idea and especially to its messages relevant to economic life has been such that a survey of my thesis as I have expanded it through several subsequent papers should make a clarification of some issues worthwhile."
>
> (Georgescu-Roegen 1986, p.1)

Many of the critiques of Georgescu-Roegen's work have focused on his attempts at introducing a fourth law into thermodynamics, to acknowledge the impossibility of infinite materials recycling, and emphasize the equally dissipative nature of matter and its implications for long term growth and viability, what he called "materials entropy". In the same retrospect article quoted above, Georgescu-Roegen addressed this issue extensively:

> "In my earlier writings I took for granted that thermodynamics had paid attention to what happens not only to the quality of energy as things keep happening but also to that of matter (matter in bulk, as distinguished from microscopic matter). I also thought that they had seen that friction does not only degrade energy but matter as well.
>
> Subsequently, however, I saw that I was wrong. Thermodynamics have stopped short from considering all effects of friction. Undoubtedly because friction is a most elusive phenomenon.

(Georgescu-Roegen 1986, p.6-7)

However, in this article, Georgescu-Roegen reiterated his position on materials entropy, only seeing the need to explain it further (Georgescu-Roegen 1986).

Additionally, I believe an important reason why Georgescu-Roegen's ideas may not have initially been well received, is that he often identified his concerns about population growth, pollution and exhaustion of resources with the old doctrines of the classical economist Thomas Malthus. In fact, as of the 1960s, a group of economists and biologists began reviving Malthus's ideas of absolute limits to population and impending famines and doom. Thus Georgescu-Roegen was also *easily categorized* as one of those "neo-Malthusians" whose pessimistic outlook and repeated catastrophic predictions could often easily be refuted by simple historical evidence; whereupon scientific revolutions and so many technological inventions had succeeded in eluding the limited imagination of the Malthusians.

As an example of this type of criticism, an early reviewer of Georgescu-Roegen's 1971 book cogently commented on Georgescu-Roegen's use of the entropy law in economics:

> "As an operational proposition, and so far as its policy implications are concerned, the entropy law turns out simply to be another extreme form of Malthusianism. […] I find it amazing that so many distinguished scientists (like Georgescu-Roegen) should so completely lose touch with the first command of the scientific endeavor, namely, to check prediction against performance, just as soon as they venture into the realm of social policy. […] Georgescu-Roegen has told us that 'whenever a Spencerian tragedy—a theory killed by a fact—takes place, then the minds of the scholarly world know no rest until a new logical foundation is laid'. How many facts are required to kill Malthusian (or entropian) theory applied to social event?" (Solo 1974, p.516-517)[30]

One of the well-known radicals on the *opposite* side of the infinite growth vs

[30] That is Robert A. Solo. Not the same person as Robert N. Solow (Nobel Prize economist)

impeding apocalyptic catastrophe debate, economist Julian Simon (1998), claimed many times to have perfectly refuted both the Malthusian authors of the *Limits to Growth* and the entropic economy theory (Georgescu-Roegen) through empirical evidence (Simon 1998). The debate persists, however, because the claims coming from the other radical side of the table (the side of the neoclassical economists, and in the case of Julian Simon and Milton Friedman in particular: the blind magic of the perfectly rational markets) also fail to stand the rigorous test of historical evidence, scientific reasoning, logic and academic honesty (Daly 1999, Smil 2001, 2005).

3.4.2 Renewed interest since the 1990s: focus on materials entropy controversy

Since the early 1990s, climate change and sustainability politics have created the context for serious and lively intellectual debate, especially between environmental economists and ecological economists (Amir 1994, Ayres 1998, 1999, Bianciardi et al. 1993, Daly 1995, 1997b, Kaberger and Mansson 2001, Krysiak 2006, Lozada 1995, 2006, Ruth 1995, Sallner 1997, Williamson 1993). The debate has focused on the relevance of thermodynamics in general to economic science and growth theories in particular, and Georgescu-Roegen's specific ideas on the topic, mainly his entropy hourglass model, and his concept of "materials entropy".

Arguments tend to cluster around three broad positions.

Some argue that Georgescu-Roegen's interpretation of thermodynamics itself is rather flawed, and/or that thermodynamics is by in large irrelevant to economics. Others argue that Georgescu-Roegen's understanding of thermodynamics is quite accurate; that thermodynamics is extremely relevant to economic constraints (in terms of materials and energy) both in the short term and long term (thus the 1st and second laws are both important). A third group of scholars advise caution in not overstating, yet also appreciating, the worth of a thermodynamic approach to aspects of the economic process, while correcting some common flaws in both camps along the way.

In this new context, the issue of materials entropy uniquely raised by Georgescu-Roegen has so far dominated the discussion, and deserves a few short comments.

"Materials entropy" was an important factor in Georgescu-Roegen's "hour glass" model, his assessment of the impossibility of infinite materials recycling, and the impossibility of a steady-state economy in the long-term. He even proposed a fourth law of thermodynamics to emphasize its particular relevance[31]. Many have quickly attempted to correct this aspect of Georgescu-Roegen's work, noting first, that materials entropy is already contained within the second law, as Gibbs chemical diffusion, and needs no special status of its own (Bianciardi, Tiezzi, and Ulgiati 1993). Second, important examples of complete recycling exist in nature's own economy, such as with long term biogeochemical cycles and living processes. Thus, given an abundant energy source, the second law does not imply the impossibility of complete materials recycling.

The minimum consensus seems to be that the ultimate relevance of thermodynamic principles for matter in economics is that the energy costs of materials degradation, dispersal and recycling must *not* be ignored, and many specific non-substitutible essential elements, and matter generally, is also a corequisit to all agro-industrial economic activity. Thus the thermodynamic principles of dissipation and conservation of materials apply as well.

[31] Technically, a fith law, if one counts the 0^{th} law of thermodynamics, and the third law. There are currently four accepted laws of thermodynamics: the 0^{th}, 1^{st}, 2^{nd}, and 3^{rd}.

Not withstanding these important considerations with materials (related to finite am.ounts of rare elements), many strongly believe that by far the more fundamental thermodynamic constraint (first and second law) for economic processes may ultimately lie at the level of energy availability .

3.4.3 Other research avenues: implications of NET for ecological economics

A few researchers have asked whether fundamental breakthroughs in modern non-equilibrium thermodynamic may further substantiate or rather invalidate many of Georgescu-Roegen's initial conclusions about the fate of long term macro-economic processes.

As we saw in Chapter 2, many challenging contradictions arise from the attempt to apply Claussius' or Boltzman's "entropy" within a unified theory of non-equilibrium thermodynamics. In the last decades a true storm has taken over the field, in the realization that 19th century's (equilibrium) thermodynamics rather resembles a kind of *static* special case, and that it lacks the true *dynamic* characteristic of real irreversible processes, change and evolution writ large (Kondepudi 2008, Chaisson 2004).

Robert Costanza (one of the founders of the international society for ecological economics) summarized currently active areas of research within ecological economics, including 1) multi-scale modeling of complex non-linear systems, 2) non-equilibrium thermodynamics of ecosystems and economies, and 3) theories of cultural and biological co-evolution (Costanza 2009). I have identified unresolved issues with Georgescu-Roegen's original hourglass model, for which modern non-equilibrium thermodynamics (NET) may be of good use.

3.5 Assumptions of the Hourglass Model

There are two misconceptions and one important implicit assumption introduced by Georgescu-Roegen, related to the growth and maintenance of complex economic structures and functions, which I reevaluate in this thesis from the point of view of modern non-equilibrium thermodynamics.

The two misconceptions are: first, the role of irreversible processes as exclusively destructive of complex structure and function; and second, and the role of finite biogeophysical space as exclusively limiting[32]. The important assumption is that energy and spatial boundaries can be *fixed* once and for all in the analysis of coevolving economic and ecological systems, independent of evolutionary processes (path independence) occurring both inside and outside the system of interest. These two misconceptions and the assumption result in erroneous conclusions, and are not justified from the point of view of modern non-equilibrium thermodynamics. In contrast, I will rather emphasize the historically dynamic (as opposed to static or fixed) nature of these energy and spatial boundaries, as being more consistent with modern non-equilibrium thermodynamics.

In summary, contrary to others who wrote on this subject, Georgescu-Roegen hypothesized that even a perfectly steady state system were impossible within a finite environment for an indefinite period of time. To make this claim, Georgescu-Roegen used arguments based on thermodynamic principles. As he repeatedly emphasizes, his arguments and thermodynamic thinking were largely derived from 19th century thermodynamics (which may now be quite outdated).

[32] Limiting in terms of growth and maintenance of complex structures and functions.

Chapter 4

Modern Non-equilibrium Thermodynamics (NET)

Non-equilibrium thermodynamics (NET) and non-equilibrium *statistical* thermodynamics are very advanced fields of theoretical and applied research, with many coexisting "schools of thought"[33]. This can make the topic quite vast and complex. However, many key characteristics of NET can be summarized in plain language, and for the purposes of this thesis, I will make use of only a few of the most important and relevant concepts.

In this chapter, I first briefly introduce NET from the perspective developed by physical chemist and Nobel Prize laureate Ilya Prigogine. Next, I summarize key differences between equilibrium thermodynamics and NET. Thirdly, I then provide paradigmatic examples of the modern NET perspective applied to cosmology, and global ecosystems ecology (earth-system science). These examples will help demonstrate the importance of considering the dynamic nature of energy and spatial boundary conditions for the long term growth and development of complex dissipative structures. They include systems, both non-living and living, whose spatial scales are above and below that described by Georgescu-Roegen's hourglass: the Earth-System. Together, the key concepts and examples taken from modern NET and explained in this chapter highlight important misconceptions and assumptions implicit in the nature of Georgescu-Roegen's thermodynamic arguments and prepare the more detailed discussion of Georgescu-Roegen's hourglass in the next chapter.

[33] Some work in non-equilibrium thermodynamics dates back to the 19th century, to Fourier, Frick, Ohm, Maxwell, Kelvin and Boltzman. A key turning point in the development of modern non-equilibrium thermodynamics was Lars Onsager's work, in the early 1930s (Nobel Prize in 1968), and central to the approach later taken by Prigogine.

4.1. NET vs Equilibrium Thermodynamics

I have identified important differences between NET and equilibrium thermodynamics which are relevant to this thesis. These are:

1) in general, because the range of conditions which modern non-equilibrium thermodynamics (NET) covers is much greater, NET is now considered the more general science, while 19th equilibrium thermodynamics (thermo-*statics*) is considered a special case (Chaisson 2004). Following Prigogine et al. modern thermodynamics can be divided into three regimes according to distance from equilibrium: at equilibrium (i.e. thermo-*statics*), near equilibrium (i.e. linear-thermodynamics), and far-from-equilibrium (i.e. non-linear thermodynamics). See Appendix 3.

2) NET typically deals with open systems where thermodynamic gradients exist and can even increase in time through process coupling and energy and material exchanges with the environment. In equilibrium thermodynamics on the other hand, the standard system is the isolated system, where all gradients are inevitably destroyed.

3) In NET, the *rates* of irreversible processes and the *rates* of entropy *production* are accounted for in detail (in space and time). To accomplish this in NET, a clear distinction is made between irreversible entropy production (dSi) and *reversible* entropy exchange (dSe) associated with the infinitely slow (timeless) exchange of matter or heat under ideal equilibrium conditions. In equilibrium thermodynamics only system-wide equilibrium *states* can be accounted for (initial and final, connected by imaginary reversible processes). In equilibrium thermodynamics, time rates of change (dynamics) are excluded.

4) In NET, it is recognized that irreversible processes can play a *constructive* role, leading to the emergence of new dynamic states of organization of matter (order). Under far-from-equilibrium conditions (and with open systems) diverse and *qualitatively* unexpected phenomena can spontaneously emerge or self-organize (see the appendix 4). Prigogine famously called this set of emergent, dynamic, processes "dissipative structures", to distinguish them from well-known equilibrium, static, "structures" of physical-chemistry, such as crystal lattices. While in equilibrium thermodynamics, irreversible processes are associated with the destruction of *dynamic* order[34]. Again, using the authority of Prof. Kondepudi's textbook:

> "While it is true that increase of entropy can be associated with increase in disorder and dissipation of usable energy, entropy-producing irreversible processes can yet generate the ordered structures we see in Nature. […] Modern [non-equilibrium –AP] thermodynamics also gives us a paradigm for the order and self-organization we see in nature that is different from the clockwork paradigm of mechanics. […] Such structures, which are created and maintained by irreversible processes, were termed dissipative structures by Ilya Prigogine.
>
> (Kondepudi 2008, p.2)

More importantly for this thesis:

5) In NET, the spatial boundaries of "open" systems can be extremely complex and diverse in terms of structure and physical-chemical properties. They can also vary greatly both among and within different kinds of "open" systems[35].

[34] Even equilibrium phase *transitions*, which can lead to ordered structures such as crystals, actually depend on non-equilibrium conditions irreversible processes (chemical or nuclear reactions which release heat). If non-equilibrium conditions were not present, the *transition* itself would not occur, and different phase components would merely coexist throughout a mixture.

[35] For example: the *continuous* pressure-moisture-temperature gradients which loosely contain an atmospheric cloud; the more *discrete,* chemically-specific and functionally complex nature of eukaryotic cell membranes and protein-ion-channels; the highly dynamic nature of the ozone layer and the magnetosphere. All of which are considered "open" systems.

Therefore, in NET, it is best to supplement the concept of an "open" system and "open" boundaries with that of systems and boundaries having *selective-permeability* (both for specific types and rates/intensities of matter and energy flow). Furthermore, the properties of open spatial boundaries, and therefore the topology of open systems[36], can change dynamically in time. These properties can evolve. In this context, the finite and enclosed spatial boundaries of "open systems" can play an *extremely* important, *active* and *constructive* role in the emergence and maintenance of complex dissipative systems. Meanwhile, in equilibrium thermodynamics, the isolated system has absolutely impermeable and fixed spatial boundaries[37]. They provide the topological conditions which inevitably destroy dynamic complexity, order and all processes within a system.

6) As irreversibility is reintroduced into physics (as in NET), so too is the concept of "path dependence" (i.e. that *history* matters). Path dependence makes the prediction of future states of a system complicated. The future state is dependent not only on initial conditions and dynamic laws (or state functions and specified forcing values), but also on specific trajectories (path histories) selected among *many* possible alternatives. In this way the evolutionary behavior of far-from-equilibrium physical-

[36] Connectivity is a topological characteristic. If two enclosed systems (spaces) can exchange a specific *type* of matter-energy across their boundary, they are topologically connected for that type of matter-energy. Continuously varying rates and intensities would usually not be topologically important. However rates/intensities are important when the systems or spatial boundary has a physical threshold of matter-energy flow/intensity, beyond which the spatial connectivity of the system suddenly changes, and perhaps irreversibly destroys, denatures, or builds up the spatial boundary itself (thus changing the system's topology). Changes in topological features are discontinuous, and are associated to phase transitions. They can however be caused by a combination of continuous change (say energy-intensity) and non-linear, threshold, mechanism (say minimal chemical activation energy).

