*Energy, aesthetics and knowledge in complex economic systems**

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Abstract

It is argued that the fact that economic systems are dissipative structures must be taken fully into account in economics if we are to understand the nature of the economic-ecological interface and how to deal with emergent environmental problems, such as global warming. Such problems are a product of economic growth, which is widely accepted to be the outcome of the acquisition and application of knowledge. Drawing upon disparate literatures within and outside economics, it is argued that economic growth should be more properly viewed as the outcome of a co-evolutionary process that involves the autocatalytic interaction of new knowledge and access of increasing amounts of free energy to do increasingly specialized forms of work. The conventional view is that energy is just a factor of production used increasingly as new knowledge is employed. The possibility of reverse causation is considered here. Specifically, the relevance of the œenergy hypothesis,ô associated with Eric Schneider and his collaborators, is assessed. This hypothesis states that all dissipative structures have, as their primary objective, the reduction of accessible free energy gradients. It is concluded that such a hypothesis cannot be rejected in the context of economic behaviour and that this opens up an important research agenda for economists. It is argued that such research has to be interdisciplinary because our economic behaviour is driven by aspirational goals which are aesthetic constructions in the mind and strongly connected to our emotions. In this regard, recent neuropsychological literature, arguing that certain emotional dispositions are necessary before we can employ our cognitive capabilities effectively, is important to digest. Thus, the possibility exists that it is in the emotional domain of the mind that the energy hypothesis is operative. Aesthetic constructions are, thus, connecting agents in the knowledge-energy co-evolutionary process. Some of the macroeconomic evidence concerning the relationship between free energy use and economic growth is considered and it is found that the energy hypothesis cannot be rejected in the economic domain. However, considerably more research needs to be undertaken before any firm conclusions can be drawn.

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1. Introduction

As evidence has mounted that global warming is occurring and that this may be associated with global economic growth, the interface between economic and ecological systems has begun to receive more attention in economic research. The Stern Report, which had a major impact in increasing awareness of the problem, was written from a mainstream economic standpoint. However, what becomes clear in reading this important report is that modern mainstream economics is not well equipped to deal with problems at the economic-ecological interface. Of course, much has been written that is useful in the sub-field of ecological economics but this has received surprisingly little attention by policy-makers. So the relentless pursuit of maximal economic growth is still strongly advocated by many mainstream economists and this remains a primary objective of governments worldwide.

The goal of this article is to offer a perspective that might lead to a better understanding of why we avidly consume energy in complex economic systems, even when we donǹt need to, and how this is leading to serious environmental problems. However, there is no attempt to offer a new economic ómodelô here simply because we are dealing with a fast evolutionary economic process interacting with a slow natural evolutionary process. Standard mathematical logic is not very useful tool when interactive system dynamics are unknown and shifting. What is required right now is an assessment of how other disciplines can help us to understand why economic behaviour is so environmentally destructive. However, since the strongest levers that we have to solve these problems, in modern, advanced societies, are primarily economic in nature the consistent thread in this article remains an economic one. Although the ódismal scienceô lives on and is appended by thermodynamic considerations that, on the face of it, seem even more dismal, the kind of economic perspective offered is, in the end, quite optimistic. We tend to grossly under-estimate the adaptive capabilities of humans in complex and difficult situations

Here, we begin from the standpoint of neo-Schumpeterian evolutionary economics, rather than the mainstream of the discipline. It seems to be the best starting point when enquiring into how complex economic systems interact with complex ecological systems (Van den Bergh and Gowdy (2000)). This is not to say that mainstream economic theory is not important ï the strategic and non-strategic constrained optimization that lies at its heart has clearly played an increasingly important role in our economic behaviour in many contexts and economists have helped us to understand what the outcomes of such behaviour are and how they affect the prices and quantities that are established in well-developed markets for goods and services. Nothing that is said here diminishes the importance of this work. But the simple fact is that, although the array of analytical tools on offer can help us answer specific questions in well-specified contexts, they are, in the main, not suitable for answering questions about non-equilibrating behaviour in the presence of uncertainty and significant structural change.

Modern evolutionary economics really got going following the seminal work of Nelson and Winter (1982). In turn, they were inspired by the contributions of Joseph Schumpeter in the first half of the 20th Century. Evolutionary economics is often associated with the use of Darwinian biological analogy concerning operation of competitive selection. However, unlike Thorstein Veblen (1898), Schumpeter did not use Darwinian biological analogy to underpin his depiction of economic evolution and its ñgales of creative destruction.ò He offered a much more sophisticated perspective on economic evolution, centring on the acquisition and use of knowledge in economic contexts. What we would later come to know as processes of óself-organisationô were anticipated in his work and regarded as important in economic evolution (see Foster (2000)). However, modern neo-Schumpeterian evolutionary economists have been more willing to use biological analogy directly in their work. In particular, there has been widespread reliance on the mathematics of replicator dynamics, drawing on the work of biologist R.A. Fisher, to capture the process of competitive selection (see Metcalfe (1998)). Of course, in the economic context, competitive selection across random mutations is not the primary focus of attention but, rather, it is non-random, purposeful innovations that employ new knowledge that are seen as the relevant units of selection.[1]

The key actor in this process is the entrepreneurial individual or group that is brave enough to employ new knowledge to devise new combinations of technologies, new organisational structures and new combinations of skills to produce novel goods and services in states of uncertainty. The presence of uncertainty means that such behaviour cannot be represented in the mathematics favoured in conventional economics, namely, constrained optimization.[2] It is for this reason that conventional economists have had little to say about the role of entrepreneurial behaviour, despite its clear importance in economic development and growth. The presence of

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[1] For those relatively unfamiliar with neo-Schumpeterian evolutionary economics, two of the best sources are Dopfer (2005) and Hanusch and Pyka (2007).

[2] Veblen (1909) offered what is still one of the best explanations as to why this is so.

uncertainty has also raised fundamental questions concerning the theoretical treatment of knowledge. It cannot be treated as a commodity, as it is in the conventional theory of economic growth (see Steedman (2004)). Knowledge is a virtual network structure that is held in the brain. New knowledge applied by entrepreneurs is, necessarily, a sparse structure with limited elements and incomplete connections. As learning by doing and incremental innovation occur, this structure expands and fills out and it becomes clearer whether the entrepreneurial project is viable or not. Despite initial optimism, the majority of entrepreneurial ventures fail.

The process, whereby new knowledge is created and applied in a variety of novel ways by entrepreneurs has been given most attention by neo-Austrian economists. Friedrich Hayek was a pioneer and, in more recent times, what might be called the óknowledge-based theory of economic evolutionô has been refined most notably by Brian Loasby in a series of insightful contributions (see, particularly, Loasby (2002), (2009)). He, in turn, was inspired by the seminal work of George Shackle (see, for example Shackle (1972)), who developed a perspective on knowledge which combined the óradical subjectivismô of his neo-Austrian friend, Ludwig Lachmann, and the treatment of radical uncertainty by John Maynard Keynes, stemming from his *Treatise on Probability*. Unlike in standard economic theory, such perspectives are not expressed in mathematics for the simple reason that they cannot be because of the pervasiveness of uncertainty (see Boettke (1997)). In the mainstream, this position has been labelled by many as a ónihilisticô but the neo-Austrian challenge to mainstream economists to provide a mathematical representation of the formation and application of knowledge in states of uncertainty remains largely unanswered (see Li and Ayres (2008), pp.7-9).

In this article, the problem of dealing with knowledge is approached in a different way. We begin with a simple question: what kind of systems are we really dealing with in economics? The answer is that we are, necessarily, dealing with ódissipative structuresô that engage in two activities: first, they process available free energy to engage in actions (óworkô) that yield goods and services for consumption and, second, they invest in more complex structure that enables them to produce more goods and services using more free energy, or use existing free energy more efficiently. These dissipative structures must, necessarily, exhibit a degree of physical and organisational irreversibility to remain coherent, functioning entities. It will be argued that these features of dissipative structures have important implications when we assess the role of knowledge in economic systems. New knowledge can result in economic growth but its capacity to do so is always subject to a limit ï all dissipative structures have finite lives (see Fisk and Kerhervé (2006)).

Biological, social and economic systems differ in important ways with regard to the acquisition and use of knowledge but they have something fundamental in common: their energetic character. So when we try to understand how economic evolution comes about we have to examine how new knowledge interacts with the physical rules that all dissipative structures must, necessarily, obey when they use free energy. It is argued here that, in economic systems, the utilisation of new knowledge and increases in the work done through the application of free energy are intimately related and feed upon each other. This has often been ignored by economists who commonly make extremely strong assumptions concerning the availability of knowledge and treat energy as just another factor of production, mostly ignored because of its strong complementary relationship with the use of physical capital goods:

> The fundamental problem is that neo-classical economic theory has no role for physical materials, energy or the laws of thermodynamics. Energy and materials exist in the theory as outputs ï products and services ï but not as inputs or drivers. It is fundamentally a theory about relationships between immaterial abstractions. Moreover, standard theory assumes that scarcity does not exist in reality, because any threat of scarcity is automatically compensated by rising prices that induce reduced demand and increased supply or substitution. One implausible consequence of this theory is that energy consumption can be reduced arbitrarily with no implication or consequence for economic growth. Future growth is simply assumed to be automatic, cost-free and independent of future energy costs. Thus the standard neoclassical economic theory is, in effect, õdematerializedö. It needs to be õrematerializedö in the sense of incorporating the laws of thermodynamics as real constraints on possible outcomes. Ayres (2008), p. 294.

Economists with an evolutionary perspective have tended to make much weaker assumptions concerning the extent of knowledge and its application, but they too have tended to understate the importance of the energetic dimensions of economic systems. Of course, there have been important exceptions, such as Nicholas Georgescu-Roegen , Kenneth Boulding and, more recently, Robert Ayres, cited above but, in the main, it is in modern ecological economics (see, for example, Daly (1996) and Lozada (1999)), not evolutionary economics, that we find most attention given to the energetic features of economic systems.[3] Buenstorf (2000) argued that, given the importance of knowledge and organisation, we should regard energy throughput

[3] An important recent exception in evolutionary economics is Metcalfe (2009) in which the theories of technology and technical change are discussed. Energy is dealt with in some detail and in a manner that is compatible with the approach taken here.

as an emergent property of self-organising economic systems as they evolve. Here it is argued that the role of energy throughput may be more fundamental that this.

In the first half of the twentieth century, when Joseph Schumpeter was trying to understand the growth and fluctuations of economic systems, the provision of free energy was not really an issue. Coal and oil were plentiful and political problems seemed to be a much more serious threat to capitalism than energy limitations and associated wastes and pollutants. The old warnings of Stanley Jevons in *The Coal Question* concerning the finite nature of energy stocks seemed to most economists, including Schumpeter himself in his *History of Economic Analysis,* to be misplaced or just plain wrong. So the notion that energy is just a tap that can always be turned on and, thus, unimportant to deal with explicitly in economic analysis, beyond the analysis of price movements and their impacts, was widespread. The result is that, today, when oil is peaking and fossil fuel emissions face carbon dioxide and other entropic waste boundaries, the economics that we have is not well-equipped to understand how the global economic system ended up in such a situation or to tell us what policies can be applied to render economic systems environmentally sustainable. It is hoped that the perspective offered in this article will begin to help remedy this situation.

2. The economic system is an energetic system

Economic systems are complex and adaptive and belong to a class of ‘dissipative structures’ that maintain themselves far from thermodynamic equilibrium through the throughput of free energy available to do work (see Prigogine (1978), Brooks and Wiley (1986), Allen (1998) and Ayres (1998)). Thus, a free energy gradient is utilised to develop and mobilise structure and an entropy gradient is resisted, through maintenance and repair activities. In cases where free energy is imposed directly on physical matter, dissipation is the expected system response. In some cases that are close to thermodynamic equilibrium, patterned structure forms, as in the case of Bernard cells. In biological systems that maintain themselves away from thermodynamic equilibrium, physical structure exhibits a degree of irreversibility so that when, for example, the sun sets or winter arrives, a tree can maintain itself without the need to immediately turn solar energy into chemical energy through photosynthesis. Higher level biological systems, such as mammals, do not use direct free energy gradients, instead, they consume organic structures that contain chemical energy and structure-building matter. They too have to maintain highly irreversible structures to do this.

Complex biological systems have evolved a capacity to use imported free energy to self-organise synergetic interactions within their structures. Competitive selection mechanisms tend to favour systems that can transform more free energy into work and, when it is restricted in supply, those that process energy into work most efficiently (see Kiala, Ville and Annila (2008)). In the popular mind, this is often thought of in terms of the physical strength and agility of an organism but competitive selection is much more subtle than this, and even more so in the economic domain. Humans and ants, for example, have not succeeded because of the physical strength of individuals. Both have found ways to communicate and cooperate effectively as groups, resulting in self-organised structures that have been successful. For example, communicating groups of humans can develop a capability to hunt and kill a large animal. This isnôt just due to there being a large number of strong people, it is due to the common adoption of óunderstandingsô or rules. In other words, the quality of commonly held knowledge, some of it genetically endowed and some of it acquired through learning, is crucial. What we can call óeffective knowledgeô can turn free energy, extracted from metabolised food and externally controlled free energy flows, into work.

Of course, the second law of thermodynamics implies that, eventually, all physical systems must wear out, so, for a system to maintain itself over a significant period of time, some type of regeneration mechanism is required. Cycling and autocatalysis perform fundamental roles in maintaining adaptive systems far from thermodynamic equilibrium (see Kauffman, (1993) and Christensen and Hooker (1997)). Autocatalytic processes are energetically efficient because the structure in which energy utilization occurs is retained for future use. It has been well established that such processes are effective in the emergence, maintenance and development of non-equilibrium physical and chemical systems (Prigogine and Stengers (1997)). Schneider and Kay (1994), stimulated by the writings of Jeffrey Wicken (see, for example, Wicken (1987)), argued, more controversially, that throughput of energy to do work and the associated removal of energy gradients is the primary goal of all dissipative structures, living and non-living. For them, reducing free energy gradients is not just a means to an end, it is an end in itself. Furthermore, they speculate that this must be true for all dissipative structures, including those in the biological and socio-economic domains. This general proposition was considered in Raine, Foster and Potts (2006) and it was concluded that this view, although controversial, deserved further consideration by economists.

Clearly, Schneider and Kayôs ó energy hypothesisô (restated in Schneider and Sagan (2005)) needs very careful assessment in the socioeconomic domain because it is not just analogy that is being proposed but, rather, a general homology similar in nature to that made concerning the biological determinants of social behaviour by some socio-biologists. Although the proposition that socio-biological theory offers a general explanation of socio-economic behaviour is difficult to accept, it is clear that some aspects of behaviour that do conform to this theory (see, for example, Witt (1991)). So it is also possible that aspects of socio-economic behaviour are determined by an even more fundamental energetic force. Indeed, it may help us to understand those instances when genetic explanations do not hold.

Flirtation with this idea is not new - interest really began in the work of, for example, Jean Baptiste de Lamarck, Herbert Spencer and Ludwig Boltzmann, who all argued that energy acquisition and use were core processes in living systems. In the 20th Century, physicist Alfred Lotka (1922) went further and linked success in energy acquisition and use with natural selection and was one of the first to suggest that an energetic a perspective might also lead to a better understanding of economic behaviour. Physical chemist and Nobel Laureate Frederick Soddy (see Soddy (1912)) was also a proponent of the view that the origin of all economic value lay in energy acquisition and use. Like Stanley Jevons before him, he worried about the finite nature of the fossil fuel resources that the human race had come to depend on increasingly.[4]

It is notable that we had to wait until the 1970s for prominent economists to express a serious interest in the relationship between economics and thermodynamics. Nicholas Georgescu-Roegen (1971, 1976, 1977a, 1977b, 1977c, 1979) was an accomplished economic theorist who turned almost all of his attention to this relationship. His books became popular amongst ecological economists with interests in economy/natural environment interactions. Kenneth Boulding (1978, 1981) developed a version of evolutionary economics in which thermodynamics and energy supply play an influential role. The differing thermodynamic

[4]After World War II, some anthropologists and ecologists even began to embrace energetic theories of cultural evolution. Corning and Kline (1998) single out Leslie White, Richard Adams, Fred Cottrell Eugene Odum and Howard Odum as good examples.

perspectives of Georgescu-Roegen and Boulding stimulated wider interest in the relationship between the 1st and 2nd laws of thermodynamics and economics. Examples of useful contributions are: Hannon (1973), Slesser (1975), Gilliland (1975), Huettner (1976), Berndt (1978), Costanza (1980), Parsons and Harrison (1981), Bryant (1982), Roberts (1982), Ayres and Nair (1984), Proops, (1983, 1985, 1987), Odum (1988), Faber and Proops (1990), Burley and Foster (1992), Binswanger (1993), Giampietro et al. (1993), Ayres (1998) and Buenstorf (2004). In the 21st century, we began to observe discussions of the role of energy in the context of the emerging field of complex adaptive economics systems. McKelvey (2004) provides a relatively recent review of this literature.

A problem with the Georgescu-Roegen approach is that it focuses upon the entropy process and it has been established by a number of writers that he was in error on several counts in his understanding of thermodynamics (see, for example, Beard and Lozada (1999) for discussion). This proved to be a setback in the incorporation of energetic considerations into economics. However, the alternative perspective in the cited literature above, that it is free energy flow and the work that is done through the reduction of free energy gradients which is the key process in dissipative structures, lived on. From this literature emerged what Corning (2002) referred to as ñthermoeconomic principlesò.