[37] The isolated system is (theoretically) absolutely impermeable to *all* types and intensities of energy and matter flows. The closed system is absolutely impermeable to all types and intensities of matter flows. The spatial boundaries of a system are often assumed to be fixed, non-evolving, conditions of the system.

chemical systems resembles important aspects of biological and social systems evolution (e.g. chance, history, necessity, and also novelty and diversity). In NET, irreversible processes and topological changes are extremely important. Both independently violate the conditions for path-independence, and therefore violate many assumptions associated to *equilibrium* thermodynamics. This becomes very important when trying to estimate, uniquely, either the maximum quantity of entropy which can be *produced* in a system or the maximum amount of free energy available to do work (i.e. the systems limits of evolution)[38]. In reality, both maximum entropy and maximum free energy are often moving targets (Chaisson 2001, 2005). On the other hand, *equilibrium* thermodynamics depends absolutely on the assumption of path independence. With this condition, the final equilibrium state of a system is uniquely determined. In an isolated system, the final equilibrium state uniquely corresponds to the *state* of maximum entropy, and is achieved, in time, after the maximum amount of entropy has been *produced* within the system boundaries (the end, or death, of the system's evolution).

In terms of my thesis, path dependence of evolving systems makes the kind of thermodynamic analysis employed by Georgescu-Roegen inappropriate and misleading (see Chapter 5).

There are several other very important points relevant to the modern NET perspective.

One is related modern nuclear physics:

7) The nuclear/thermodynamic instability of all atomic elements differing from iron (hydrogen in particular).

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[38] With new degrees of freedom, these values change, and the system can continue to evolve.

Another is related to quantum mechanics:

8) The discrete thresholds (quantum energy spacing) between different modes of both kinetic (translational, rotational, vibration, and potential energy (electrostatic, nuclear).

The other two are related to the thermodynamics of gravitational systems and modern cosmology.

9) The negative heat capacity of gravitational systems, and

10) The accelerating expansion and dynamic nature of physical space-time itself.

These last points are discussed with the help of examples.

4.2 Cosmic Evolution and NET: the Big Picture

> "… the evolution of the universe is dominated by the paradox of order and disorder. The paradox is the apparent contradiction between two facts. On the one hand, the total disorder in the universe, as measured by the quantity that physicists call entropy, increases steadily as we go from past to future. On the other hand, the total order in the universe, as measured by the complexity and permanence of organized structures, also increases steadily as we go from past to future. How can it happen that both order and disorder are constantly increasing with time? This is the paradox that we have to understand.[39]
>
> (Dyson 2007, p.61-62)

The paradox of order and disorder has both delighted and troubled the human mind for millennia. The requirements of energy and material flows in open systems for the construction and maintenance of ordered structures, including living processes and human societies, has been known intuitively for quite some time. In

[39] Physicist Freeman Dyson goes on to present 4 reasons why order can increase against a flow of increasing entropy in our universe. These are: 1) the expansion of the universe, 2) negative heat capacities of thermodynamic systems, 3) the occurrence of symmetry-breaking phase transitions, and 4) the phenomenon of symbiosis (broadly considered). We present a very similar, if not identical, account hear, only in a *form* which matches more closely the specific problems encountered in G-R's reasoning, and in some areas, using more quantitative explanations.

modern history, the science of thermodynamics and statistical thermodynamics has greatly contributed to reformulating the old paradoxes associated to order and disorder into mathematically precise and experimentally verifiable statements and predictions.

The thermodynamics of the 19th century led many scientists to gloomy conclusions. According to many assumptions discussed previously, it was thought that, regardless of *local* and momentary islands of order, thermodynamic gradients at higher levels of system hierarchy should steadily be decreasing in time, for the system as a whole. Thus, in the very long term, the cosmic-environmental conditions required for the emergence and maintenance of both order in general in the universe, and life and complex societies in particular, should slowly be declining in time, monotonically. This situation is represented in Figure 5, which shows increasing entropy (TΔS) and decreasing free energy (ΔF) of an isolated system in time.

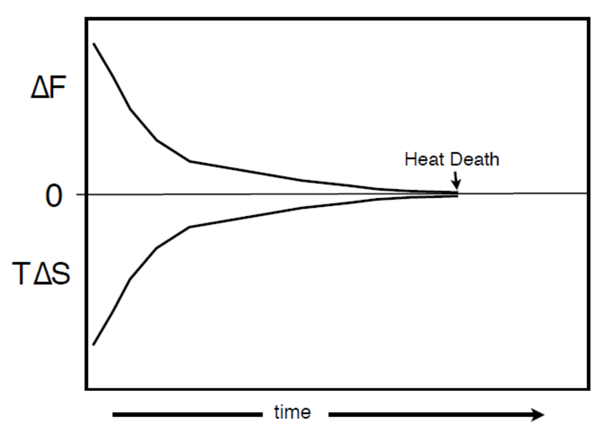

Figure 5. Entropy increase (ΔS) and free energy decrease (ΔF) in an isolated system

However, this graph describes a very particular type of system: a "branch system" originally in a state of disequilibrium, which is then cut off and isolated from the rest of the universe by absolutely impermeable, everlasting *and fixed spatial and energy boundary conditions* (Davies 1977). Several important questions remain: how did the "branch system" come to achieve its state of disequilibrium in the first place? That is, what ultimately generates the matter-energy gradients (free energy, necessary for complexity) at higher levels of the system hierarchy, and are these gradients really decreasing in time? Furthermore, what *physical* process generated the peculiar spatial boundaries of the system? And by implication, are these spatial boundaries fixed in time?

By asking such questions, modern cosmology and NET has cast great doubt on the gloomy and simplified picture of universal heat death scenario, including similar versions at more regional scales of the cosmos. Though still inconclusive in many respects (Egan 2009; Krauss 2000), the *range* of current predictions (possibilities, not pre-determined outcomes) for the future of complexity in our evolving universe are quite large and surprising (Dyson 1979, 2007).

The general pattern of emergent complexity described in the examples below has become paradigmatic of a new way of thinking about complex evolutionary processes occurring at many different scales, from the point of view of NET. This includes biological and human socio-economic systems (Chaisson 2001). Furthermore, the examples (and specific scales) selected and presented below, will be indispensable to help situate, hierarchically and functionally, our rapidly evolving human economic society, in its larger bio-physical and cosmic context. This cosmic-environmental context has itself been evolving and undergoing tremendous transformations, simultaneously at all spatial-scales, since the Big Bang, 14.5 billion years ago.

4.3.1 NET and the Expansion of the Universe

On the largest of scales, the expansion of physical space-time itself ultimately helps create the thermodynamic conditions necessary for the emergence of order in the universe (Chaisson 2002). Following the big bang, the young universe under rapid expansion had a uniform distribution of radiation and was in a state of thermodynamic equilibrium (maximum disorder or maximum entropy). Progressively, the universe and gas of photons cooled through reversible adiabatic expansion. As it cooled, the universe evolved through a series of monumental non-equilibrium phase transitions, resulting in the condensation/formation of matter, stable atoms, molecules, and eventually large gravitational clusters. These abrupt phase transitions led the universe into successive states of *greater* thermodynamic *disequilibrium* and progressive development of ordered structures (see Chaisson 2001, 2005, Davies 1977, Dyson 2007).

Phase transitions are associated with discontinuous breaks in an entropy vs thermodynamic forcing graph (*state* of entropy in the former, *rate* of entropy production in the latter). Upon reaching a phase transition, the state of maximum entropy and the maximum total amount of entropy which is possible to produce within the newly evolved boundary conditions of the system[40] can *dramatically* change. Why is this important? The state of maximum entropy (S max) defines the final resting equilibrium of an evolving system (the limit of its evolution). This state of equilibrium is reached when no further entropy can be produced within the newly evolved boundary conditions. If these maximums are moving targets, then the

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[40] The same considerations will apply to free energy under non-equilibrium phase transitions. The free energy available to do work may change dramatically upon reaching a new threshold. For free energy to be positive, there must exist a difference between the actual state of entropy of the system, and state of maximum possible entropy.

system may continue to evolve.

The following figure produced by Chaisson (2005) illustrates the tremendous importance of this fact.

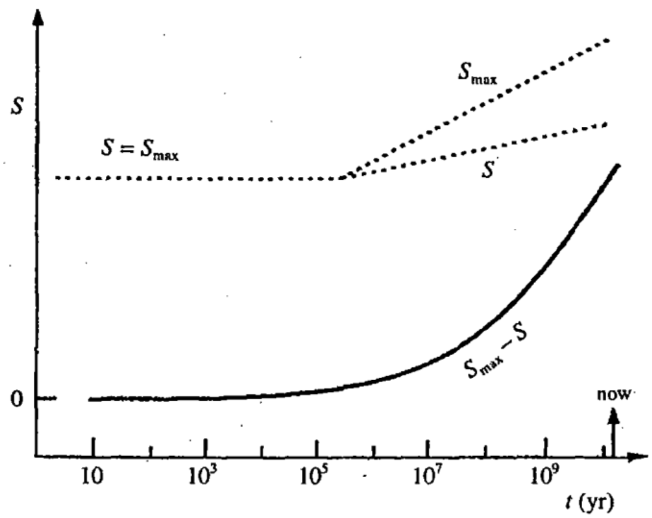

Figure 6. Free energy (S-So) increasing in the universe

"In the expanding Universe, the actual entropy, S, increases less rapidly than the maximum possible entropy, S max, once the symmetry of equilibrium broke when matter and radiation decoupled at ~10^5 years. By contrast in the early equilibrated Universe, S=Smax for the prevailing conditions. The potential for the growth of order (Smax -S), shown as the thick black curve – has increased ever since the start of the Matter Era. Accordingly, the expansion of the Universe [and the abrupt phase transitions—AP] can be judged as the ultimate source of free energy, promoting the evolution of order in the cosmos."

(Chaisson 2005, p.27)

As the Chaisson explains, it is the *difference* between the actual amount of entropy in a system and its maximum possible amount which defines the free energy available to do work. Following the expansion of the universe and the monumental phase transition which led to the separation of matter from the background cosmic radiation, free energy and thermodynamic gradients have been increasing in time. However, as Freeman Dyson explains:

"The expanding universe solves the paradox of order and disorder for processes happening on the scale of the entire universe. The paradox on the

> universal scale is solved, because order can increase in one part of the universe while disorder increases in another part [separation of matter and radiation—AP]. But the paradox also exists on a local scale, for processes confined to local regions. [...] We therefore need another solution of the paradox, a solution that explains how order and disorder can both increase in a local neighborhood, independently of what the universe outside the neighborhood may be doing"
>
> (Dyson 2007, p.78-79)

We must therefore follow the argument down to the next hierarchical level, that of solar systems, stars and planets.

4.3.2 Gravitational Systems, NET and Negative Heat Capacities

As previously mentioned, the intuitive association between the second law of thermodynamics and increasing disorder (diffusion/dispersal) in time is challenged when considering the evolution (or development) of gravitational systems. Figure 7 shows the difference between a collection of particles evolving in time with and without gravitational effects. In the case of gas diffusion in a negligible gravitational field, local concentrations of matter decrease in time. However, in the case of a system of particles under the significant influence of gravity, particles tend to coalesce (aggregate) in time. Matter becomes increasingly concentrated into a small volume, leaving the cosmic environment relatively empty. This creates important spatial in-homogeneities (and thermodynamic gradients) in the distribution of matter and energy, without ever violating the second law of thermodynamics.

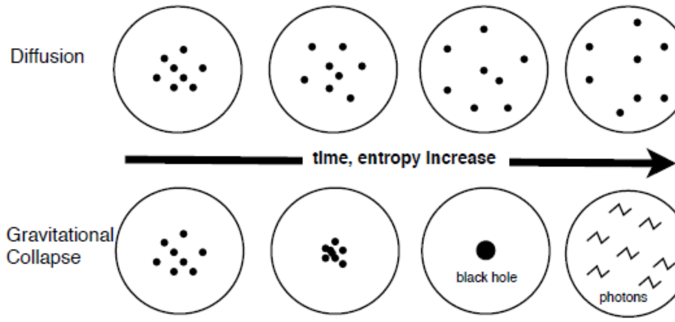

Figure 7. Entropy increase: without and without a gravitational field (Egan 2009, p.151)

At different stages, local fluctuations in the density of matter in these systems will be unstable, due to: 1) the gravitational force increasing with matter density (creating a positive feedback), 2) irreversible processes allowing for a *loss* of energy from the system, 3) the fact that the system is open and can *lose* the energy released from irreversible processes, 4) the negative heat capacity of gravitational systems causing system temperatures to rise, as energy is lost (positive feedback, as we will explain), and 5) the nuclear instability of hydrogen and helium (the most abundant elements in the universe), leading to further increases in mass density. At other times, the fluctuations will be damped, or stable, due to: 1) electromagnetic repulsion, 2) radiation pressure, and 3) quantum-mechanic effects (degeneracy pressure). Upon reaching critical energy threshold points (of energy density), the relative strength of the stabilizing vs destabilizing forces may shift dramatically.

Initially, matter and energy may be almost uniformly (randomly) distributed in a cosmic environment as a cloud of galactic gas and dust. Local fluctuations cause local gravitational forces to increase and particle clusters to attract each other. It is important to note, however, that *without irreversible processes and the net loss* of energy to the cold cosmic background, particles of matter attracted by gravitational forces would endlessly rebound against each other, like galactic pendulums. In fact, it is due to the open system's ability to *lose* energy into outer space that solar systems can form and self-organize into relatively more complex (ordered) structures. In a perfectly reversible universe, galaxies, stars and planets would never even begin to form.

Meanwhile, and paradoxically, the loss of heat energy into the colder cosmic background actually *increases* the system's overall temperature. In this case, as heat flows from hot to cold, the hot reservoir gets hotter still (a very counterintuitive property called "negative heat capacity")[41]. This whole process causes important thermodynamic gradients (temperature, pressure, chemical potential) to *increase* in time within such systems, pushing them farther away from thermodynamic equilibrium.

The larger the total accumulated mass, the greater the absolute internal temperatures and pressures (density), and internal thermodynamic *gradients*. For gravitational systems, such as stars, which reach a threshold of accumulated mass and critical internal energy density (see Figure 8, second bifurcation point, Ec2), thermonuclear fusion reactions are ignited in the core.

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[41]Most systems (materials) we are familiar with have positive heat capacities: as heat/energy leaves a system, its temperature decreases; as heat/energy is added to a system, its temperature increases. This is, however, not the case with gravitational systems (more specifically, systems undergoing gravitational collapse) which have negative heat capacities. As gravitational systems loose potential energy (through second law, irreversible processes), their temperatures actually increase (the kinetic energy, or speed and vibrations, of their components).