Humans, as living dissipative structures, are seen as seeking to increase access to free energy sources, and/or increase the efficiency of currently employed energy transformation processes to do more work. The development of technological and human capabilities, and the organizational structures in which they are applied, increase organised complexity and enable the quantity and/or quality of outputs to be increased. For a complex system to be coherent, it must apply a set of rules. Technological rules determine the extent to which non-food free energy can be translated into work through the use of capital goods. Work practice rules, or routines, enable skilled and creative people, using capital equipment, to use their metabolic energy to produce specialised outputs that are of a consistent quality and complementary with other specialised outputs. Organizational rules ensure that coordination can occur in a complex production process. These too involve the use of significant amounts of work using food and non-food free energy in management and administration.

Rules of this kind are human creations involving much shared knowledge accumulated both through learning by doing and the creative use of logic and imagination. So it becomes clear that, even if food and non-food free energy are fundamental in the process of generating economic value, which they must be, the actual amount of work done and economic value generated depend crucially upon the acquisition and application of knowledge. This is obvious in the economic case, but it is also true to some degree in all complex systems with dissipative features.[5] In biological systems, knowledge is genetic, embedded in DNA structures. Species donðt choose this kind of knowledge, it is imposed upon them by selection processes. However, sophisticated biological systems with brains, such as mammals, can acquire non-genetic knowledge from experience or, predominantly in the human case, from the imagination and the exercise of logic. Thus, selection becomes less about physical power and more about brainpower and intelligence.

So we can think in terms of a hierarchy of complex systems from the physio-chemical, which is driven entirely by imposed energy flow and imposed ôknowledgeö in the form of a set of rules that are defined by natural laws, up to the socio-economic level, where sophisticated systems use knowledge, acquired from imagination and the exercise of logic, to turn acquired energy flow into specialised forms of work to produce heterogeneous goods and services (see Foster (2005)). When we think in these terms it seems, on the face of it, that Schneider and Kayðs energy hypothesis is not very important in understanding why economic systems exist and how they operate.

However, in our discussion up to this point, only limited attention has been given to the fact that the economic systems that we study are constantly in an evolutionary flux. In such a flux, new knowledge is acquired both randomly and purposefully and it is applied in states that are uncertain in varying degrees. In the biological case, it is presumed by many evolutionary biologists that genetic knowledge is the outcome of natural selection from a set of random mutations. However, in the economic case, it is clear that knowledge is also acquired from the non-random patterning of sensory information using logic and imagination. So what seems to be driving processes that use free energy of some kind is not ôobjectiveö knowledge but rather subjective knowledge that is hypothetical, i.e., it involves patterns of novel connections that yield a uniquely framed aspiration which may be aimed at through actions of various kinds. So what

[5] Lozada (2006), in commenting on Gillett (2005), stresses that we cannot argue that it is the free energy embodied in something that determines its economic value. It is necessary for free energy to be available but, without knowledge, it will not be set to work and, even then, there may be no economic value.

we have in the uncertain realm of economic evolution is not constrained optimization but, rather, a process of discovery.[6]

What impels people to embark on hazardous journeys to win the trappings of wealth and is this related to the same motivation that drives people to risk all in their adventurous quests to discover new worlds? This clearly takes us into the discipline of psychology where much has been written about such motivations but our quest is deeper because we also want to know if there is an autocatalytic connection between such motivations and the control of energy throughput. As we shall, see anthropologists tend to have more to say about this than psychologists.

3. The economic system as a co-evolutionary knowledge-energy system

As noted, the key difference between humans and other living systems is their capacity to use new knowledge, beyond that gained from experience, to make more effective use of human energy. So even when there was reliance mainly upon human energy, for example to construct the Pyramids in Egypt, clever systems were devised to transport, shape and build them. And, of course, the utilisation of non-human free energy sources later in history vastly increased the productivity of human work. The development of human cognitive capacity, beyond genetically-driven emotional responses, produced a capability to create abstract representations of reality (through, for example, language and mathematics) and an ability to communicate these to others.

Linguistic communication provided a significant boost to the transmission, sharing and use of new knowledge.[7] This conferred a competitive advantage on humans allowing access to greater amounts of food energy. Enhanced food security and associated surpluses provided an opportunity for population to grow but it also allowed more time to be spent engaging in social rituals and various crafts. The latter were important because they solidified group connectedness and the sharing of knowledge which, in turn, made the group more effective in hunting,

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[6] However, constrained optimization may well be used as a logical aid in appropriate contexts

[7] Horan, Bulte and Shogren (2008) argue, using a simulation model, that there is likely to have been a co-evolutionary relationship between the development of language and the emergence of trading between individuals and groups. J Econ Growth (2008) 13:293ï 313
Coevolution of human speech and trade
Richard D. Horan · Erwin H. Bulte · Jason F. Shogren

gathering and warfare. In contradiction to the thesis of Thomas Malthus, anthropologists have provided evidence that hunter-gatherers did not maximize their rate of population growth to the point of minimal subsistence (see, for example, Sahlins (1998) and Hartmann (2000)). Working hours were very low by modern standards and significant food surpluses did not lead to population increase because they were generally anticipated to be temporary and unreliable.[8] As with the ópotlachô of Indian tribes in the Canadian North West, such surpluses were often used in socially reinforcing celebrations and gift exchanges. There was even deliberate destruction of valued items as a display of superior wealth. óConspicuous consumptionô identified by Veblen (1899b) has been with us for a long time and it has always been associated with cementing social status and acceptance by a reference group.

No one really knows when humans began to use fire to produce metals to make better tools for hunting, gathering and warfare. But this application of new knowledge and energy ultimately restructured human society in fundamental ways. Pastoralism was initially nomadic and not too different socially from hunting-gathering. But sedentary agriculture was radically different with hierarchically organised societies emerging that used increasingly sophisticated tools to grow food and increase their populations to procure and work more land. Gradually, animal, water and wind power were employed, using technologies developed in growing urban areas. When fossil fuels became accessed on a commercial scale, the productivity of agricultural land increased very significantly providing a food surplus large enough to allow modern industrial societies to emerge.

We generally think of this long process of economic evolution, resulting in the provision of more and more complex capital and consumption goods per capita, as óprogressô due to the continual discovery and use of new knowledge. And it is true that new knowledge was vital but it was a necessary, but not sufficient, condition for economic growth to occur. Higher levels of GDP involve more work and this always requires more free energy or the more efficient use of such energy. Importantly, as discussed in Section 6 below, there is little evidence to suggest that more efficient use of free energy has led to a reduction in its overall use. New knowledge has been quickly acquired and applied to employ saved free energy in new ways. So technological progress has resulted in an autocatalytic process, where energy saving innovations have

[8] Galor and Moav (2002) argue that this non-Malthusian capacity to control the quantity of population, allowing the quality to rise, initially reflected in cultural attributes, created the pre-requisites for the future takeoff of economic growth as those with higher levels of human and social capital were selected favourably.

produced energy surpluses that have, in turn, allowed resources to be devoted to further innovations that have kept energy use growing, despite efficiency gains:

> ñBased on these results we argue that the improved exergy conversion to useful work efficiency acts as a proxy in the model for technical progress. é Exergy efficiency and economic growth ï capital accumulation and investments in technical progress ï recursively drive each otheré .. It appears that sustained economic growth in our current economic system depends on high inputs of fossil fuels despite considerable efficiency gains.ò P.139, Warr, Schandl and Ayres (2008).

As has been noted, Kiala, Ville and Annila (2008), provide support for the hypothesis that increased efficiency in the use of energy is consistent with the growth in energy throughput also in biological contexts. In Nature, we do not see species which become more efficient in energy use reducing their free energy throughput, they seek to occupy the new niche that this opens up by increasing their populations.

Economic decision-makers do not think in direct energetic terms but, rather, they are concerned with flows and stocks of monetary value. They donôt seek to use up free energy gradients to do work for its own sake, they seek to discover what we might label as óknowledge gradientsô that can be exploited to earn money. But these are not always easy to discover and there is always an array of pre-existing socio-cultural institutions that make it difficult to enact a radically novel project. This is most pronounced in the case of entrepreneurship in an uncertain environment. It is only in relatively modern times that being an entrepreneur has become a respectable activity and, even today, it is a formidable challenge. In order to achieve an entrepreneurial aspiration, technical knowledge, organisational knowledge, institutional knowledge, embodied knowledge in capital goods, the skills of a selected group of people and a flow of useable physical free energy all have to be combined effectively. Because all this is a highly uncertain business, conventional economists have tended to shy away from dealing with it, even though nothing could be more óeconomicô than this kind of decision-making.