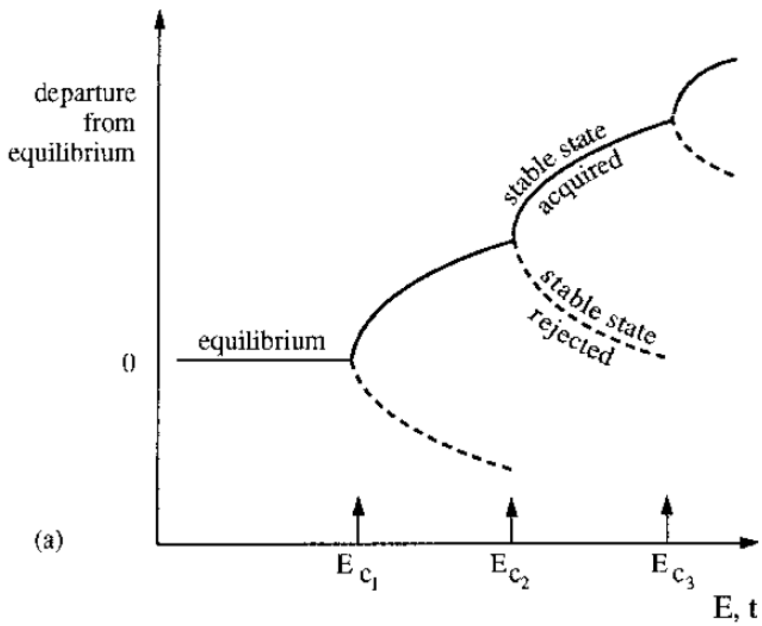

Figure 8. Schematic representation: NET and stellar evolution

"The extent to which open systems depart from equilibrium is drawn here as a function of both time and energy. The time axis makes clear that this is an historical, evolutionary process, whereas the parallel energy axis denotes the free energy flowing through an open system as a vital part of its being. At certain critical energies, labeled here *E*c, the system can spontaneously change, or bifurcate, into new, non-equilibrium, dynamic steady states."

(Chaisson 2004, p.16)

Eventually, the rate of radiation heat loss and the rate of fusion reaction equalize. In this way the star may be relatively stable (in a steady state) for billions of years, while increasing slightly its luminosity over time (Figure 8, on a stable branch), until it runs out of hydrogen fuel. For stars which attain an even larger threshold of total accumulated mass (and critical energy density), the even greater internal pressures and temperatures will eventually allow for the star to reach another critical value. Rather than simply running out of a finite supply of nuclear fuel (hydrogen), the very massive star can "switch" its nuclear fuel source to also include helium atoms (fusion helium into carbon, Figure 8, third bifurcation point, Ec3). This reaction is self-reinforcing, since the new source of fuel, helium, was generated as a "waste product" of hydrogen fusion. Following this critical step, these stars values move even further away from classical thermodynamic equilibrium (temperature, pressure, and matter), and develop greater internal structure and order.

For planets however, the situation is different, but fits nicely within the NET evolutionary framework. Their mass (and internal energy density) was never great enough to ignite fusion reactions. Their initial rise in temperature and development of internal gradients occurs until the cosmic environment is relatively cleared of debris. The rate of impacts decreases (i.e. their initial source of "fuel", both matter and energy) runs out. Though nuclear fission of heavy atomic elements insures a very important and long-lasting source of internal heat, the planet's outer layers generally cool as they lose energy to the cosmic background. The progressive loss of surface heat (form cooling) implies that the planet continue to collapse gravitationally on itself, making the inner core denser and hotter still. The external cooling and deep internal heating continues to produce strong internal energy gradients, giving a planet complex structure and order.

However, the story doesn't end there. The colder surfaces of planets now interact with the warm solar radiation (a new source of fuel external heat), and in between them, a nice temperature gradient in formed. It is the temperature *gradient*, which makes give the solar energy a qualitatively high value (free energy).

Going back to the initial diagram (Figure 7), we note that in both cases (diffusion and gravitational collapse), the total entropy of the universe increases. Interestingly in the case of the gravitational system, the total *rate* of entropy production can also dramatically increase (accelerate) with time, as with the total maximum amount of possible entropy production. This *only* occurs in successive steps, upon reaching new critical energy density values, stronger internal gradients, and new structured states of organization (state of dynamic complexity).

This is a most important result. As the gravitational system evolves it departs increasingly from classical thermodynamic equilibrium (pressure, energy, matter), following a series of irreversible and self-reinforcing reactions (driven by gravitational forces and nuclear reactions). As critical values of energy density are surpassed, the maximum amount of possible entropy production (S max, usually assumed to be fixed) suddenly increases (state of maximum disorder, within the new boundary conditions); while at the same time, the *rate* of entropy production also increases (heat transfer to the cold cosmic background). Finally, also upon reaching critical energy density values, the total amount of free energy flow increases (actually free energy rate density), and with it the *potential* for the creation of order and complex structures. We enter increasingly within the domain of non-equilibrium thermodynamics.

This should convince the reader that, in the very long term evolution of complex systems considered here (solar systems, stars and planets in particular), and their co-evolving cosmic environment (the Universe as a whole), it is very important to consider:

1) that irreversible processes governed by the second law also play a fundamentally constructive role (solar systems would never self-organize in a perfectly reversible universe)
2) the constructive role of finite, enclosed, spatial boundaries (gravitational confinement for nuclear fusion) and most importantly

3) the dynamic spatial and energy boundary conditions of the system (branching evolution influenced by reaching critical energy density thresholds)

The fact that gravitational systems, under the influence of the second law of thermodynamics typically progress towards higher states of thermodynamic disequilibrium in time (larger thermal gradients) is extremely significant for the emergence, maintenance and evolution of life, and other forms of complex (ordered) structures and processes in the universe.

As before, and following astrophysicist Freeman Dyson's logic, we must now follow the argument down to the next hierarchical level, the evolution of the Biosphere, and complex living systems on planets.

4.3 NET and the Directed Evolution of the Biosphere

> "[…] recent, exciting advances in highly non-equilibrium statistical mechanics are providing a thermodynamic basis for the understanding of life. For the purposes of time asymmetry, biological change can be considered as a branch of thermodynamics."
>
> (Davies 1977, p.62)

In 1925, Alfred Lotka proposed studying biology and evolution from the perspective of the physics of irreversible *processes*, which he associated with the second law of thermodynamics (Lotka 1925). Meanwhile, also in the 1920s, Russian mineralogist and biogeochemist Vladimir I. Vernadsky published two groundbreaking book-length essays, "*Geochemistry*" and "*The Biosphere*" (Vernadsky 1926; Vernadsky 2007). For Vernadsky, energy-matter-space-and-time could not be separated in any considerations of modern *physics or living processes*[42], nor could space-time of living processes be assumed to be the same as that of non-living processes[43]. He said these frontier questions would inevitably radically transform our very notions of both biology *and* physics (Vernadsky 1944).

In his many papers and essays on the thermodynamics of evolution, Lotka proposed an energy criteria for the evolution of living systems in their environment (not individuals, but communities), a principle now called the maximum-power principle. This principle says that "natural selection tends to make the energy flux through the system a maximum, so far as compatible with the constraints to which the system is subject" (Lotka 1922, p.148).

Similar to Lotka, Vernadsky also posited an unmistakable *direction* in evolutionary processes within the Biosphere. Vernadsky emphasized that living matter (and systems) in the long term, had progressively become the most powerful geological force on the face of the earth (note that Vernadsky is the founder of biogeochemistry). The action of living matter radically transformed the deep layers of the earth's crust, its minerals, and chemistry, and the same for the oceans, and the atmosphere. A process of co-evolution had been pushing the Biosphere as a whole (both the environmental constraints and living organisms themselves) increasingly towards far-from-equilibrium thermodynamic conditions (Vernadsky 2002). Vernadsky developed the following empirical generalizations of biogeochemistry. Very long-term evolution proceeded in the *direction* of:

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[42] Consider the work of Einstein: space-time and matter-energy are unified in special and general relativity.

[43] Louis Pasteur first discovered spatial symmetry breaking in crystals derived from living processes. Pasteur's work on geometric space-time and molecular and morphological dissymmetry of living processes was continued by Pierre Curie (dissymmetry), Vernadsky and others, including Prigogine.

1) a successional increase in the *amount* (and diversity) of living matter involved in biogeochemical cycles, and thus punctuated expansions of the Biosphere's spatial boundaries in time, into entirely new domains,

2) a successional increase in the *intensity* of energy and matter flows involved in biogeochemical cycles, and thus punctuated *increases* in the amount of free energy available to do work within the Biosphere,

3) an increasingly active role of technical activity and conscious thought involved in biogeochemical cycles, and a recent transition into a distinctly new geological era, dominated by what he called the Noosphere.

Vernadsky's views on evolution, he said, were not contradictory to Darwin's, only that Darwin's natural selection mechanism necessarily occurred within, and as a function of, the much broader context of the *directed* thermodynamic evolution of both the Biosphere and Cosmos as a whole.

These major book-length essays by Lotka and Vernadsky constitute the distant origins of a burgeoning scientific revolution: the application of NET to the emergence and directed evolution of complex living systems. Of particular interest to us is the very long term evolution of the Biosphere as a whole towards increasingly far-from-equilibrium conditions (its dynamic spatial and energetic boundary conditions).

Importantly, Erwin Schrödinger also applied a thermodynamic approach to help elucidate cellular metabolism, and genetic reproduction (Schrodinger 1945). Together, Lotka, Vernadsky and Schrodinger's application of thermodynamic to living processes continue to stimulate modern research on the implications of the *directedness* of thermodynamics in driving biological, biospheric and even cosmological evolution (Lindeman 1942, Odum EP 1971, Odum HT 1971 Nicolis and Prigogine 1971, 1977, 1989, Schneider and Kay 1994, 1995, Margalef 1997, Margulis 1999, Chaisson 2004, Lorenz and Kleidon 2005, Schneider and Sagan 2007, Jorgensen 2001, 2008, Jorgensen and Svirezhev 2004).

The extensive research which has been conducted in this broad field since the time of Lotka and Vernadsky has tended to confirm and simply render much more precise the original ideas of these two scientists (i.e. *dynamic* spatial and energy boundary conditions, increasingly far-from-equilibrium). For the purposes of this thesis, much of these essential concepts, related to NET and the *directed* evolution of living systems and the Biosphere (and its relation to the rest of the cosmos), are already contained in the few lines presented above.

Schneider and Kay (1994, 1995) have demonstrated that as ecosystems develop, grow, and complexify, in a pattern called ecosystem succession, the total ecosystem entropy production and rate of entropy production increases (temperature gradient destruction) up to a certain unstable plateau. Meanwhile Jorgensen et al. (Jørgensen 2004, 2008a, Jorgensen 1992, 1999, Jorgensen and Svirezhev 2004, Jorgensen and Fath 2004, Jorgensen and Nielsen 2007, Jorgensen et al. 1995, Jorgensen et al. 2000) have demonstrated that this progression also corresponds to an increase in the free energy and dynamic information content (storage) of the ecosystem (the combination of the two, free-energy and live genetic information, he calls eco-exergy). Kleidon et al. (Kleidon and Lorenz 2005a) have demonstrated (perhaps still tentatively) that many key global biogeochemical systems of the Biosphere (Gaia, or earth-system), including the interconnected, or coupled, global climate-lithosphere-biosphere system, tend to self-organize to a dynamic near-steady state condition which maximizes entropy production, under the existing constraints (complex biogeochemical energy and spatial boundary conditions, and biotic conditions necessary for successful reproduction). The fact that this global entropy production rate has tended to increase (or even collapse at times) through successive, sharp, discontinuous transitions (punctuated equilibrium) on the longest of time scales, confirms the importance of considering the Biosphere's spatial and energy boundary conditions as dynamic, and not fixed.

The combined work of Lorenz, Kleidon, Catling, Schwartzman, and Lineweaver (see Kleidon and Lorentz 2005) demonstrates with more recent evidence, the role of critical energy density thresholds in periods of biological evolution. One of the examples they use is the sharp rise inter-connection between the evolution of new metabolisms (oxygenic photosynthesis), reaching critical free energy density thresholds in the environment (concentration threshold in atmospheric oxygen), and great leaps in evolutionary complexity (the appearance and radiation of multicellular organisms).

Thus, the dynamic (near-steady) state of maximum (rate and quantity) of entropy production in the Biosphere is generally on the rise. So too, is the theoretical final static state of maximum entropy. The system's (Biosphere's) theoretical state of maximal static disorder, the system's final limit of thermodynamic evolution, is a *moving target*, connected with reaching critical free energy density thresholds.

Conclusion

In this chapter, I discussed the important differences between nineteenth century equilibrium thermodynamics and modern NET, trying to emphasize misconceptions and assumptions that would most affect Georgescu-Roegen's conclusion, when carried over to evolving socio-economic systems.

In the beginning of the chapter, we listed 10 features which distinguish modern NET from 19^{th} century thermo-statics, particularly emphasizing:

- The constructive role of irreversible processes governed by the second law (solar systems would never self-organize in a perfectly reversible universe)
- The constructive role of finite, enclosed, spatial boundaries (gravitational confinement for nuclear fusion), and most importantly,
- The effect of considering dynamic spatial and energy boundary conditions of systems in their very long term evolution (branching evolution influenced by critical energy density thresholds).

With regards to energy constraints, I have emphasized that in NET (and modern cosmology) thermodynamic gradients at higher levels of system hierarchy are not necessarily decreasing in time and contrary to common expectations, may often be increasing; and that upon reaching critical energy density thresholds, important phase transitions may occur, leading to discontinuous changes in the systems limits of evolution (its state of maximum entropy).

Truly irreversible processes and the presence of discontinuities in the history of an evolving system (related to energy density thresholds and topological changes in spatial boundary conditions of systems far from equilibrium) violate the condition of *path independence* upon which equilibrium thermo-statics depends. Thus, it violates conditions for applying methods of equilibrium thermo-statics to the analysis of systems evolving far-from equilibrium.

Therefore, as I discuss in our next chapter, the kind of thermodynamic analysis employed by Georgescu-Roegen, is therefore inappropriate and misleading. These methods attempt to isolate (or close) systems within fixed and impermeable boxes (and fixed or declining energy densities, and energy gradients), thereby destroying their very potential for change.

Chapter 5
Implications of NET for Georgescu-Roegen 's Hourglass

"It is impossible to calculate in detail the long-range future of the universe without including the effects of life and intelligence."

(Dyson 1979, p. 447)

In this chapter I elaborate on the implications of modern NET for Georgescu-Roegen's very long term macro-economic growth theory (hourglass model). Based on my broad historical review, I propose a different model which depicts a more complex relationship between rates of consumption of free energy, or "low entropy material" stocks, and variations in the total remaining longevity of complex stock-based civilizations. I discuss the problems with Georgescu-Roegen 's hourglass model from the standpoint of the pessimistic 19th century heat-death worldview from which it is derived. Finally, I introduce my new model, and describe its implication for Georgescu-Roegen's very long-term macro-economic growth theory.

5.1 Georgescu-Roegen's Hourglass Revisited

Georgescu-Roegen's general reasoning about economics and thermodynamics had many merits (see Chapter 3). However, I have identified misconceptions and assumptions contained in Georgescu-Roegen's notion of thermodynamics.

I begin this chapter by presenting a heuristic graph by Prigogine (1980, 1984) influenced by NET reasoning, and applied to evolving human economies. The descriptive graph (Figure 9) shows a staged non-linear increase in regional human populations and carrying capacity in time[77].

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[77] In analogy to developing ecosystems, successive increases in the human carrying capacity (plateaus) follow qualitative (non-linear) changes in the system's structural and functional

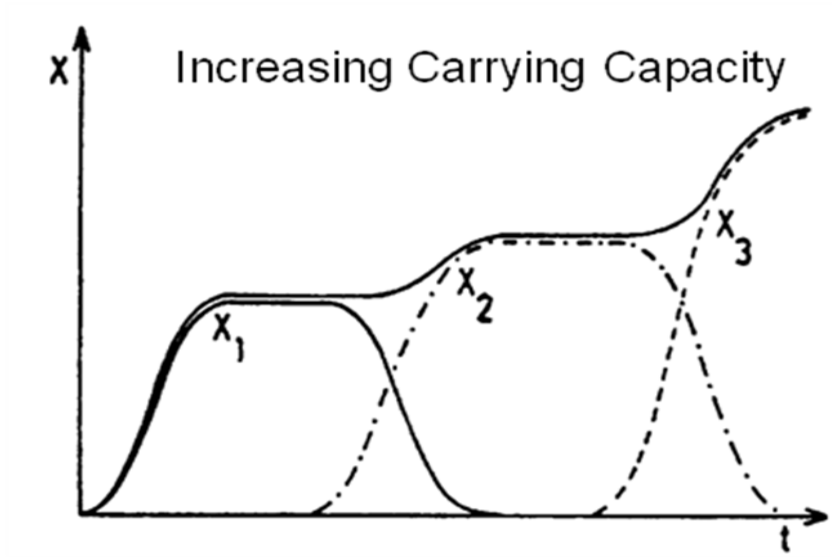

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Figure 9. Prigogine's graph of increasing human carrying capacity
"On the left, human population (X) is shown, reaching successive plateaus (limits) of carrying capacity, while time (t) is on the bottom axis. Implied, is the association between increased carrying capacity and increased rate of free energy consumption (and the rate of entropy production), in first approximation."

(Prigogine 1980, p.125)

Many researchers over the last decades have also argued that the human carrying capacity is not fixed (biologically or ecologically), but rather that it is dynamic (a moving target), and can evolve rapidly due to changing human-environment interactions, especially cultural evolution (Boserup 1981, Diamond 1997, Meadows et al. 2004)[78]. Along these lines, Prigogine and many other NET researchers and economists (Allen 1997, Ayres and Warr 2009, Buenstorf 2000,

complexity. Examples of structural changes include the emergence of new sectors (types) of economic activity and the regional accumulation of productive and residential infrastructure. Examples of functional changes include increased rates of both free energy and materials use (flow), and increased rates of entropy production in time. Note however, that a relationship between increased carrying capacity and rate of free energy use is non-linear (and in fact discontinuous): it is mediated by the introduction of qualitatively new structures and processes. This allows for a conceptual distinction between mere growth (quantitative) and development (qualitative) (Schneider and Kay 1995, Daly and Farley 2004).

[78] Important factors influencing human carrying capacity include advances in: scientific knowledge; categories of technologies, languages, social organization, social-ethical standards; access to new energy and material resources; and access and expansion into new environments.

Chaisson 2001, Chaisson 2004, Costanza et al. 2009, GiamPietro and Pimentel 1991, Lotka 1925, Margalef 1997, Odum H. T.1971, Odum H. T. and Odum 1976, Raine et al. 2006, Ruth 2005, Schneider and Sagan 2005, Smil 2005, Vernadski and McMenamin 1997), have emphasized that this picture of long term increases in complexity and carrying capacity of human civilizations is consistent to varying degrees with far-from equilibrium thermodynamics and the very long term evolution of complexity in the Biosphere.

It is important to remember, however, that Georgescu-Roegen did *not* argue that changes in *momentary* carrying capacity (as well as momentary economic growth) were impossible. Georgescu-Roegen's hourglass model is made to draw particular attention to the trade-offs between high rates of resources consumption and shorter total *longevity* of a civilization, embedded in a finite environment. For Georgescu-Roegen therefore, the above graph by Prigogine merely implies a *faster rate of decline* in the total fixed stock of low entropy resources (energy and matter), a faster rate of filling of pollution sinks, and ultimately a *faster rate of monotonic decline* in the remaining total life-span of human civilization.

The deductions following from Georgescu-Roegen's assumptions were exactly identical to the well-known graph of the isolated system (Figure 10, a and b).

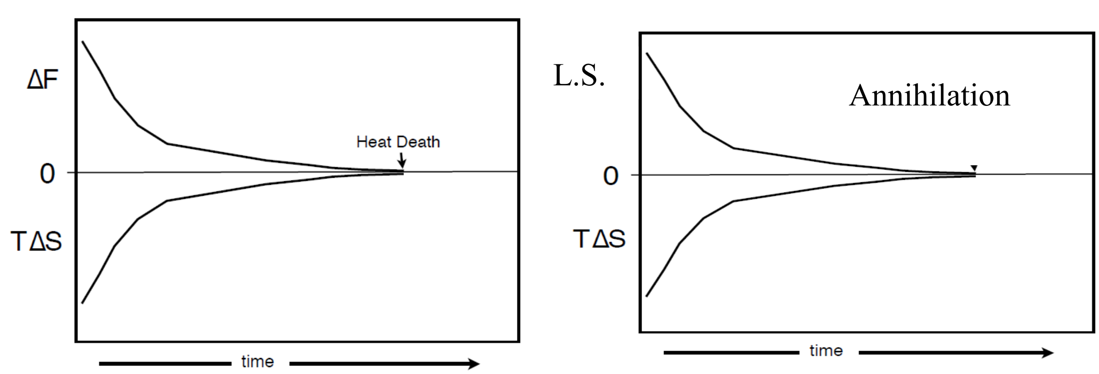

Figure 10: a) Entropy increase in an isolated system, b) remaining life-span (LS) decrease of a stock-based civilization in a closed system

The main point illustrated by Georgescu-Roegen's hourglass model is that higher momentary rates of consumption of free energy (and/or "low entropy material") stocks *only* contribute to a higher rate of decline in the total maximum longevity of stock-based civilizations, independently of the economy's long term evolutionary trajectory (path independence)[79].

In contrast, I argue here that Georgescu-Roegen's hourglass model contains important misconceptions and assumptions derived from 19th century thermodynamics, which in light of modern NET, make the hourglass model scientifically inaccurate and misleading.

5.2 A New Worldview (and pre-analytic vision)

The dual problem of the forecaster or analyst in economics is that the *future* is never entirely determined by the present state or trajectory of society and, furthermore, that the forecast outcome is not independent of the forecast itself. That is, societies adapt and change in response to changing conditions as well as to forecasts themselves (Morowitz 1991, p.125). Forecasts such as Georgescu-Roegen's are particularly susceptible to being self-fulfilling prophecies, and more reflective of a general worldview than its scientific content.

Georgescu-Roegen adopted a thermodynamics-based worldview which contrasted sharply with that implied by reversible analytical mechanics (the dominant

[79] It is in this sense that he thought the hourglass model would be useful for very long term macro-economic growth models and policies. The main policy recommendation which is derived from the hourglass is therefore to reduce the rates of consumption of low entropy stocks and shift to an economy based on renewable resources, derived from a fixed solar flow.

worldview of neoclassical economics) (see Chapter 3). For recognizing and emphasizing the importance of irreversibility and its fundamental connection to many evolutionary processes, he deserves much credit. However, with this change in emphasis came Georgescu-Roegen's adoption of the grim cosmology derived from 19th century thermodynamics (i.e. universal heat death).

The intellectual grip of the all-encompassing entropy law was profound, even within the life sciences. In 1950, the founder of cybernetics, Norbert Wiener, situated life on earth, and human society in the larger context of the universal entropy law, in the following terms:

> "It is a foregone conclusion that the lucky accident which permits the continuation of life in any form on this earth, even without restricting life to something like human life, is bound to come to a complete and disastrous end. […] In a very real sense we are shipwrecked passengers on a doomed planet. […] Up to this point we have been talking of a pessimism which is much more the intellectual pessimism of the professional scientist than an emotional pessimism which touches the layman." (Wiener 1967, p.57-58)

On a more profound level, Wiener explained that the entropic worldview which dominated physics and science for more than half a century was of the same "line of intellectual descent" as Thomas Malthus's famous writing on population and economics (Wiener 1967, p.53). That is, the entropic worldview was complementary to Malthus' deeply subjective[80], *philosophical* opposition to the idealism and optimism of the American and French Revolutions: particularly, the notion of perfectibility of man and society as well as Nature (Malthus 1988). These deep philosophical connections would need further elaboration. However, this broad intellectual landscape is consistent with Georgescu-Roegen's own adherence to the entropic

---

[80] Worldviews are man-made – they do not necessarily emanate directly from nature or science *per se*.

cosmology and his revival of the old Malthusian economic and *philosophical* project (Georgescu-Roegen 1971, p.317).

In NET and modern cosmology, the idea that the entropy law and irreversible processes *only* imply the inevitable decay and destruction of complex structures is now considered scientifically *wrong,* and intellectually misleading. In Chapter 4 I showed that in the second half of the 20th century, Onsager, Prigogine and others initiated a major revolution in thermodynamics. In far-from-equilibrium thermodynamics (NET), the second law of thermodynamics is also a *driver* of order. We presented examples[81] that clearly demonstrate the *essential* role of irreversible processes in building complex structures (including the very *loss* of energy). To reemphasize the point: in a perfectly reversible universe, galaxies, stars and planets would not even form. It follows that the the more complex and successive evolution of life and the Biosphere,would not form either.

It is not that local pockets of order can occur accidentally at the expense of even greater global loss of order (i.e. entropy increase). But rather, the global cosmic-environmental *conditions* (such as disequilibrium) necessary for the rise of further order in the universe at *many* scales have generally been *increasing* in time, as a whole, and at an accelerating (though highly non-uniform[82]) rate (Chaisson 2001, Dyson 2007).

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[81] The evolution of the universe as a whole, solar system formation, and very long term evolution of the Biosphere.

[82]Non-uniform in space and time. In this picture, the general trend of instabilities leading towards increasing organization does not exclude sudden collapses in system organization and complexity, due to either external disturbances, or even internally generated disturbances. A famous paper and (later) book by physicist Per Bak (1987, 1996) discusses this. Prior to Per Bak, the work of C.S. Holling in ecosystems ecology, and Schumpeter in economics, emphasized the importance of cycles of growing complexity and organization, followed by phases of sudden collapse, and recovery or transformation. In far-from equilibrium thermodynamics, many things can also go wrong.

In the introduction of an important book on revolutionary developments in contemporary physics, astrophysicist Paul Davies explained that self-organization in far-from-equilibrium thermodynamics has been "brought to fame by the work of Ilya Prigogine and his co-workers" (Davies ed. 1989, p.5). In his opinion, self-organization in modern NET does not contradict the second law of thermodynamics. However, it does overturn many old misconceptions:

> "Nevertheless, self-organization certainly challenges the *spirit* of the second law, as well as the prevalent world view that goes with it, based as it is on the idea that the universe is running down amid spiraling entropy. Prigogine and his colleagues believe they have initiated nothing less than a fundamental paradigm shift (Davies 1989, p.5).

Elsewhere, Davies further explains, in reference to his own work in cosmology:

> "The new paradigm will drastically alter the way we view the evolution of the universe. In the Newtonian paradigm the universe is a clockwork, a slave of deterministic forces trapped irretrievably on a predetermined pathway to an unalterable fate. The [old—AP] thermodynamic paradigm gives us a universe that has to be started in an unusual state of order, and then degenerates. Its fate is equally inevitable, and uniformly *bad*.
>
> In both the above pictures *creation* is an instantaneous affair. After the initial event nothing fundamentally new ever comes into existence. In the Newtonian Universe atoms merely rearrange themselves, while in the thermodynamic picture the history of the universe is one of loss, leading towards featurelessness.
>
> The emerging picture of cosmological development is altogether less gloomy. Creation is not instantaneous; it is an ongoing process. The universe has a life history. Instead of sliding into featurelessness, it *rises* out of featurelessness, *growing rather than dying*, developing new structures, processes and potentialities all the time, unfolding like a flower."
>
> (Davies 2004, p.199-200)

Similar conclusions concerning a new world view of *increasing* potential for complexity in our universe and in our immediate Biosphere have been drawn by ecosystems thermodynamicist Jorgensen:

> "[…] if, what is most probable according to the last hypothesis in astrophysics, the universe is expanding faster and faster, it will imply that the $exergy_{available}$ the total exergy[83] of the universe may even increase. The pessimistic prediction about "heat death" is therefore wrong. It is interesting in this context that the exergy flow density in the sequence, galaxy → stars → planets → [...] biological evolution, towards more and more complex life forms, increases, indicating a clear direction of development."
>
> (Jørgensen 2008a, p.99)

Finally, astrophysicist Eric Chaisson has boldly attempted to integrate the new emerging perspective coming from NET research in many broad fields (physical chemistry, systems engineering, evolutionary biology, ecosystems ecology, global biogeochemistry, cosmology, anthropology and economic history) and across widely varying spatial scales. He developed the following summary graph, based on calculations of two complementary proxies for complexity writ large (information content and free energy rate density of various systems (see Figure 11 and explanations). It depicts the successive emergence of increasingly complex structures and systems in timescales encompassing all of what he calls cosmic evolution.

[83] Exergy is another term for free energy: the maximum energy available to do useful work.

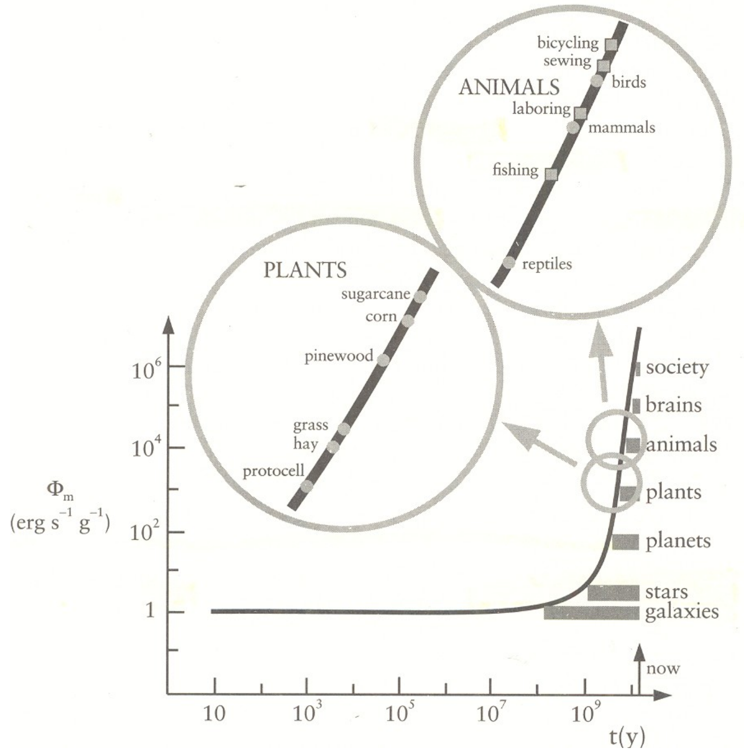

Figure 11. NET and the evolution of complexity (free energy flux density)

(Chaisson 2001, p.192)

The relationships shown in the graph are graph founded on an underlying causal thermodynamic understanding presented in Chapter 4 (see Figures 6 and 8). Due to many factors which are only recently becoming better understood [84], thermodynamics gradients at many scales in the universe are actually *increasing* in time, and, perhaps, at an accelerating rate. With the rise in thermodynamic gradients comes the increased potential for, and actual emergence of, systems depicting successively higher forms of structural and functional complexity.