As Shackle (1972) pointed out, the knowledge relevant to an entrepreneurial decision is ókaleidicô in nature ï it involves patterns of elements and connections in the imagination that must have an aesthetic quality that excites:

> ñThere are those who believe that life consists of a series of imposed situations to each of which there is one right response, and there are those who think that we impose upon the

> material chaos a psychic order of our own invention, not seeking to solve a problem but to conceive a work of art.ò (Shackle 1966, p.755)

Shackle was of the view that it is mistaken to only view knowledge as something that concerns real, objective phenomena when, much of the time, there is no real, objective information available. He argued that subjective beliefs, even if they turn out to be erroneous assessments of reality, are knowledge. But subjective knowledge has to be óframedô in some way and that is why he felt that the aesthetic content of entrepreneurial imagination must be important. And, because imagined patterns can turn out to have significant impacts in the real world, such imaginings have to be taken into account by others:

> ñLies, myths, `misinformation' or `disinformation' of various kinds may also serve as `control information' insofar as they affect a user's behavior. It is not the veracity which counts in the control information paradigm but the functional effects that are produced.é . There is, in fact, a large literature in behavioral biology on the evolution and use of `deception' as a strategy for achieving various functional outcomes.ò (Corning and Kline (1998), p. 473)

> ñThought, imagining many potential scenarios, most of which are not true or realistic, pays its way evolutionarily by occasionally finding new gradients, and helping social animals to coordinate their activities by fine tuning perception and communication.ò (Schneider and Sagan p.308).

The notion that people work towards aspirational goals that are aesthetic constructions of the mind is widely accepted when we are dealing with artists and other creative people. However, this also seems to lie at the core of those inventive, innovative and entrepreneurial activities that result in economic outcomes. But, as with the artist, what is perceived as a new knowledge gradient to be exploited often turns out to be a mirage with failure the outcome. But failure is fundamentally important ï if entrepreneurs are unwilling to risk failure there will be no successes. We depend on their imagining because they generate the very diversity of knowledge from which the best processes and products emerge. Because this is not órationalô in the conventional sense, economists are uneasy about analysing the behaviour of entrepreneurs. Even neo-Schumpeterian economists, who do stress the importance of entrepreneurship in generating economic growth, tend to stop short of examining what actually drives entrepreneurial behaviour (see Witt (2007)). Examinations of the psychological dispositions of entrepreneurs are rare in economics but when they are touched upon, they can have a large impact. For example, John Maynard Keynes was braver than most and referred to entrepreneurial behaviour in uncertainty, which he saw as the root cause of both economic growth and business cycle fluctuations, as driven by ‘animal spirits’, namely, the ‘will to action over inaction’ (Keynes (1936)). This immediately forges a connection with the energy hypothesis since it is concerned with goal-driven action, or work, for its own sake. Veblen (1914) had previously argued, more generally, that the desire to work is instinctive but more in a cultural, rather than a genetic, sense.

These kinds of arguments suggest that our actions have emotional drivers, despite the fact that cognitively based logic can be used extensively to plan and execute plans (Loasby (2007)). With entrepreneurs, in particular, it has been found that they tend to be unjustifiably optimistic, allowing their imaginings to over-rule realistic possibilities. There is now a growing body of evidence in neuropsychology supporting the view that emotional drivers are primary and cognition acts more as a rational tool in the service of the former (see Ariely (2008) and Lehrer (2009) for reviews of this evidence for a general audience).

Entrepreneurs seem to be more decisively driven by their emotional connection with their aspirational goals than most of us, at least in the economic domain. They seek to discover and exploit new knowledge gradients in a similar way to a biological system seeking to discover and exploit new energy gradients. And the result is the same, more free energy throughput occurs. So if the entrepreneur is, indeed, the primary source of economic evolution and associated economic growth, then the energy hypothesis does seem to be relevant to understanding why economic growth occurs.[9] However, the co-evolutionary connection between new knowledge and increases utilization of free energy is not entirely straightforward. We can conceive of circumstances where economic growth occurs using the existing state of knowledge in a routine way but with increases in free energy utilization. We can also conceive of cases where there are increases in the discovery and utilization of new knowledge without much increase in free energy use – the internet comes to mind in this regard. So, clearly, if there is a co-evolutionary relationship it must exhibit dynamics that are both complex and nonlinear and only be reliably observed over long periods.

There is already a large literature on innovation diffusion which tracks the uptake of new knowledge in new economic activities – it can take several decades for a radical innovation to be fully utilised and, thus, reach its maximum potential in relation to free energy utilization. In

[9] Chen and Vinig (2007) have shown that it is possible to develop a theory of entrepreneurship based upon non-equilibrium thermodynamic principles.

relation to the routine use of existing knowledge, many people involved in the productive side of the economy engage in very little innovation or entrepreneurship. However, their efforts can still lead to increased energy utilization because they have aspirational goals in the context of their consumption expenditure. These goals are also formulated in aesthetic imagery and heavily worked on by marketing and advertising agencies. This, in turn, determines what goods and services are demanded and these must be designed creatively.

4. Aesthetics and energy

The aesthetic quality of a good or service is important because of the real or imagined power, immediately or in the future, that it signals to us. Our emotions are programmed to select beauty over rude utilitarianism, except in necessity. So, for example, the dress uniform means much to the military recruit, as does the colourful marching band. Without aesthetic excitement and the feeling of being part of something big and important, there would be no recruits. The lover must be wooed, the entrepreneur dreams of mansions and luxury cars while suicide bombers dream of virgins in Heaven. So action, the use of free energy, requires an aesthetic trigger that is emotionally stimulating. Outside of basic physical needs, such as food and warmth, there has to be an aspiration before action, i.e., free energy throughput, occurs. If all we want to do is release free energy, we can just burn things down but, with the exception of a few arsonists, we usually want to use free energy to do work to create aesthetically pleasing experiences and structures. Thus, the connection between aesthetic appreciation and energy throughput seems to be fundamental.[10] Something that is perceived to be ugly can also stimulate action but this will be an act of avoidance or negation. Disharmony, degeneration and breakdown, i.e., manifestations of the second law of thermodynamics, do not stimulate aspirational goals in our imagination, they stimulate flight to an aesthetically more acceptable environment. We are programmed emotionally to form aspirations that have positive aesthetic qualities, which involve a mix of novelty and structural harmony. This also gives us a related capacity to appreciate the aesthetic quality of structures in our surrounding environment, both humanly-constructed and natural, even if we are not trying to possess them. We appreciate the energetic harmony that we see in, for example, natural landscapes and the energy invested by an artist or an architect in their

[10] Winiarski (1899) was one of the first to make this connection

creations. This is directly related to the aesthetic creativity and appreciation in ritual dance, music and ceremonial wear in our hunter-gatherer past as well as a deep aesthetic integration with the natural environment.

Dutton (2009) argues that, because an aesthetic sense stimulates us to action and also tends to solidify our identification with a power group, it confers a competitive advantage and, thus, must have been important in human evolution. The association of aesthetics with ópower,ô of course, is an association with free energy throughput of some kind. In modern society, our aesthetic appreciation has become more strongly focussed upon material possessions that provide an individual with a direct sense of power over human and non-human free energy throughput. This has led to accumulations of assets and throughput of free energy far beyond the needs of many individuals, at least in the most highly developed countries. Dutton (2009) noted that Darwin, quite early in his research program, began to suspect that aesthetics may have a role to play in natural evolution. He was puzzled by the fact that selection often seemed to throw up exotic characteristics that did not seem to be in the best interests of a species. Thus, he decided that there must be sexual selection as well as natural selection. Peahens choose peacocks to mate with on the basis of the aesthetic qualities of their tails and this, in turn, leads to the evolution of even more spectacular tails. What seems to occur in Nature is a tendency for aesthetics play a role in selection in localities where food energy is in plentiful supply and there are no strong predatory pressures. Female peacocks choose ógood lookingô males, often not very well-equipped to escape a predator. However, the irresistible logic of natural selection tells us that this aesthetic choice must have conferred some advantage otherwise the peacock would long be extinct.

Closer study of this case has led some biologists to conclude that a strong aesthetic display signals the good health of a male which has, for example, immunity to parasites, etc. From the energy hypothesis perspective, good health in a living dissipative structure suggests a low rate of entropic degeneration and an associated capacity to throughput energy over a relatively long life which, in certain environments, is more important than strength or speed. Much of the beauty that has evolved in Nature can be viewed as due to the evolution of efficient energy using structures that exhibit harmony that reflects internal physical health rather than just a capacity to fend off predators. Dawkins (2009) argues that choices based upon aesthetics have been very pervasive in natural evolution, resulting in species that we class as beautiful, such as flowers with exotic characteristics promoted by the aesthetic choices of insects.[11]

When we turn to economic systems, aesthetics are even more important.[12] What gets selected in the marketplace is the most aesthetic product in terms of design, look and efficiency, subject to price. And even price is sometimes used as an indicator of quality. Loosely speaking, goods perceived as high quality are relatively expensive and, therefore, have used up more energy in their production, distribution and marketing. But consumers are not directly concerned with the energy throughput associated with a good or a service. We can identify some highly priced goods with perceived high aesthetic quality, but with relatively low energy throughput involved in their production and distribution. For example, high fashion goods or works of art can fit in this category. But we must remember that such goods are only a very small minority of those in their class. For every valuable piece of art there are vast numbers of other pieces that are relatively valueless. In an energetic sense we have to look at the total energy throughput of artists or clothes designers, not just the throughput of the successful. Economists argue that works of art are expensive because they are rare but that is also a cumulative product of many aesthetic assessments that are made relative to a large body of other works of art ï the valuation is, necessarily, a relative one. Possession of a rare art work is a signal of belonging to group that can afford to buy impractical but rare items produced using large amounts of energy.[13]

So, to understand these aesthetic considerations from the energy hypothesis perspective, we have to consider the perceptions of the purchasers of goods rather than just the throughput of energy in their production. Aesthetic sense can be individual but it is mostly socially determined. It relates to our identification with a particular group that we perceive ourselves to be a member of, or aspire to be a member of. We often buy goods to display our membership of a status group which exercises power that we try to identify with. And power is either power over people

[11] ñA meadow full of flowers is natureôs Times Square, natureôs Piccadilly Circusé . This floral extravaganza, splashed across the green canvas of a meadow, has been shaped and coloured, magnified and titivated by the past choices made by animal eyesé ò Dawkins (2009), p. 51.

[12] De Fraja (2009) has set the discussion of aesthetic choice in the context conventional utility maximization analysis, arguing that óconspicuous consumptionô in modern economic systems can be directly linked with sexual selection. However, underlying energetic considerations are not dealt with.

[13] Economists have, for a long time, used the ówater and diamonds paradoxô to argue that prices are not well related to use values but, instead, are driven by relative scarcity and associated marginal valuations. But there is also an aesthetic dimension. Diamonds are status goods because they are both rare and aesthetic. Ugly rare things generally have little value.

(human energy) or power over productive, free energy-using assets. So buying an expensive painting or an expensive car is, to some degree, buying visible evidence of being part of a powerful group. There need not be a strong connection between the aesthetic quality of a good and the energy cost involved in its supply. What is important is the power it can exercise.

A great deal of the energy throughput that we experience is metabolic, namely, engaging in activity fuelled by food. We enjoy the associated physical and mental activities, such as jogging using our legs or engaging in a conversation using our brains.[14] Maintaining stable metabolic conversion provides a sense of well-being which enables us to engage in activities and these activities, in turn, ensure that we use up free energy, often in seeking more free energy. Activity occurs at two levels of consciousness. First, there is the level of the routine at which behaviour is activated in a relatively unconscious manner. This can be genetically determined or an acquired habit. Routines and habits provide a secure platform for conscious behaviour that is stimulated by a sense of excitement and novelty. This duality spills into our perceptions. We like to see harmony in the structures around us, be they natural, social or physical. Harmony in structure is the product of the well-honed use of free energy gradients. In contrast, novelty is something that is surprising and unpredictable that involves bursts of free energy use. But, to be attractive, novel experiences or perceptions must have a positive aesthetic quality ï your house unexpectedly burning down is not but an unexpected firework display may be.

What drives us is the aesthetics that we associate with the security of harmony and the excitement of novelty, not the energy throughput that underlies them. We buy a large house because we think it is beautiful and will signal to others that we are powerful, not because large free energy gradients were tapped to build it and because further free energy throughput will be required to maintain it. The aesthetics of harmony and novelty drive our activity and our economic choices. But lurking behind all such choices are energetic considerations. When harmony is associated with the security and power of owning economic wealth and novelty is associated with the acquisition of new material possessions, they become vehicles for increasing free energy throughput.

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[14] ñé thinking, so heavily dependent upon glucose metabolism, is part of the bodyôs relatively stable means of gradient reduction: that is its context, and even the most uncompromising metaphysician must support his habit by eating.ò Schneider and Sagan (2005), p.308.

These choices involve processes of discovery, learning and experimentation but their end result in macro terms will be the sustained growth in free energy throughput, if free energy is available. By analogy, sexual activity is also a result of discovery, learning and experimentation. It involves aesthetic taste and a range of social behaviours and is, to a large degree, pursued as a pleasurable activity. Some sexual unions result in reproduction, which is the underlying genetic reason for the activity, although this is not seen as the primary reason by many people. We can view the free energy throughput outcome in the same way. We do not see free energy throughput as the primary reason for our economic behaviour but this is what eventuates. And, of course, some people engage in sexual union specifically to reproduce and, in the same way, some people throughput free energy directly as a desired activity. The controlled release of free energy, in a range of contexts, is a popular activity.

So structures with very positive aesthetic qualities are deemed to be powerful because they reflect high levels of coordination of human and non-human free energy in their construction and/or operation. This is important in relation to the energy hypothesis because it means that selection does not just favour those that are most efficient, it can also favour the most aesthetic which, in turn, can require more energy to produce. So, for example, increases in the efficiency of producing standard goods releases human and non-human energy that can be used to produce goods with specific aesthetic qualities, such as hand-made arts and crafts or stylish dinners in high class restaurants. As the manufacturing sector has become more productive employing less labour, so there has been a dramatic expansion in the service sector. Any energy saved in the highly productive sector is, thus, offset by new demands for human and non-human energy in the service sector. Goods and services with more aesthetic and less utilitarian characteristics are demanded and they generally require more free energy throughput.

In relation to the hypothesis that knowledge and free energy use co-evolve, what the above discussion suggests is that our aesthetic sensibility is what connects our knowledge with the throughput of free energy. We are pre-programmed, both genetically and culturally, to structure knowledge in patterns that have an aesthetic quality and our actions, using free energy of some kind, are dictated by goals that are aesthetic constructions in our imaginations. Achieving such goals then ódocks inô both free energy throughput and specific knowledge which then constitutes the structured platform for the formation of new goals. We cannot understand the nature of knowledge or our use of it without understanding the aesthetic constructions that form in our minds. Advertising agencies have understood this for a long time, now this must be incorporated explicitly into models of economic behaviour.

But a question still hangs over this discussion: how did we move from a low free energy using hunter-gathering culture to a modern high energy using urban-industrial one? The usual answer in the literature on economic growth is cast in terms of the rise in the quantity and quality of knowledge. But here it has been argued that the application of new knowledge has to be mediated by aesthetic constructions. So there must have been a shift in these constructions of the mind firmly towards goals that resulted in the throughput more free energy. Related questions arise: why did this process begin to speed up about 10,000 year ago and why did it begin to accelerate rapidly about 300 years ago? As has been suggested above, the formation and application of aesthetic constructions in our minds are mainly determined socio-culturally. So to answer such questions, it is necessary to understand how and why the socio-cultural norms and rules that underpin our aesthetic evaluations and our capacity to act on them have shifted historically.

5. The unit of identification

It is common in economics to make strong and unrealistic presumptions about the extent of knowledge and our capacity to act on it that contradict real world experience. As has been noted, neo-Austrian economists have been some of the strongest critics of this way of dealing with knowledge, yet they share the conventional view that the individual should be the building block of economic analysis, but from a much more explicit subjectivist perspective. And it is true that self aware humans are prone to having a highly subjective view of the world ï egocentric self awareness suggests to an individual that s/he is central. In the face of ignorance about many aspects of reality, suitable compensating myths are relied upon. The fact that an individual is really just a mere flicker in the infinities of space and time, as modern science would have it, doesnĝt go down too well from a subjective perspective. Long ago, it was hard for people to depart from their subjective view that the Earth is flat and at the centre of the Universe. Later on, it was difficult for them to accept that humans are the outcome of a long, natural evolutionary process and not made by a god who looked like them. Dawkins (2009) has reminded us that a great many people still do not accept this.

Since the Enlightenment, attempts to provide objective scientific evidence have been increasingly tolerated as useful activities and very significant advances in our understanding of the natural world around us and our place in it have been made. Yet the individual-centric view has survived, but in a new guise. No longer is it just concerned with me and my imagined relationship with a god that can help me deal with uncertainty and ignorance. Thomas Hobbes had asserted that the individual is essentially a conflicted and conflicting self that has to be controlled by religion and the State. The new rationalist/materialist vision that emerged in the 18^{th} century portrayed individuals as self-interested but with a capacity to form rational plans, to enact them through efficient cognitive processes and to be able to cooperate with others when there is material gain from doing so. This view, promulgated most insistently by Adam Smith, meant that individuals did not necessarily require myths and/or socio-political control to successfully pursue their materialist goals. This was, of course, itself a myth in a world where people remained uncertain and ignorant about many things and, therefore, in need of religious and other kinds of myths to feel secure and happy. But adherence to this new myth would eventually lead to unparalleled economic growth.

This new rationalist/materialist mythology became powerful because it gradually liberated people to make individual decisions to produce economically valuable goods and services and to choose who to cooperate with in economic activities even though there remained many restrictive rules in operation in the socio-political domain. Correspondingly, new rules gradually emerged to protect economic freedom and property rights. For example, organizational rules evolved that allowed individuals to participate effectively in productive hierarchies, institutional rules emerged that allowed market and contractual systems to work reliably and rules were devised to protect individuals from strategic opportunism and rent seeking. So growing adherence to the rationalist/ materialist myth led to the emergence of a complex, adaptive economic system focused upon material self-betterment.