The contrast in world views is dramatic and the implications for very long term development and growth theories are profound.

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84 Factors including: the cosmological expansion of the universe, non-equilibrium phase transitions, the negative heat capacities of gravitational systems, the capacity for auto-catalysis reactions in chemical systems, and the capacity for genetic self-replication, adaptability, symbiosis and natural selection in living systems, and the conscious cultural transmission of scientific, technological and social-ethical knowledge in human societies.

The remarkable change in paradigm can be explained by scientific discoveries in cosmology and NET which occurred in the second half of the 20th century, and particularly since the late 1970s. However, this shift in perspective was prepared earlier in the 20th century by scientists and philosophers such as Henri Bergson, Alfred North Whitehead, Alfred Lotka, Schrodinger, De Chardin, and V.I Vernadsky. Of this mixed group of scientists and philosophers, Alfred Lotka was quite eloquent when it came to conveying the divide existing in the scientific community, over the significance of the second law. In 1925, in his ground-breaking book, *Elements of Physical Biology*, Lotka beautifully remarked:

> "There is a certain fashionable cynicism abroad which affects a scientific pose. There are those who, having hitched their wagon to a hog, fare forth proclaiming that the world is nothing but a dung heap; and those who advocate a humoring of the elementary man in us as a health measure. […] Cynicism has its uses. But in the end no one, not even the cynic himself, takes it seriously. The pessimist spends his energy in jeremiads while the optimist is covering the ground with his forward stride. Let us endorse the stand taken by L. Witmer:
>
> > 'What the world needs today is more of the *optimism* of the progressive and a little less of the pathological fear of the standpatter, more faith in *creative evolution* [of Bergson—AP], more hope of reaching yet higher levels of achievement, and more of that freedom from prejudice called charity, another name for love –the productive passion.' "
> >
> > (Lotka 1925, p.428)

In stark contrast to Georgescu-Roegen's often bleak prognosis (as with the other inheritors of the 200-year old Malthusian *philosophical* project), these individuals were each involved in some way or another in *overturning* the dominant "heat-death" cosmology introduced in the 19th century, with its needlessly grim outlook and predictions. Lotka himself was particularly instrumental in laying the early foundations for the biophysical, ecological and evolutionary economics programs (Georgescu-Roegen 1971). For now, I shall say that it is more in this "line of intellectual descent" (as well as with Boulding's evolutionary economics and aspects of Georgescu-Roegen's later work on Promethean technologies) that I situate my own revised model of very-long term macro-economic behavior (evolution).

5.3 NET and Path Dependence: a New Model

> "When a metaphor parades as a model, it can sometimes be very dangerous and misleading, particularly as metaphors are so much more convincing than models, and are much more apt to change people's images of the world."
> (Boulding 1993, p.311)

Georgescu-Roegen believed that irreversible processes, non-linear mechanisms and evolving human-environment interactions were extremely relevant to evolving economic systems. In his earlier work, Georgescu-Roegen developed models that incorporated non-linear mechanisms into micro-economic models. In particular, see Bear and Lozada (1999) for a discussion of Georgescu-Roegen's use of path dependence, threshold phenomena and hysteresis. Ironically, his very long term population longevity equation, which he derived from his hourglass model, is a prime example of the use of assumptions of linearity, *reversibility* in thermodynamics, path independence, and static environmental boundary conditions: the exact type of *non-evolutionary* thinking that he seemed to despise in his neoclassical colleagues.

I argue here that in particular, critical free energy density and critical materials strength density thresholds can abruptly change the maximum state of entropy of a system (the system's limits of evolution), and thus also abruptly increase the maximum lifespan of stock-based civilizations[85]. These considerations are informed by the discussion of NET in Chapter 4.

The new conceptual model presented in figure 12, supplements Prigogine's

[85] By changing energy and space availabilities (energy spatial boundary conditions).

NET diagram[86] discussed previously, and addresses directly Georgescu-Roegen's concern for the maximum life-span (L.S.) of complex civilizations. Three variables increase on the vertical axis: 1) carrying capacity (X) of a developing stock-based civilization embedded in a biophysical environment, 2) the rate of free energy use, per area of that stock-based civilization embedded in a biophysical environment, and 3) the estimated remaining life span (LS) of that stock-based civilization. The horizontal axis represents time. The dashed vertical lines show discontinuous changes in resources type. The model is simple and aims to show only key variables and relationships, especially the notion of path dependence and the role of critical energy density thresholds (both in energy fuels and materials).

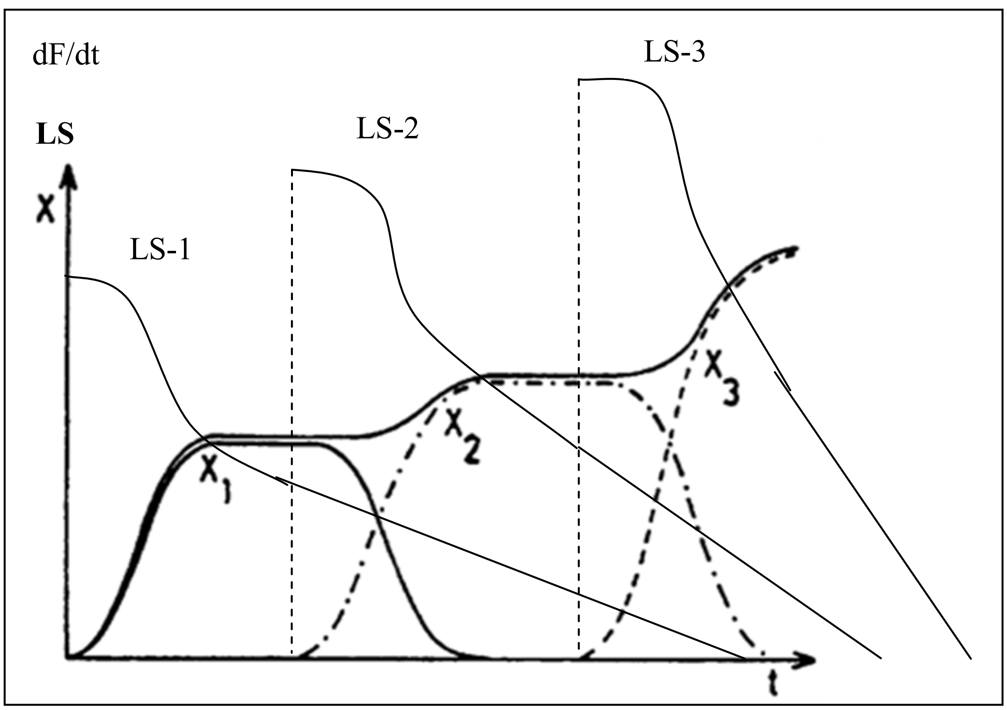

Figure 12. New NET-based macroeconomics model.

Carrying capacity (per area) is assumed to be proportional to the rate (flow)

[86] And many other similar ones relating increasing carrying capacity to increasing energy consumption

of free energy use per area, in first degree of approximation. As in Georgescu-Roegen's model, the remaining life span of a stock-based civilization is also assumed to be proportional to the remaining stocks of "low entropy" resources (free energy and concentrated materials) in a finite environment. Upon reaching a carrying capacity plateau, the rate of free energy use is modeled here as constant, and therefore the rate of depletion of "low entropy" stocks is linear. However, the rate of depletion is considered higher upon reaching higher levels of organization, and therefore the slopes of resources depletion are greater. The intersection of the remaining life-span (LS) curves with the time axis indicates, heuristically, the time at which the stocks of "low entropy" resources are exhausted and thus (following Georgescu-Roegen's logic) the time of annihilation of the stock-based civilization.

Contrary to Georgescu-Roegen's hourglass however, I do not assume the path independence of the thermodynamic model. In the new NET version, discontinuities in resource type (dashed vertical lines) appear when a civilization reaches critical energy density and critical materials strength density thresholds (explained below)[87]. The higher energy density of fuels and the higher strength density of materials correspond to an increase in the thermodynamic quality of resources used. Upon reaching such thresholds, a civilization can transition to a new mode of economic activity, characterized by increased levels of structural and functional complexity, and increased rates and densities of free energy use.

The discontinuities in resource type (quality) and use (rate) can abruptly

[87] Presumably the discontinuities in low entropy resource type (quality-density) and use (rate) are preceded by leaps in new scientific and technological knowledge (information). However, we accept the wisdom and logic that information without resources and energy are like a recipe without ingredients (Daly, 1999), and so the model emphasizes free energy rate density in particular, and not vague notions of technology and information.

change the maximum "low entropy" resource stocks (fuels and materials) available to the civilization, and therefore also change, abruptly, the remaining life-span of the stock-based civilization. The lifespan can increase if the size of the newly available "low entropy" stock[88] is large enough, and compensates for the increased rate of use of free energy.

The remaining available "low entropy" stocks (and remaining lifespan), are not independent of evolutionary trajectory, if achieving transitions in resource type and use is *causally connected* to the ability in achieving critical energy density thresholds[89]. Examples from NET where this was the case were provided in Chapter 4. Most importantly, in our NET model, we claim that the very long-term evolution of macro-economic processes is tied to reaching critical energy density thresholds. Thus the limit of evolution of a macro-economic system is *path dependent*.

Implications for Georgescu-Roegen's Model

Because of this path dependence, the logic of Georgescu-Roegen's hour-glass model breaks down. In summary, the state of maximum entropy (the system's limits of evolution, or its remaining life-span) is in fact a *moving target* (as discussed in Chapter 4). That is, a macro-economy's limits of evolution are *not* independent of the society's long-term evolutionary economic trajectory, and especially, not independent of the ability to reach new critical energy density thresholds.

The implications are that, contrary to intuition, and contrary to the policy recommendations derived from Georgescu-Roegen's hour-glass model, *increasing* the

[88] For example, the amount of free energy contained in fissionable or transmutable uranium or thorium in geological deposits; or that contained in deuterium, for fusion.
[89] Again, same as above.

per capita or per square kilometer rate of free energy consumption of a stock-based civilization may actually contribute to *increasing the life-span* of the complex civilizations, in first approximation. Conversely, for the same reasons, *decreasing* the per capita or per square kilometer rate of free energy consumption of a stock-based civilization, may actually contribute to *decreasing the longevity* of a that civilization.

Since, in my new model, a successful transition depends on both higher energy density fuel and a larger total amount of stored free energy of that new type, the crucial question one must ask is : *why* would we expect stocks of higher density energies to be increasingly large, and not the contrary (see Figure 12, the increasingly high pillars)? Indeed if the stocks of the new resource are not high enough, the transition does not increase longevity (see Figure 13). There are in fact good reasons to expect increasing stocks with transitions in some important cases (nuclear fission breeder reactors and thermonuclear fusion), but a full discussion of this is beyond the scope of this work. However see David Mackay (MacKay 2009) for estimates of expected life spans of civilizations with these resources.

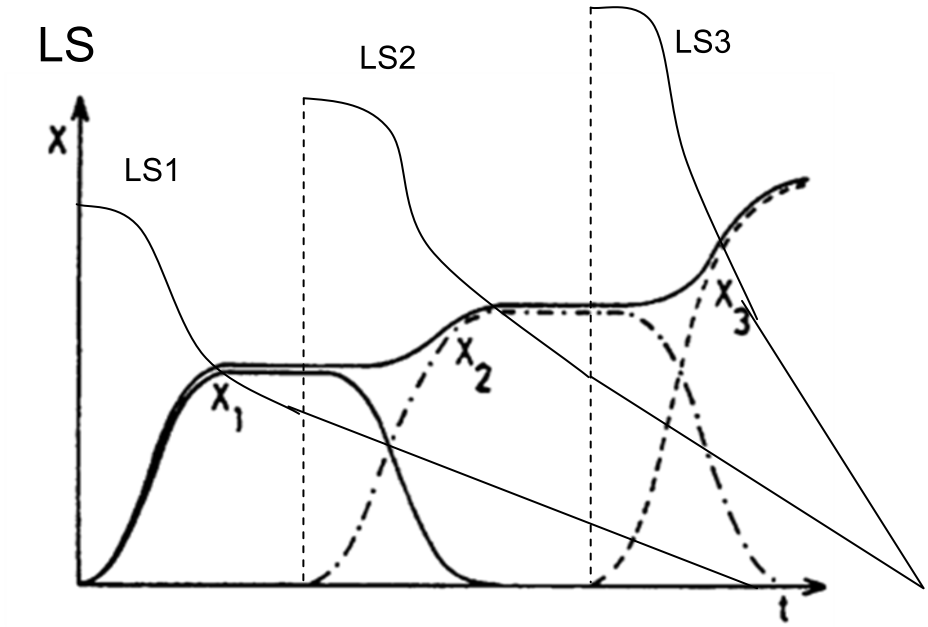

Figure 13. Case where a transition does not increase longevity.

Also of particular importance to Georgescu-Roegen's work and ecological economics in general, the density effect in both cases (energy and matter-strength) also allows for *reductions* in the amount of material pollution output per free energy and materials use, per weight and/or volume. This effect also depends on process efficiency. However, process efficiency itself also often depends on achieving higher energy density thresholds or larger thermodynamic gradients [90] : higher net temperatures (more complete combustion) and temperature gradients (Carnot

[90] The notion, promulgated in all thermodynamic textbooks, that the maximum efficiencies of processes (ideal Carnot cycle) are achieved at infinitely low speeds and infinitesimal gradients (in terms of heat transfers) is extremely misleading from a practical point of view, arising from the significant difference of emphasis between "work" and "power", rate at which work is accomplished (ironic for me perhaps…). One element of Carnot's cycle (the adiabatic expansion) can be achieved with maximum efficiency at high speeds. At low speeds (and low pressure gradients), the proportional loss of motive "power" is high due to imperfect insulation, and static and dynamic friction. As with everything, there are tradeoffs. At high speeds mechanical shocks and resonant vibrations are more likely, though these effects are also a function of materials quality (again, strength density) and design (configurations and precision). In practice, Carnot's essay, "Reflections on the motive *power* of fire" recommends the shift to "high pressure" steam engines, operating over greater temperature (energy density) gradients, as well as at higher speeds.

efficiency), or higher pressure gradients to achieve greater speeds of transportation (reductions in static friction, and reductions in the ratio of dynamic friction to free energy use[91]), and higher voltage thus higher thermodynamic gradients. The implication is that the ecological footprint and ecological damage caused by the embedded civilization does not necessarily rise upon achieving a transition to a new stage of development; it may even *decrease*, though the process is clearly much more complex than our very simple model accounts for.

Finally, it is not excluded here that, again for similar reasons, momentarily increasing the per capita or per square kilometer rate of free energy consumption of a civilization may also help in transitioning from a stock-based civilization to a civilization based on *renewable* material and energy flows (flow-based, solar and wind power).