The Enlightenment was clearly about changing the nature of knowledge and it is no surprise, from our perspective here, to observe that it was as much about shifts in commonly held aesthetic perceptions as it was about seeking a more objective basis for knowledge. The Industrial Revolution, which got going in the late 18^{th} Century, was concerned with the aesthetics of engineering design and this led to the construction of plant and equipment that could increase the use of non-human free energy, both in agricultural and industrial applications. Frederick Soddy remarked that:

> óThe conversion of thermal energy into mechanical energy, first practically effected by the invention and perfection of the steam engine, has brought about in a single century more permanent change in the manner of living, and even in the habits of thought of the inhabitants of the world, than any combination of political, social, or personal influences could have effectedò Soddy (1912) p. 240.

But such a statement misses the fact that new knowledge and energy must co-evolve - ñpolitical, social and personal influencesò are also important. The implication of his statement is that socio-economic dissipative structures are no different to physio-chemical ones. Abel and Trevors (2006) have argued strongly that this cannot be so even comparing biological and physio-chemical dissipative structures. They found no evidence that self-organisation, which is a feature of biological systems, occurs at the physio-chemical level. Thus, they argued that the formation of structure in physio-chemical dissipative structures through the imposition of energy should be referred to as ósself-ordering:ô

> In biology, the sequencing of nucleotide selections into digital prescriptions and
> the use of a formal encryption/decryption, rule-based system is what organizes life. No such cybernetic system can self-order or self-assemble. (p.224)

Thus, they claimed that the self-organisational connection between the physio-chemical and the biological made by, for example, Prigogine and Stengers (1997) is invalid. Biological self-organisation can only be understood in the context of knowledge formation, retention and inheritance. They acknowledge, however, that the decisive selective force is access to and use of free energy:

> Genetic control is algorithmic and cybernetic. It employs a representational sign system, dynamically-inert configurable switches, coding encryption/decryption, formal computational halting, and meaningful messages *understood in terms of eventual metabolic success*. (p.224 ï italics added).

Lineweaver and Egan (2008) have recently offered additional evidence in support of the energy hypothesis in all dissipative systems, living and non-living. But, remembering the words of Abel and Trevors (2006) above, this seems to pose a dilemma. How did life get going if the behaviour of a self-ordering physio-chemical system is quite different to a biological self-organising one that uses and replicates knowledge? Of more interest here is how the sophisticated knowledge systems employed by humans in modern economic systems got going after a very long history of hunter-gathering subsistence? Much has been written in cultural anthropology trying to answer such questions and a range of theories have been offered (see, for example, Boyd and Richerson (2005) and Hill, et al (2009)). It is not our purpose here to answer such questions except to note, along with Soddy, that the observed shift from the 18th Century onwards was accompanied, necessarily, by matching increases in free energy throughput. So we cannot eliminate the possibility that the co-evolutionary growth of knowledge has been driven by the growth in energy throughput, not the other way around, i.e., the energy hypothesis may hold in economic systems.

Despite being caught up in a world of material aspirations and the associated escalation of free energy use, such a hypothesis may seem unreasonable because, as individuals, we often seek to economize in the use of free energy. However, this ignores the fact that, more often or not, we are acting, not as isolated individuals, but with reference to some group that we identify with. We seek recognition and status and, in turn, we enjoy identification with the collective power of a chosen group. Indeed, we may choose to sacrifice our own individual power over free energy throughput to strengthen the groupôs power. Again, aesthetic constructions in our minds play a key role in forging the emotional connections between individuals and what we can call óunits of identification.ô Such a unit can be as small as a nuclear family or as big as a nation. So in assessing free energy throughput, we need to know what the unit of identification is and individuals may well relate to many more than one.[15] Before the Enlightenment, when good outcomes occurred, those with religious beliefs attributed these to the work of gods. Bad outcomes were the work of some evil force. Churches promoted morals and ethics that resulted in group identification that proved to be advantageous socially. When the secular rational/materialist belief system emerged, good outcomes became increasingly viewed as due to the capacity of people to acquire and use knowledge in rational and effective ways. Bad outcomes were seen as due to óirrationalityô. This tended to weaken traditional religious group identification but the óanonymous cooperationô that emerged in productive enterprises and in the market place more than offset the economic disadvantages of this. Economic growth and human

[15] This can lead to the well-known problem of ócognitive dissonanceô when the goals of different units of identification are contradictory in some sense.

betterment were stimulated to a degree that held successful capitalist systems together, despite serious challenges from older collectivist and authoritarian ideologies.

In practice, of course, the secular myth did not fully take over. Instead, Western capitalism relied upon a combination of religious (mainly Protestant) and secular world views, as noted a century ago by Max Weber. So an individual could identify with a god and, at the same time, identify with the rationalist/materialist myth, so well encapsulated in neoclassical economic theory, in his or her economic affairs. Thus, there emerged a hybrid belief system with a uniquely strong capacity to generate economic growth through the commercial application of technological, organisational and institutional innovations that led to the use free energy in ever-increasing amounts. Material ćprogressô became sacred, irrespective of which belief system or combination that was upheld. To understand why the unit of identification is so important when analysing knowledge-energy co-evolution, it is worth providing a very brief sketch of how socio-cultural change occurred in human history and how this led to increasing economic activity.[16]

In the age of hunting and gathering, individuals strongly identified with their band and with the natural environment. The former identification was expressed in cultural practices and the latter through naturalistic myths about animal gods, etc. In such a world, there was a strong concern for future (and past) generations that were genetically connected and there was a respect and sensitivity to the natural environment that was very immediate. With the advent of horticulture and animal husbandry, the identification of now relatively non-nomadic people extended beyond the band to the óvillageô or the ćclanô and myths concerning gods began to take on a more human form, reflecting the increased control of the environment that was evolving.[17]

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[16] See Foster (1987) for a discussion of how we can deal with economic evolution when the behaviour of individuals is dictated by the adoption of a ćcollective consciousnessô. Mokyr (2002) offered a very useful historical account of how the use and spread of knowledge came about in human history. Witt (2005) offered some interesting insights into how production evolved as the nature of knowledge changed. Weisdorf (2005) reviewed the literature on the causes and consequences of the shift from hunting and gathering to farming. Van den Bergh and Gowdy (2009) reviewed the related literature on group dynamics and group selection in cultural and economic contexts. Lipsey (2009) discussed how technical change requires the co-evolution of appropriate institutions and explains, historically, why this occurred more quickly in Western Europe, compared to other parts of the World.

[17] Woodburn (1998) discussed the distinguishing characteristics of the egalitarian óimmediate returnô system of hunter-gatherers and the in-egalitarian ódelayed-return systemô that emerged in the transition to the horticultural/pastoral stage of human development. Arnold (1996) stresses that hunter gatherer societies were complex systems and their cultures and practices varied greatly in different locations. This makes simple generalisations concerning the timing and nature of their transitions somewhat misleading, particularly given the paucity of reliable archaeological and anthropological evidence.

Respect for the environment remained but with a particular concern to protect grazing stock from predators which resulted in emergent fears about ‘the wild’.

When small scale horticulture evolved into large scale, labour intensive agriculture, human society changed considerably.[18] Males became farmers and females lost the status that they had enjoyed as gatherers and became domestic, child producing servants (Veblen (1899a)). Extending agriculture required more labour energy and so family size was maximised to this end. The family remained important but now it wasn’t the clan that was identified with but, instead, the powerful hierarchies that were built up in agrarian societies, such as that in ancient Egypt or the highlands of Peru. Such societies later developed religions that were monotheistic that could span whole nations. Christianity became the most important agrarian religion, promoting moral and ethical rules consistent with agricultural success in a hierarchically organised society.

In the agricultural era, villages evolved into cities and, in these cities, which had looser social connections and were more secular, enterprise and trade developed, leading to innovations that would raise agricultural productivity and provide surpluses that permitted the formation of urban-based industries producing a range of goods and services. The agriculturalists lost their old hunter-gatherer identification with Nature and, instead, viewed the natural environment as a resource for producing food for a growing population. By the Middle Ages, agriculture in Europe had become feudal, shifting to the employment of serfs rather than slaves to provide human energy in agriculture. Individual identification was with the power of the lord and the fiefdom, supported by the Catholic version of Christianity that allowed oppressed people to identify with the imagined power of a god.