[91] Static friction occurs when trying to move an object at rest against a surface. A threshold rate of work (power) is required to overcome in. Dynamic friction occurs once the object is in motion. It is nearly independent of speed, meaning that for increasing speeds (power input), the friction is proportionately less (and the process is therefore more efficient). A relative decrease in friction with speed also results from lubrication effects due to melting and the formation of a fluid film. Other types of friction increase with speed, such as drag.

Chapter 6

CONCLUSION

Four decades ago, Nicolas Georgescu-Roegen developed an alternative framework for macro-economics (the hourglass model) based on two principles of classical thermodynamics applied to the earth-system as a whole. His approach had many advantages over the neoclassical circular flow of exchanges model. First, it extended the boundaries of analysis of macro-economics to include a changing environment upon which human economic systems depend. Second, Georgescu-Roegen's model adopted a provocatively realistic approach by making irreversible evolutionary processes central to very long-term macro-economic thinking. Third, though many types of resources can be *substituted* in an agro-industrial production process, nonetheless, Georgescu-Roegen's thermodynamic approach makes clear the fact that, ultimately, *there is no substitute to free energy* itself (or "low entropy" energy-matter).

However, the hourglass also contained many misconceptions which make it misleading, particularly in light of new discoveries in non-equilibrium thermodynamics and self-organizing complex systems. Unfortunately, Georgescu-Roegen associated the "entropy law" and irreversible processes with only either 1) the immediate decay and gradual destruction of existing complex structures, or 2) the inevitable decrease in the potential to sustain *future* complex structures. Modern NET and cosmology demonstrate, on the other hand, that we live in a universe where conditions for higher orders of complexity may actually be increasing, discontinuously in time. This includes increases in: 1) available energy/materials gradients and fluxes in the environment, and 2) internal capacity (information, structure, function) to harness and metabolize higher rates of free energy flux densities. As the astrophysicist Paul Davies (1989) explained, self-organization in non-living systems does not contradict the “entropy law”, but “it certainly challenges the *spirit* of the second law, as well as the prevalent world view that goes with it, based as it is on the idea that the universe is running down amid spiraling entropy” (Davies 1989, p.5).

Based on a broad historical review of literature from many fields (thermodynamics, cosmology, ecosystems ecology and economics), I argue that Georgescu-Roegen’s hourglass model contains misconceptions and assumptions which originate from 19th century thermodynamics (including an out-dated cosmology). The misconceptions introduced by Georgescu-Roegen which I chose to reinvestigate from the perspective of modern non-equilibrium thermodynamics are his emphasis on 1) the role irreversible processes as exclusively destructive of complex structure and function, and 2) the role of finite biogeophysical space as exclusively limiting (in terms of growth and maintenance of complex structures and functions). The important implicit assumption introduced by Georgescu-Roegen in his hourglass conceptual model it is that, in the analysis of coevolving economic and ecological systems, energy and spatial boundaries can be *fixed* once and for all, *independent of evolutionary processes occurring both inside and outside the system of interest*.

In light of modern NET, I propose a different model. Contrary to Georgescu-Roegen’s hourglass, I do not assume the path independence and linearity of the entropy function. In the new model, achieving critical free energy rate density thresholds can abruptly increase the level of complexity and maximum remaining lifespan of stock-based civilizations (under certain conditions).

In fact, rather than completely overturning Georgescu-Roegen's thermodynamic approach, my new conceptual model for very long term macro-economic development is consistent with: principles of far-from equilibrium thermodynamics (historically, one of the major influences on EEs thinking); the general evolutionary outlook adopted in ecological economics; and finally, specific ideas introduced by Georgescu-Roegen in some of his later work on “promethean technologies” (Georgescu-Roegen 1986). I argue that Georgescu-Roegen's published work on “promethean technologies” should be seen as a more advanced standpoint, more consistent with the principles of NET, than the monotonic, and path independent hourglass model[92].

Therefore, the constructive criticism and new model I introduced here, is already consistent with many of the above-mentioned principles of ecological economics, and provides ecological economics with new, more dynamic (from an evolutionary perspective), grounds for a continued critique of the biophysically blind neoclassical growth models and policy recommendations.

[92] This latter assessment contrasts sharply with that of several researchers in the ecological economics litterature (Beard and Lozada, 1999) Gowdy J, Mesner S. 1998. The evolution of Georgescu-Roegen's bioeconomics. Review of Social Economy 56: 153-156..

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APPENDIX 1

Statements of the Second Law

Carnot statement:
No engine working between two heat reservoirs can be more efficient than a reversible engine working between those two reservoirs.

Kelvin statement:
It is impossible to remove thermal energy from a system at a single temperature and convert it into mechanical work without changing the system or surroundings in some other way.
Or
It is impossible to convert heat completely into work in a cyclic process.

Claussius statement:
There can be no process whose final result is to transfer thermal energy from a cooler object to a hotter one.

Entropy statement:
In a reversible process, the entropy change of the universe is zero.
For an irreversible process, the entropy of the universe increases.
For any process, the entropy of the universe never decreases.

Entropy statement: isolated system:
The entropy of an isolated system will increase until it reaches a maximum at equilibrium

Irreversibility and loss of work:

When an irreversible process occurs, energy is conserved, but some of the energy is 'wasted', meaning it becomes unavailable to do work. […] In an irreversible process, energy equal to $T\Delta S_u$ becomes unavailable for doing work, where T is the temperature of the coldest available reservoir.

***Remark* on order and disorder:**

There are many irreversible processes that cannot be described by the heat engine or refrigerator statements of the second law, such as a glass falling to the floor and breaking. However, all irreversible processes have one thing in common—the system plus its surroundings moves toward a less ordered state.

(Tipler 1999, p.607-623)

APPENDIX 2

Path Independence

Both "work" and "heat" are two forms of energy *transfers*, i.e. they do not "exist" other than as *processes*. Additionally, there is a general inequality between work energy and heat energy it terms of the facility to convert one into the other ($W < Q$). The inequality between work and heat reflects the inequality between potential energy (PE, or position energy), and energy of motion, or kinetic energy. We can say that there is a qualitative difference between the two, in that kinetic energy can easily be scattered in all directions and disorganized. This qualitative difference made the mathematical (differential) expression of thermodynamics challenging at first, the technical reason being that work and heat, as processes of energy transfer, are *path dependent*. I explain.

Potential energy represents a measure of position, or state, in an energy field (e.g. height on a mountain). For example, change in gravitational potential energy, ΔU, represents a change between an initial and a final height (Δh), say on a mountain. In reality, there are many pathways one can take to climb or descend a mountain, or transfer bodies (mass) from one vertical position to another. However, both the value of potential energy (U) at a given height (or state), and the difference in potential energies between two heights (ΔU) are independent of the many paths available (e.g. the different trails chosen to climb the mountain). Vertical height on a mountain, and the gravitational potential energy associated with it, are examples of variables which are called *path independence*. So too are the *differences* in these same variables (Δh and ΔU). What about energy expenditure, or work (W)?

In reality, because of friction and heat loss, energy expenditure, unlike gravitational potential, should be *path dependent*. For example, there should be approximately one unique path by which a mass can be transported between any two vertical positions on a mountain surface through a minimal amount of energy expenditure (a path of least action)[93]. However, if all paths or trajectories between two points on a mountain were perfectly frictionless (or are assumed to be), then no matter which route taken, all paths would require the same amount of energy expenditure (W). In this ideal case, the energy expenditure would be reversible, since no energy would be lost in the process. The amount of reversible energy expenditure (Wr) would correspond exactly to the change in potential energy between the two positions (ΔU). Thus, in this context and with these assumptions, the total amount of reversible energy expenditure (Wr) would all truly be *path independent* (independent of spatial trajectories, rates of processes and energy densities).

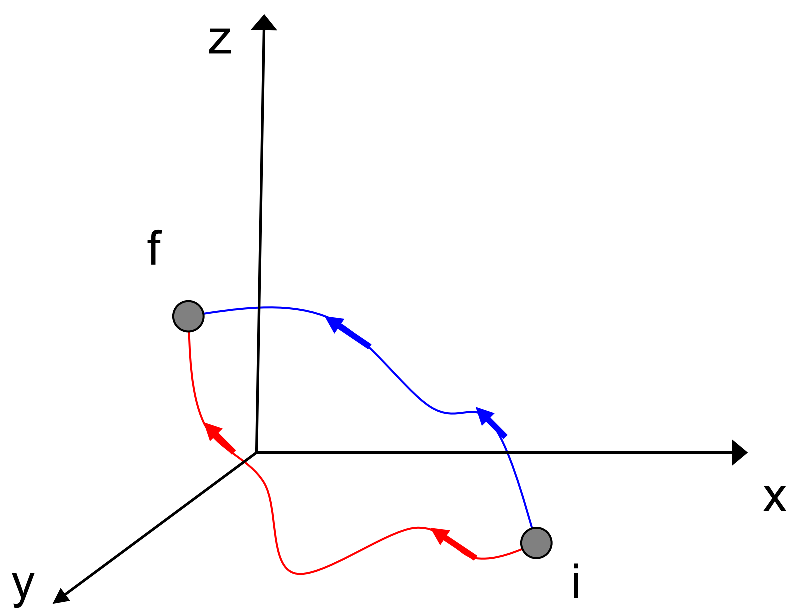

Figure 14: Path Independence of frictionless energy expenditure

[93] If no singularities are present

The same reasoning applies in equilibrium thermodynamics.

Path Independence in Equilibrium Thermodynamics

In the typical case, in hydrostatics, one deals with systems (gases) which have the following state variables: volume, pressure and temperature (P, V, T), and number of molecules and type of molecules ($\sum Ni$) when necessary. The total energy of the system (U) plays the same role as gravitational potential energy in the previous case, and is in fact called a thermodynamic potential.

The question is: are the expenditure of energy (W) and the transfer of heat (Q) path independent? The answer, in all real situations should be: no. This made the mathematical (differential) expression of thermodynamics challenging at first

To deal with the problematic qualitative difference between work (W) and heat (Q), or potential energy and energy of motion, Claussius, created a new state variable which is path independent: entropy (S). This state variable should be described as reversible entropy (Sr).

In the same way that we imagined ideal, frictionless and reversible pathways for energy expenditure on a mountain side (thus defining reversible work, Wr), here Claussius used what Carnot had accomplished earlier to imagine "frictionless" pathways for heat transfers. He thus defined a reversible heat exchange (Qr), with a new system of state variables, including entropy, which are path independent.

Work can be decomposed into coordinates of pressure and volume change ($W = P\Delta V$), while reversible heat transfer (Qr), can be decomposed into the coordinates of temperature and entropy ($Qr = T\Delta Sr$). And the first law of thermodynamics can be expressed as:

$$\Delta U = Q - W = T\Delta S - P\Delta V$$

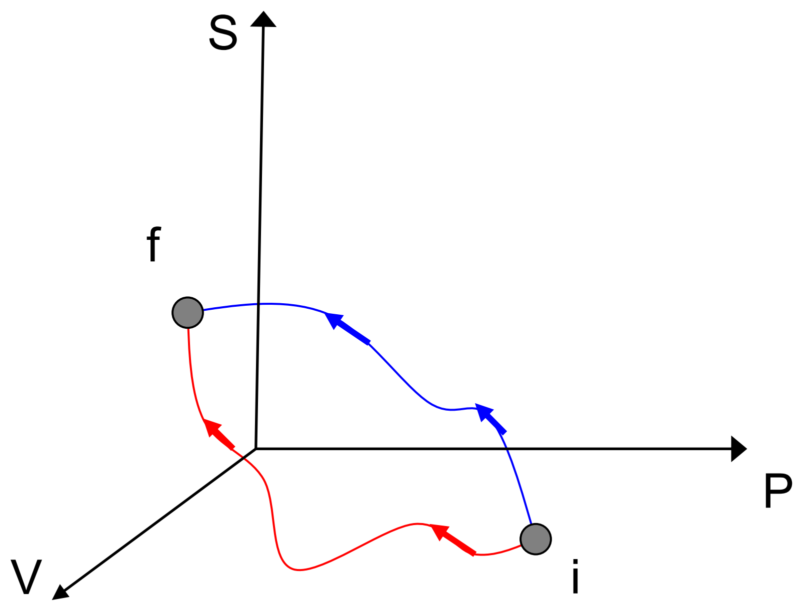

Figure 15: Path independence of entropy as a state variable. This reversible entropy (Sr) is only calculated for equilibrium states and reversible pathways

In equilibrium thermodynamics, entropy as a state variable is defined under the special assumption that an infinite amount of reversible paths of heat exchange can be defined between two states. Along these reversible paths, heat is imagined to be transferred infinitely slowly, without friction and irreversible heat loss, through a series of reservoirs which are always infinitely close to equilibrium conditions. All positions, or states, along such reversible paths in equilibrium thermodynamics have values of entropy (S) (as well as temperature, T, and other state variable), which are all path independent, just as all positions on a mountain have coordinates of height, independently of which mountain trail one chooses.

In summary, the mathematical formulation of equilibrium thermodynamics developed by Claussius and others in the 19th century is based on equilibrium *states,* reversible paths and state. It is not based on real *processes* which occur in non-equilibrium conditions.

Path Dependence of the Maximum Entropy State

An isolated system composed of two sub-systems, maintained far-from equilibrium by an ephemeral boundary.

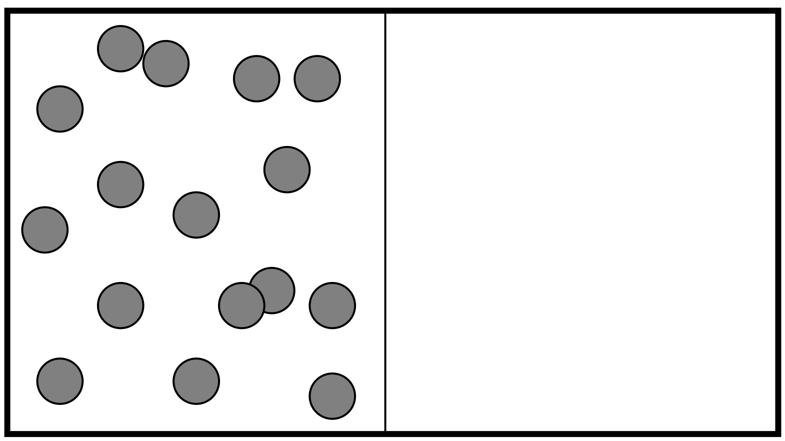

Figure 16.A: An isolated system composed of two sub-systems.

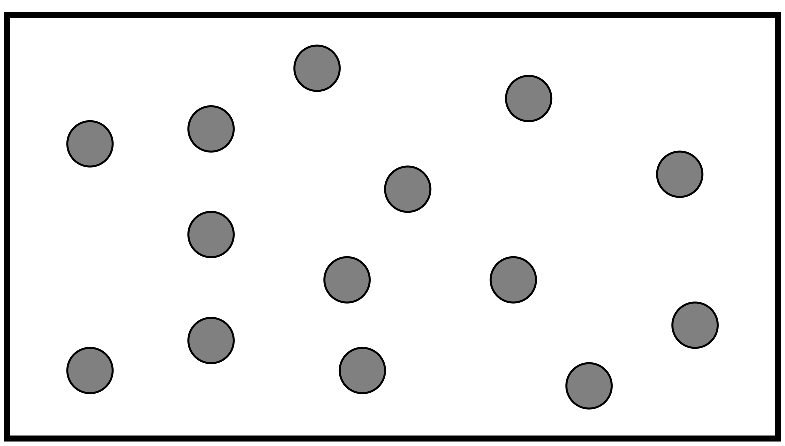

Figure 16.B: Removal of the boundary: maximum entropy and equilibrium

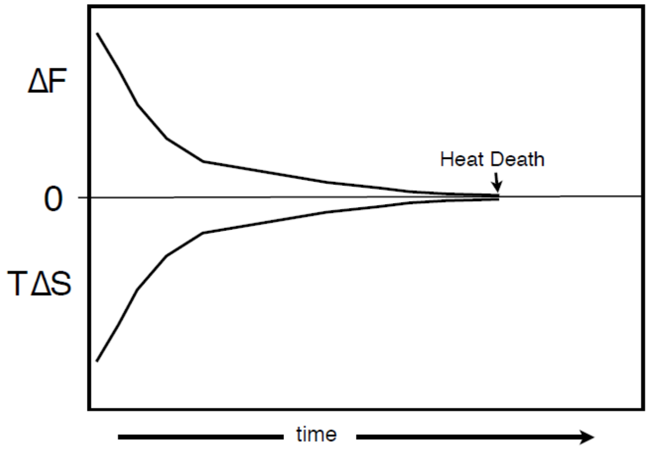

Figure 17. Monotonic entropy increase, reaching a maximum at equilibrium

After removal of the boundary, the isolated system reaches a state of equilibrium, with maximum entropy. This final state of maximum entropy is usually assumed to be path independent, given fixed volume, number of particles and total system energy (i.e. fixed spatial and energy boundary conditions). That is, the system is assumed to reach this final state, regardless of the specific trajectory history of any of the particles, and regardless of process rate (the rate of convergence to equilibrium).

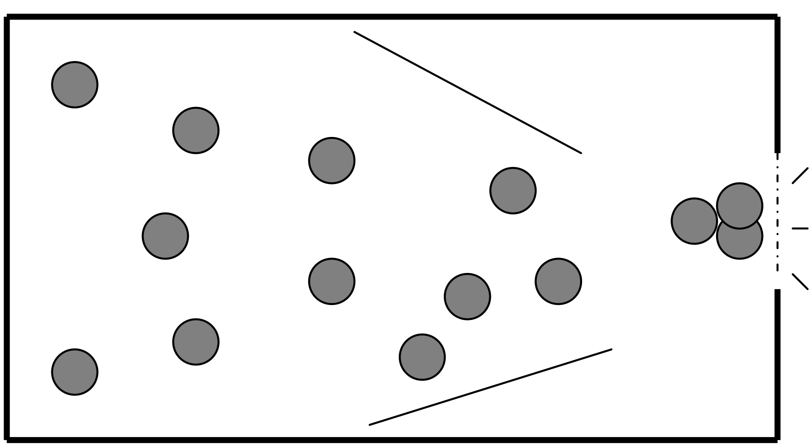

Figure 18. Path dependence of the maximum entropy state. A: The external boundary of the isolated system is broken by high energy density collisions.

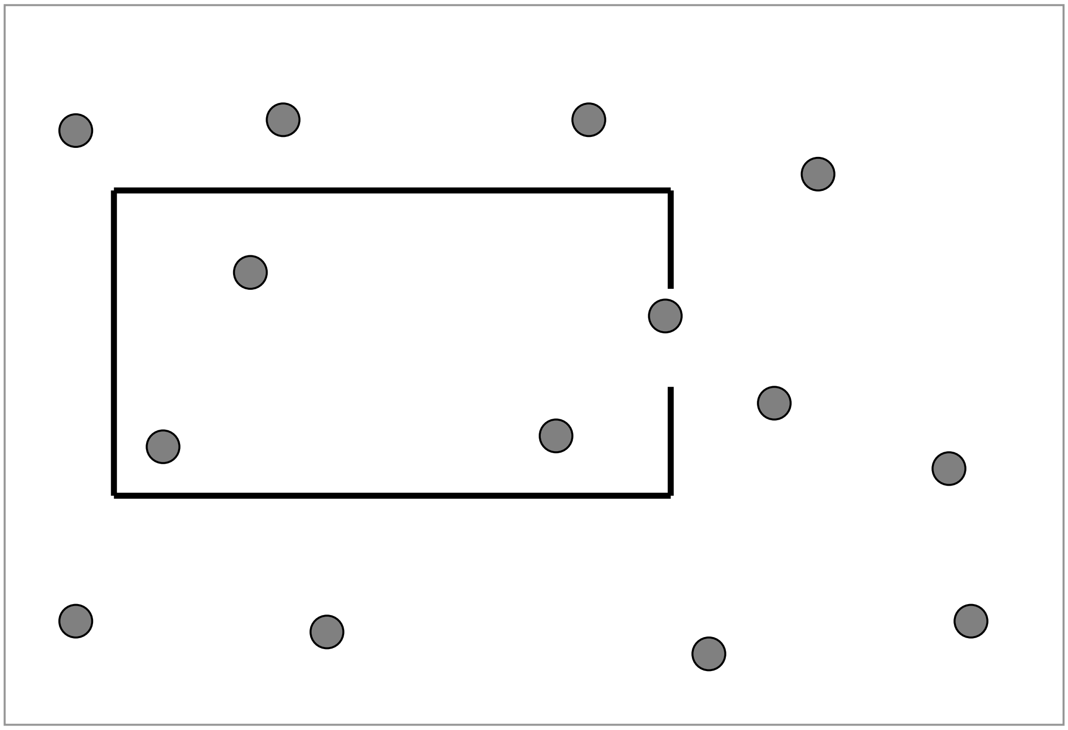

Figure 18.B: A new state of maximum entropy will be achieved.

In reality, it is possible that the spatial boundary of the isolated system itself be removed, or broken by thresholds of energy density and high rates of free energy flow. In this case, the final state of equilibrium and maximum entropy will in fact be dependent on path, through achieving critical energy density thresholds.

APPENDIX 3

Neoclassical Economics and the Mechanical World View

Strangely, the founders of neoclassical economics (Jevons, Walras, Edgworth, Pareto, and Fisher) closely patterned their new science of economics on 19th century theoretical physics, especially analytical mechanics[94]. They borrowed from it *more* than just the same idealized axiomatic thinking, analytical methods (infinitesimal calculus, calculus of variation), and perhaps distant analogies (see Mirowski, Nadeau, Edgeworth, Fisher).

Stanley Jevons, one of the founders of neoclassical economics, referred to his new scientific-analytical approach to human economic psychology as "the mechanics of utility and self-interest"[95]. For example, he believed that:

> "Just as the gravitating force of a material body depends not alone on the mass of that body, but upon the masses and relative positions and distances of the surrounding material bodies, so [marginal] utility is an attraction between a wanting being and what is wanted."
>
> (Jevons, from Mirowski 1991, p.14)

The core theme animating neoclassical economic epistemology was that an idealized rational human being (*homo economicus*), mathematically equivalent to a particle-mass moving in a potential energy field according to an energy optimizing

[94] Analytical mechanics is founded upon the concepts of a potential energy field (position), kinetic energy or momentum (motion), depending on the specific equations (Hamilton's or Lagrange's) and least action or optimizing pathways.

[95] See Jevons, "To return however to the topic of the present work, the theory here given may be described as the mechanics of utility and self-interest. […]. Its method is as sure and demonstrative as that of kinematics or statics, nay, almost as self-evident as are the elements of Euclid, when the real meaning of the formulae is fully seized."

principle[96]. The exact details of this strong analogy changed from author to author, but the general idea was the same: given a continuous field of priced commodities and budgetary constraints, the ideal rational human agent will seek out the optimal combination of purchases which minimize costs[97] and maximize his/her satisfaction (utility[98]) (Nadeau 2003, Mirowski 1991).

Stanley Jevons was by no means alone among the founders of neoclassical economics (Jevons, Walras, Edgeworth, Fisher, and Pareto) in his hopes of reducing human psychology to mechanics and energy optimization principles. Francis Edgeworth carried the rhetorical art to an unsurpassed extreme, to the point, as you will see, of astonishing ridicule. He pushed ahead the translation of these simplistic ideas into ever more precise mathematical language.

> "Mécanique Sociale' may one day take her place along with 'Mécanique Celeste,' throned each upon the double-sided height of one maximum principle: the supreme pinnacle of moral as of physical science. As the movements of each particle, constrained or loose, in a material cosmos are continually subordinated to one maximum sum-total of accumulated

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96 For Lagrangian and Hamiltonian mechanics, see Hand LN, Finch JD. 2008. Analytical Mechanics. New York, NY: Cambridge University Press.

97 In analytical mechanics, the "action" is minimized along the path followed by a particle; the unique pathway which minimizes the difference between potential energy and kinetic energy is selected. In this new economics: an individual is constrained by his/her budget, but wants to maximize their satisfaction (utility) at minimal cost; he/she is presented with a field of options, a continuous field of commodity types, quantities and prices; given the budget constraints, he/she will purchase the combination of commodity type/quantity/price which minimizes the costs while maximizing the satisfaction (utility).

98 In general, following the philosophical tradition of Bentham and Mill, utility is a psychological quantity which represents the satisfaction of desires (ex:: pleasure from consumption). Neoclassical economics adopted utility as the foundation of economic value, and measured it as the product of the quantity of a commodity with its marginal utility at equilibrium (ie quantity of goods x price = utility). Like energy, as their analogy goes, utility is a scalar magnitude; in fact utility was the integral of marginal utility over commodity space, exactly like "work", or potential energy, in mechanics, is the integral of force over distance. Marginal utility is a rate of change, or rather the gradient of utility over a quantity of a good; in the analogy, marginal utility is the psychological force which animates rational economic man; it represents a strength of desire or the strength of the willingness to pay for an extra amount of a good, and this psychological force is *ontologically* on par with the gravitational force, or the electromagnetic force.

> energy, so the movements of each soul, whether selfishly isolated or linked sympathetically, may continually be realizing the maximum energy of pleasure.
>
> Mathematics has long walked by the evidence of things not seen in the world of atoms. The invisible energy of electricity is grasped by the marvelous methods of Lagrange; the invisible energy of pleasure may admit of a similar handling. […]
>
> … at least the conception of Man as a *pleasure machine* may justify and facilitate the employment of mechanical terms and Mathematical reasoning in social science."
>
> (Edgeworth 1881, p.12-15)

To be consistent with the mathematics applied in analytical mechanics they had to make impossibly restrictive assumptions, similar to those used for the ideal pendulum and maximally efficient Carnot engine. The ultimate implication of this? Even for the simplest micro-economic context, neoclassical economics requires that the field of utility and commodity prices be *conservative*, and that a market transaction be perfectly *reversible*. The only way this is *ultimately* possible is: 1) to disregard the irreversible nature of real biophysical processes, and 2) make *homo economicus'* own mind (Edgworth's "pleasure machine") a perfectly reversible machine! [99]

It took a century for economists to untangle the assumptions implicit in the work of the founders of neoclassical economics. Economists worked on defining the very restrictive (if not impossible) conditions under which 1) utility is maximized in an ideal market transaction, 2) markets achieve efficient allocation of factors of production and incomes, and 3) prices achieve equilibrium (partial or general) which

[99] Any pleasure gained in one direction, should be capable of being exactly reversed in the opposite direction. How by an equal amount of pain, along the same opposite path; both of which MUST be convertible in a precise amount of money, the unit of utility, without changing anything else in the universe. I have not seen a discussion of this reversible "pleasure machine" elsewhere, so I cannot give a reference; but according to strict reversibility criteria, and the neoclassical "scientific" theory of rational economic man and their mechanics of utility and self interest (Mécanique Social), this should be required of the theory.

reflect actual value (Mirowski 1991). In recent decades, more work has emphasized conditions in which markets fail.

From this broad epistemological and historical perspective, we can see that the ideal conditions of neoclassical economics cannot even be rigorously met for the simplest part of the economic process which it sets out to model: a single decision by the human *mind*. Why even bother with the economic process as a whole or long term economic growth?

APPENDIX 4

Non-Equilibrium Thermodynamics

There is no general consensus at present in this very broad and dynamic field [100] on how exactly to *define* thermodynamic variables such as pressure, temperature and "entropy" under very extreme, far-from-equilibrium conditions. Nonetheless, there are "schools of thought" which have introduced unique methods in thermodynamics to deal with energetic processes, under non-equilibrium conditions[101]. Some schools abandon even entropy altogether (Schneider and Kay 1995, Schneider and Kay 1994); others discard macroscopic descriptions of entropy and work from non-equilibrium molecular kinetics (non-equilibrium statistical mechanics). On the issue of microscopic vs macroscopic descriptions, see note.

There are two slightly different schools of thought in NET which would be useful for this thesis [102]. One has its origins in physical-chemistry of non-living systems and is called the Brussels school. The Brussels school, is associated with the names of Ilya Prigogine (1917 – 2003; Nobel Prize in chemistry 1977)[103], and many

---

[100] Nor is this to be unexpected, since thermodynamics and statistical thermodynamics are never really studied on there own, but always applied in the context of more specialized fields (whether astrophysics, mechanical engineering or biochemistry), to specific systems (photon gases, turbines, or neurological networks), under different conditions (extreme temperature and chemical gradients), at different scales (microsopic vs macroscopic), and for different purposes (detailed knowledge of processes, or characteristics of wholes).

[101] Some work in non-equilibrium thermodynamics dates back to the 19th century, to Fourier, Frick, Ohm, Maxwell, Kelvin and Boltzmann. A key turning point in the development of modern non-equilibrium thermodynamics was Lars Onsager's work, in the early 1930s (Novel Prize in 1968), and central to the approach later taken by Prigogine.

[102] The distinction comes from their different traditional fields of applications; nonetheless they contain overlapping references and principles and in many textbooks are discussed together.

[103] As well as Prigogine's Professor, Théophile De Donder (1872 – 1957). Both De Donder and Pigogine were at the University of Brussels, Belgium.

of his colleagues and students, including Glansdorf, Nicolis, and Kondepudi, and is an extension of the earlier work of De Donder and Onsager. The other has its origins in the life sciences, is closely tied to general systems theory and cybernetics[104], and is often called network thermodynamics. Network thermodynamics is associated with such figures as the ecosystems ecologists Howard and Eugene Odum, Ulanowicz, Jorgensen, and other important pioneers of general and complex systems theory, and cybernetics, such as Ludwig von Bertalanffy and Norbert Wiener.

Following Prigogine et al., modern thermodynamics can be divided into three regimes according to distance from equilibrium: 1) at equilibrium (i.e. thermo-*statics*), 2) near equilibrium (i.e. linear-thermodynamics), and 3) far-from-equilibrium (i.e. non-linear thermodynamics).