The development of industry and commerce in urban areas led to a strengthening of Protestantism which sanctioned enterprise and the accumulation of wealth. This became the dominant religion of the industrial and trading city and it was disconnected from the natural environment and only loosely connected to agriculture. In urban areas, interactions had to occur with largely anonymous individuals, identification with neighbours was weak and family members began to be dispersed geographically. With the advent of the industrial revolution, the agrarian hierarchies began to lose control and urban political movements created conditions where capitalism could prosper. Large nations began to form, increasingly led by parliamentary

[18] Baker (2008) provides econometric evidence that supports the view that the shift to agriculture altered the socioeconomic growth process in a fundamental way.

assemblies rather than monarchs. National identity became stronger. The individual, although still connected to an extended family, was increasingly an economic entity identifying with a productive enterprise and engaging as an individual consumer in a market to acquire material goods and the services of others.

Gradually, the extended family unit declined and the economic priorities of the individual came to dominate much more. The religious myth was increasingly downgraded in favour of the rationalist/materialist myth, ideally suited to the urban óeconomic lifeô. By this time, in large urban contexts, near total disconnection with the natural world became widespread and, importantly, the diminishing connections with an extended family weakened individual commitment to future (and past) generations. Individual decision-making, over a relatively short term time horizon, became more prevalent. Correspondingly, there was reduced interest in sacrificing material opportunities in favour of assisting a widely dispersed family group, neighbours, future generations or the natural environment. So the unit of identification had gradually shifted away from the tight hunter-gatherer band norm which prevailed for much of human history. Individual aspirations became more focussed upon the ownership of material possessions and the power that these provided rather than identification with the collective power of a group, maintained through reinforcing rituals.

The rise of the individually oriented rationalist/materialist myth has yielded spectacular, largely peaceful economic growth in advanced countries after some difficulties in the first half of the 20th century. However, the individual accumulation of assets and consumption of goods and services has involved dramatic increases in the throughput of free energy and attendant environmental problems. The prevailing rationalist/materialist culture has made it difficult to address these problems. This has been compounded by the fact that some influential religious faiths have continued to be opposed to sustainable population and environmental strategies. It is thirty years since the humanist, Eric Fromm, posed the rhetorical question: ñto have or to be?ò (Fromm (1978)). As a social psychologist, he saw clearly that the problem that capitalism faced was a philosophical one that centred upon the knowledge and beliefs that are commonly upheld. He argued that óbeingô involved a non-materialist belief system that placed a renewed emphasis upon harmonious connections with other people, now and in the future, and the natural environment. This is not a question that many economists can relate to because it is, essentially, about the role of socially shared aesthetic perceptions not the utilitarian tastes and preferences of individuals.

Our brief sketch suggests that the aesthetic constructions that drive our actions towards aspirational goals have changed significantly over time. This has been paralleled by the discovery and utilization of increasing amounts of non-human free energy to do work of an increasingly specialized kind. However, our emotional dispositions are the same as they were in hunter-gather times. These are now operative in quite a different context. Social recognition and status are now commonly associated with ownership of material possessions, not just gifting and rituals. The instinct to gather is now played out in shopping centres while the hunting instinct is operative in business as various strategies are pursued to capture profits. So our emotional dispositions drive us to consume and accumulate material goods that require free energy throughput and power over others that provide us with services. We also seek to own assets that represent indirect power over human and non-human energy throughput. We do this óconspicuouslyô but in a much more permanent way than the hunter-gatherer because, unlike the latter, we donôt regard the bounty of Nature that we enjoy as temporary.[19] On the contrary, economic growth is widely believed to be limitless because of a belief that the continual application of new knowledge can always provide an unending supply of free energy to do more work and provide new ideas that can be used to produce new kinds of goods and services.[20]

6. Energy and economic growth

As has been noted, the vast bulk of the literature on economic growth concludes that it is the creation and application of new knowledge that is the main driver of growth. The provision of increasing supplies of free energy and its conversion to do ever more sophisticated forms of work is largely neglected. An exception is Robert Ayres who has been at the forefront in connecting the employment of greater quantities of useful energy (exergy) and economic growth in a number of important studies. He has clearly demonstrated that the unexplained óresidualô in

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[19] For further discussion of the theoretical and evidential basis for conspicuous consumption in modern societies see Arrow and Dasgupta (2009).

[20] The intense debate concerning the acceptability of the social discount rate chosen in the Stern Report illustrates both the varying confidence of different economists concerning this capability and, also, different weightings of the interests of future generations as a unit of identification.

standard econometric models of economic growth can be largely accounted for by including measures of exergy growth. So here we have one view that the missing ingredient, once the contributions of physical capital and human capital growth are taken into account, is new knowledge and another that it is growth in exergy use. This difference of opinion is, however, entirely consistent with the view expressed here that economic growth must, necessarily, be the product of a co-evolutionary knowledge-energy process. The conventional ‘production function’ view is that factors of production can be substitutes, so it is possible to substitute capital goods, using non-human free energy, for labour, using human free energy, and vice versa. This is clearly the case with free energy and knowledge but it does not mean that they are necessarily substitutes over the long term.

To be sure, we can be smarter and use less free energy to do a given amount of work or we can increase the amount of work done for a given amount of knowledge by increasing inputs of free energy. But the evidence shows that we do not observe growth persisting when knowledge is static. Neither do we see energy use declining in countries producing a lot of new knowledge. If a country is short of one or the other, then the prediction is that growth will be determined by the one that is in shorter supply.[21] So a country like Nigeria, which has large supplies of oil energy, is constrained in using it by the limited useful new knowledge that is available to it. In contrast, the US is abundant in useful new knowledge but oil energy is in short supply so it is necessary to import large amounts of oil. This, of course, means that the economic growth of the US is sensitive to movements in the price of oil and there is concern to ensure that its sources in the rest of the world are secure.

If we look at the growth equation econometrically estimated by Ayres and Warr (2005), we can view their capital stock variable as physically embodied past knowledge of how to translate energy into specific kinds of work. The labour input variable reflects the skills (process knowledge) that people employ in using capital goods plus the basic unskilled physical work done using food energy. The additional variable that they include is the growth in ‘exergy services’ in the form of non-human physical work and this fully explains the US growth residual up until the mid-1970s oil crisis. This physical work flow was necessary to drive the capital

[21] Kuran (2009) makes a similar point from a different perspective, arguing that the socio-economic development of a civilization depends on a complementary relationship between cultural and material traits. He argues that the nature of this relationship and the extent to which it gets locked in determines the fate of a civilization.

goods that were the product of the application of new knowledge. However, they found that, following the 1970s crisis, their unexplained residual grew to about 12% of growth.[22] This was attributed to the implementation of a range of new energy saving technologies due to the expectation that the high oil price would be persistent. Consistent with this, the residual stops rising when the oil price reaches its floor in 1986 after which there is a reversal down to about 9% by 1996 (the sample period ends in 2000). Thus, although a large part of the growth residual is explained by the growth in the use of free energy for work, there remains sensitivity to changes in the price of energy when its level is expected to be sustained (Newell, Jaffe and Stavins (1998)).

It has been true in past history that, when energy becomes expensive and/or the related entropic waste problem becomes costly, new knowledge is employed to economise on the use of energy and to shift to other energy sources. After oil prices rose in the early 1970s, the U.S. economy responded by becoming increasingly more energy efficient. Between 1973 and 1986, US oil consumption actually fell by 11%. However, in the 1987-2008 period, it resumed steady growth at about 3% per year. So, although there has been a steady reduction in the amount of oil required to produce a unit of GDP, the total amount of free energy used has continued to rise.

Two conclusions can be drawn from this evidence. First, there is, indeed, support for the hypothesis that new knowledge and energy use co-evolve. Energy saving has allowed free energy to be transferred to additional applications using more new knowledge. When labour is released by the substitution of machines, this allows more new knowledge to be produced which, in turn, yields goods and services that use more free energy. Thus, although the GDP productivity ópayoffô rises, the total consumption of energy continues to grow. The growth of knowledge continually pushes growth in the use of free energy. It is quite striking that, given the choice between investing in technologies that enable us to use free energy more efficiently and investing in new technologies to increase the supply of free energy more cheaply, the latter has been the dominating option. This does suggest that the energy hypothesis has been operative in our behaviour with causation going from a drive to increase the throughput of energy to the search for new knowledge to do so.

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[22] A Cobb-Douglas production function, instead of the LINEX one preferred, fits the post war data up to 2000 without there being a residual. However, it has several unacceptable properties and estimated parameter instability is evident when compared to a sample using pre-war period data.

Second, the price of a particular kind of energy has an important impact upon its consumption ï price signals tell us which sources of free energy are best to exploit. For example, coal consumption which had been declining from a peak in 1920 began to grow sharply after the 1973 oil shock, as did the supply of energy from nuclear power plants. Growth in energy supply from these two sources fully compensated for the 1973-1986 decline in oil consumption. Over the past century, there have been large shifts in the employment of different types of free energy in response to price signals. This has kept the overall consumption of free energy growing steadily with slowdowns only in recessions. If the energy hypothesis is valid, we should observe rapid switches in free energy sourcing when growth in free energy throughput is threatened. We have observed this in the past and, in a rationalist/materialist world, price signals play a crucial role in guiding our behaviour in this regard.