A.4.1 Near-equilibrium or linear thermodynamics

First, in non-equilibrium (irreversible) thermodynamics we must distinguish or separate the entropy change, dS, into two terms (see Figure 15). The first, deS is the exchange or transfer of entropy across the boundaries of the system (for example, a transfer of heat through conduction, or molecules through diffusion)[105]; it can be positive, negative or equal to zero. The second entropy term, diS, is the new entropy produced irreversibly within the system through an irreversible process (for example, friction, diffusion, chemical reactions). This irreversible entropy production, diS, is the component which adds to the total entropy of the universe,

104 See von Bertalanffy, Wiener, Odum, Ulanowicz et al.

105 The fact that this entropy exchange dSe is sometimes considered exclusively reversible is not important. In the context of many embedded systems, this entropy exchange will also be separated into a reversible and irreversible component, thus accounting for as an irreversible production of entropy as energy is transfered across a boundary.

the component which makes processes truly irreversible.

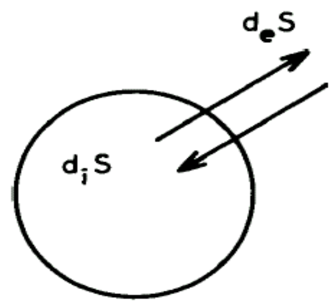

Figure 19 Entropy exchange and irreversible entropy production in an open system

The second law of thermodynamics implies that the irreversible entropy production must always be positive (or zero at equilibrium) anywhere in the universe (even at local scale); most importantly it can never be negative.

$$diS > 0 \quad (\text{or} \quad diS = 0)$$

Systems can compensate for this local production of irreversible entropy, and its accumulation within a system boundary, by increasing the entropy exchange (deS) with the environment. In this way, the second law of thermodynamics applies as much to open systems as it does to isolated systems, as much to large scales as local scales.

Since a non-equilibrium system may have both spatial and temporal variability (non-uniformity), we must also find an expression for the local entropy production (space), and the rate of entropy production (time); or in other words the entropy production as a function of space and time (remember that in equilibrium thermodynamics, entropy is only defined for the system as a whole, once it has reached a static/equilibrium).

One way of doing this is by defining local thermodynamic variables for volume elements[106] (Figure 20, Kondepudi 2008) and expressing their rates of change according to known functions (for example, Fourier's law of heat conduction). As in equilibrium thermodynamics the total energy, mass and entropy of an entire system become the sum of its local energy densities, local particle density, and local entropy density (for extensive thermodynamic variables). In the same way, temperature, pressure and chemical potential (intensive variables) are also defined locally, in unit volumes (see figure below). These local quantities are allowed to vary in both space and time according to known functions.

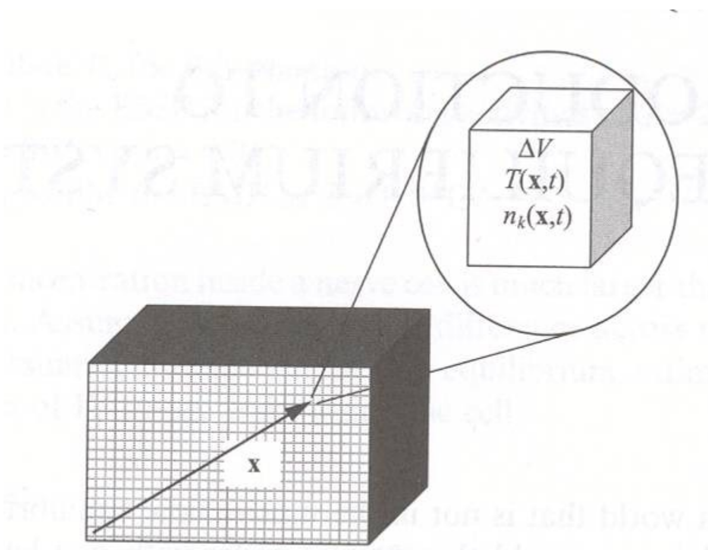

Figure 20. Local Thermodynamic variables in NET (Kondepudi 2008, p.328)

The rate of *local* (irreversible) entropy production must always be positive (or zero at equilibrium) anywhere in the universe, even at local scales; it can never be negative.

$$diS / dt > 0 \quad \text{or} \quad (diS / dt = 0)$$

In general, to express both the local rate of entropy production per unit volume as some function of space and time (dsi/dt = σ (x, t), and the *total* rate of entropy

[106] This depends on an assumption of local equilibrium (see Kondepudi 2008)

production within the system as a whole ($dSi/dt = \int \sigma(x, t)\, dV$, we must still specify a function of space and time for the irreversible processes of interest ($\sigma(x,t)$), the local rate of entropy production).

As we saw in Chapter 2, Joseph Fourier had described, early in the 19th century, a mathematical relation for the local rate of heat conduction (energy flow) as directly (linearly) proportional to the local temperature gradient in a system. Later in the 19th century, Adolf Fick described a function for the local rate of diffusion of matter (flow of particles/molecules) as directly proportional to the local concentration gradient in a system. And Georg S. Ohm described the local electric current (flow of electrons, or electric charge) as directly proportional to the local voltage (potential difference/gradient)[107]. All three of these empirical laws (Fourier's, Fick's, and Ohm's) describe irreversible processes (heat conduction, diffusion, electrical conduction) in terms of gradients (forces) and flows. These three transport laws, as they are called, become the starting point of non-equilibrium thermodynamics (Kondepudi 2008), as the entropy production per unit volume ($\sigma(x,t)$) can be generalized in terms of thermodynamic flows (J) and thermodynamic forces (F), to give:

$$\sigma = \Sigma\, F J$$

The above-mentioned non-equilibrium transport processes (heat conduction, diffusion, electric conduction) are usually treated separately, and not tied to thermodynamic variables such as entropy (since traditional thermodynamics does not treat rates of change, nor define temperature, pressure and entropy under non-equilibrium conditions). Yet it is exactly these non-equilibrium processes which are

[107] Divided by the resistivity

responsible for the irreversible production of entropy. Also, a most fascinating aspect of these non-equilibrium processes is that cross-effects, interactions, or *couplings*, occur between each of them. That is, a thermodynamic force (gradient) of one kind can influence the flow (transfer) of another. For example, a thermal gradient/force which causes a flow of heat energy, can also cause a flow of matter (Soret effect); while the contrary coupling is also possible, a concentration gradient of matter (chemical potential), which causes the flow of matter, can also cause the flow of heat (Kondepudi, 2008). Similarly, a concentration gradient of matter may also generate a flow of electric charge; and vice versa. Note that this latter phenomenon is extremely important to the biochemistry of a living cell: the proton motive force which powers ATP formation (Lehninger, 2000). Transport processes, and couplings between transport processes are now included in the broader science of modern non-equilibrium thermodynamics.

In the early 20th century, physicist Lars Onsager managed to unify the different possible couplings of transport processes under a general non-equilibrium thermodynamic framework (Onsager's reciprocal relations). Onsager's work marked a turning point in the history of thermodynamics: the range of applicability of thermodynamics was extended (from equilibrium states exclusively) to include irreversible processes. Again, according to Prigogine:

> "The importance of the Onsager relations resides in their generality. They have been submitted to many experimental tests. Their validity has for the first time shown that non-equilibrium thermodynamics leads, as does equilibrium thermodynamics, to general results independent of any specific molecular model."
>
> (Prigogine, 1977, p.4)

A.4.2 Far-from Equilibrium

Already, with an open system and under near-equilibrium conditions (the linear regime), an interesting set of interrelated (coupled) energy-materials transport phenomena become possible; and perhaps most importantly, the coupling of these different processes means that as one gradient is being dissipated, another gradient can be created.

Note that, conceptually, this brings us much closer to the original subject which interested Carnot father and son: the coupling of non-equilibrium processes (water-falls and heat transfer in steam engines) in open systems with mechanical processes on a macroscopic scale (the rate at which "work" is done, i.e. "power"[108]); only now the concept has been extended or generalized to include a large diversity of non-equilibrium transport processes, and rendered much more precise on local scales, and including rates of change.

As important as this may have been, Onsager's reciprocal relations are only strictly valid within a range of conditions where the thermodynamic forces remain linear and the coupling of processes symmetric (conditions not too far from thermodynamic equilibrium, i.e. near-equilibrium). Onsager's relations form the core of linear non-equilibrium thermodynamics (as well as non-equilibrium statistical thermodynamics). Further from thermodynamic equilibrium however, an even more diverse and unexpected set of phenomena can be observed.

Many diverse and *qualitatively* unexpected phenomena can emerge (self-organize) and persist under far-from-equilibrium conditions. This includes highly ordered

[108] Carnot's treatise was entitled "The Motive Power of Fire". The difference between work and power is that power is the time derivative of energy, or the rate at which energy is transformed into work. In all real circumstances, the engineer and industrial economist are interested in both power and work, though power is more important, for several reasons.

thermal convection cells, chemical oscillations, chemical wave patterns, chiral symmetry breaking in molecules, the synthesis of increasingly large molecules and polymers, complex bio-molecular structures (cell membranes), auto-catalytic chemical reactions, and eventually, complex self-replicating living cells and organisms (see figure for examples from hydrodynamics, chemistry and biochemistry). All of these ordered phenomena are caused by irreversible processes. Thus, whereas in equilibrium thermodynamics irreversible processes are what lead to equilibrium/stability, destruction of pattern, and homogeneity, in NET, under far-from equilibrium conditions, irreversible processes are found also to play a constructive role. On this very important point, Prigogine says:

> "It is only recently that a complete change in perspective has arisen, and we begin to understand the *constructive* role played by irreversible processes in the physical world." (Prigogine, 1980. p.78)

Prigogine famously classified the large set of ordered processes which emerge under far-from-equilibrium conditions as "dissipative structures", to distinguish them from well-known equilibrium "structures" of physical-chemistry (stable molecules and crystal lattices). According to him:

> "[…] it is useful to distinguish between two types of structures: a) equilibrium structures, and b) dissipative structures. Equilibrium structures may be maintained without any exchange of energy or matter. A crystal is a characteristic equilibrium structure. On the contrary, 'dissipative structures' are maintained only far-from equilibrium through the exchange of energy and matter with the outside world.
>
> (Prigogine, 1971, p.3)

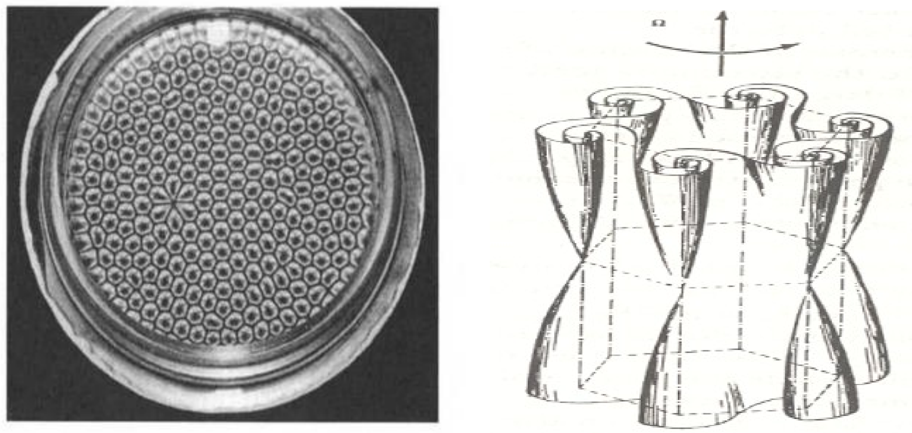

Figure 21. Dissipative structures in hydrodynamics: a) Bénard convective cells, b) Bénard cells with vortices

(Schneider ED and Sagan 2005) (Chandrasekhar 1961) p.113

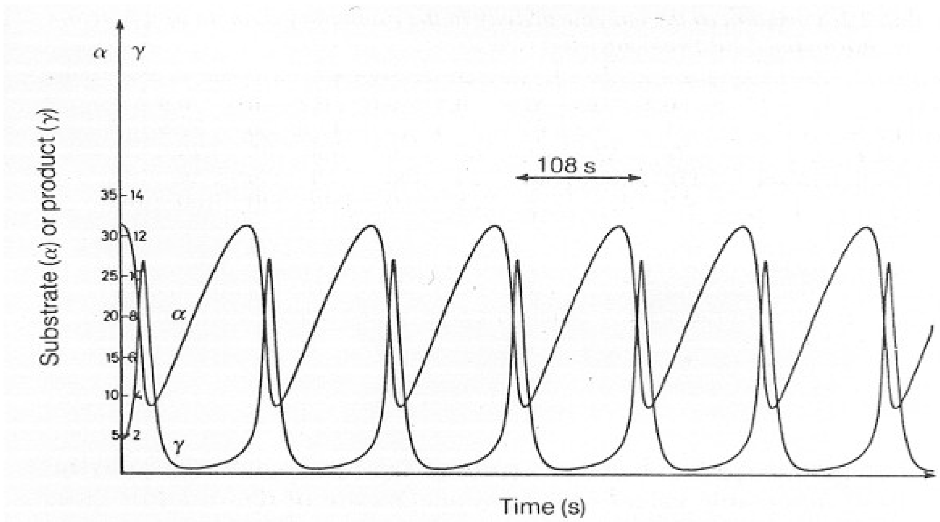

Figure 22. Dissipative structures in chemistry: B-Z reaction, coherent oscillations (Kondepudi, 2008, p.348)

Explanation for figures 21 and 22:
These examples are derived from both hydrodynamics and chemistry. Essential conditions for dissipative structures are: 1) the existence of a non-linear mechanism which amplifies an initial disturbance, 2) the maintenance of far-from-equilibrium conditions and 3) the existence of a non-linear mechanism which stabilizes the emergent structure within a range of conditions. Non-linear behavior is common in both these fields and non-equilibrium conditions are relatively easily maintained[109].

[109] In the case of chemical kinetics, the activation barrier for a chemical reaction often plays the role of maintaining non-equilibrium conditions. Molecules which should produce an exergonic reaction (energy releasing) under given chemical environment (oxidizing environment) can however be stable (thus maintaining non-equilibrium conditions), due to the high energy of activation (threshold) which may be required to initiate a reaction. For example: a sugar cube at room temperature (glucose is a highly combustible material, yet the

According to Prigogine, dissipative structures are always tied to three essential features: 1) fluctuations and instabilities, 2) emergent space-time structures, and 3) emergent function (transfer or transformation process, such as heat convection or chains of chemical reactions).

Figure 23. Three Elements of Dissipative Structures. (Prigogine, 1977, p.10)

These thermodynamic structures require at least two conditions to form, or emerge, and a two to persist: 1) the presence of far-from-equilibrium thermodynamic conditions (e.g. temperature, chemical or pressure gradients) and 2) the existence of a non-linear mechanism which amplifies an initial disturbance; 3) the existence of a non-linear mechanism which stabilizes the emergent structure within a range of far-from equilibrium conditions and 4) the maintenance of far-from-equilibrium thermodynamic conditions (gradients) (Prigogine 1971).

The concepts of emergence, maintenance and successive development of dissipative structures are central to NET

sugar cube is quite stable); a standing forest in our highly oxidized atmosphere. The simplest example of a "dissipative structure" for chemical processes is a standing flame (candle) or a moving flame front (line of advance).