The observed responsiveness of entrepreneurship and innovation to movements in the price of energy is encouraging because it suggests that the introduction of a global carbon price on fossil fuel energy use will lead to significant shifts in energy sourcing and, thus, the carbon emissions problem will be mitigated within a few decades.[23] Setting prices on behalf of the natural environment is a fundamental shift in human behaviour that compensates for our modern loss of personal contact with the natural environment and with future generations. On the face of it, lowering free energy consumption through the application of new knowledge would seem to breach both our co-evolutionary hypothesis and the related energy hypothesis. However, this need not be so for two reasons. First, initiatives such as carbon pricing represent a reconnection with a unit of identification that includes the natural environment and, inasmuch as this results in a recovery of free energy throughput in the latter, then the free energy throughput that we actually relate to need not diminish.

Second, Dyke (1990) pointed out that dissipative structures that use free energy to extract and modify the physical world incur an ñentropy debt,ò incurred because irreversible complex structures require increasing free energy to maintain their integrity and emit increasing amounts of entropic waste that has to be paid in the future. So, booming gold mining towns turn into ghost towns with seriously polluted and damaged environments.[24] What generally happens

[23] See Potts, Foster and Straton (2009) for further discussion of the role of entrepreneurship in protecting the natural environment.

[24] This includes the entropic problem of waste disposal. This has been written about extensively by ecological economists for a number of years. See OôConnor (1994) for a formal treatment in thermodynamic terms.

is that, when these debts have to be paid through heavy investments in repair, maintenance and cleaning up, the structure in question is abandoned and free energy throughput is shifted to a new project. But, of course, in restricted areas, such as an island, this may become impossible, as was the case on Easter Island. Diamond (2005) and Tainter (1988) provide a number of other examples of past human groups that have not survived because the specific configurations of their cultural and political systems and an associated lack of identification with the natural environment and the interests of future generations led to irreversible environmental degradation and abandonment.

Of course, it is both economically and energetically rational to abandon obsolete structures. The trouble is that, in a closed system, abandonment may not be an option so the only energetically rational option is to wind back structure and reduce energy throughput. This is very difficult because of the inherent irreversibility in dissipative structures and what this implies is that energy throughput in a *gross* sense may not be energetically rational because, in the end, it may result in declines in throughput in a *net* sense in the future once the terminating implications of the entropy process are taken into account. The only way that this can be avoided is through adaptive behaviour that slows entropic degeneration in the short term so that free energy throughput can be sustained in the long term. The global environmental problem we now face is analogous to that faced by islands in the past. This is accepted by many ecological economists. Notably, Arrow et al (1995) explained how this problem arises as economic growth proceeds and made a plea, largely ignored, for an explicit global environmental sustainability dimension to economic policy and the regulation of industries and markets. This would, in effect, involve a strengthening of our identification with future generations. Net energy throughput could be maintained in the future so such action would be consistent with the energy hypothesis.

7. Concluding remarks

The relevance of Schneider and Kayôs (1994) óenergy hypothesisô in the context of economic behaviour has been considered and it is clear that people do not directly seek to maximise free energy throughputs but there is a case to be made that they do so indirectly and unwittingly. It has been argued that there is a co-evolutionary relationship between energy and knowledge and, if the energy hypothesis is valid, the direction of causation is from the former to the latter. However, it is a complex dynamic relationship and much more research needs to be done to understand it better before any firm conclusions can be drawn.

People clearly do try to take advantage of free energy gradients to do work and it has been argued that this is often driven by an aesthetic sense of novelty, a desire for power or social approval. Aesthetics have been viewed as the connecting bridge between energy throughput and the application of knowledge. Our rationality is, necessarily, subjective in such a process. Given that there is a degree of uncertainty in all decision-making contexts, objective rationality is not what we should observe and this is confirmed by economic experiments (see, for example, Smith (2008) and Gintis (2009)). Only in highly specific risk settings is objective, probabilistic rationality relevant and, even then, researchers such as Smith (2009) have found that the rationality displayed tends to reflect a collective identification with a power group. Correspondingly, many of our choices are based upon assumptions that are a product of our beliefs and emotions, not objective facts. This is no more vividly demonstrated than in the case of entrepreneurs. Few are unaware of the high risk of failure, but this is offset by the satisfaction that comes from purposeful activity using free energy. Ultimate success is not the only source of satisfaction. And the benefit yielded by so many people accepting unquantifiable risks is the many varied entrepreneurial experiments from which the best outcomes are selected.

Directed action, the use of free energy, has been viewed as the primary source of human satisfaction. So an impoverished painter, despite her poverty, is satisfied with her work provided that she perceives it as moving her towards an aesthetically constructed aspirational goal that has been personally set but influenced by her identification with a group composed of other artists, critics and purchasers. Viewing our economic behaviour in this way begins to clear up some conundrums. Why do billionaires want another billion dollars of wealth when he or she already could consume everything imaginable? Wealth provides power to control the activities of others and power over non-human assets, which means control of their free energy throughput. Why do some of us prefer to have no children and accumulate material wealth instead? If we do not identify much with future generations and receive a feeling of considerable power and status from our material wealth, such a choice is logical from the standpoint of the energy hypothesis. Why do we continually want to accumulate more and more consumer durables and objects of art in our homes? Apart from their utilitarian value, a possible answer is that we are, unwittingly, trying to increase the throughput of free energy under our control or to demonstrate to others that we have a significant flow of free energy under our control. And it is clear why we arenôt always happy doing this: as we increase the number and complexity of the economic structures that we own, we have to pay more entropy debts, i.e., we have to do more servicing, maintenance, monitoring and management which makes us time poor and stressed. This curtails our future free energy throughput potential and the associated negative aesthetic experiences lead us, in the end, to abandon ship.

Sahlins (1998) argued that hunter-gather societies were much happier than we generally think they were, looking at them through our materialist lenses. But, despite this, they were not sustainable societies in the end. This provides indirect support for the hypothesis that energy throughput is a more important driver than óhappiness,ô in contradiction to conventional utilitarian ópleasure and painô economics. However, a key question is: why did it take hunter-gatherers so long to modify their behaviour to raise energy throughput if the energy hypothesis is valid? Socio-cultural institutions and, therefore, shared knowledge, are difficult to shift and this is likely to have been even more so the closer human societies were to genetically driven, biological priorities. The inherent irreversibility in all dissipative structures has a key role to play. In the modern capitalist systems that have emerged and consolidated over the past three centuries, it has gradually become easier to expand both effective knowledge and free energy availability because institutions have arisen, in line with the emergent rationalist/materialist culture, that have facilitated this process. The kind of nonlinear growth that has been experienced is commonly observed in biology to also be present when a species discovers a significant energy niche to exploit. In the human case, a niche opened up when fire was controlled but this only had explosive growth potential when fossil fuels were employed on an increasingly large scale from the 18th century on.

Approaching economic behaviour from the energetic end of the economic growth process does not require we understand the detailed nuances of the knowledge acquiring and applying processes. Indeed, because aesthetics are so central to such processes, it is impossible to quantify them anyway. By analogy, we donôt need to know the details of romantic liaisons and sexual practices to understand that, generally, the sex drive will lead to reproduction of the population. But what we do need to know if we are to understand if population growth will be high or low are the (collectively upheld) institutional rules, relating to marriage, time of marriage, attitudes to contraception, etc, are. It is the same with free energy throughput, we need to know what the cultural, institutional, organisational and technological rules are and how these have changed over time. This involves in depth historical investigations (see Mokyr (1990), Foster and Potts (2009)). Although, there are stories to tell about how particular individuals pioneered emergence of new technological (e.g., James Watt), organisational (e.g., Henry Ford) and institutional (e.g. Maynard Keynes) rules, such prominent individuals are no more than symbols of a spreading acceptance of sets of emergent rules that became relevant in particular historical episodes. Story-telling involving heroes has always been important in the transmission of ideas but the real heroes are those inventors, innovators and entrepreneurs who tried, but failed.

The connection between energy throughput and aesthetic perceptions means that poets, writers, musicians and artists ï everyone who stimulates our aesthetic imagery ï can all play a key, but often invisible, role in stimulating our emotions ways that leads us to increase the use of free energy in seeking to attain aesthetic goals. Science needs science fiction and marketers need artistic depictions that are associated with products. Aesthetic appreciation is fundamental to economic goal formation. So writers write books because of the imagined power that they have over those who read them (or just gaining órespectô) as well as the power that is conveyed by wealth, in the unlikely event that the book is a best seller.

As Joseph Schumpeter understood, the entrepreneur and the artist operate in similar spaces but with different aesthetic goals. It is they, as much as scientists and engineers, that are responsible for the economic growth that has occurred in human history and it is likely that it will be they that will eventually persuade us to stop being narrowly defined rational/materialist seekers of gross energy throughput and create the necessary myths that will promote sustainable free energy throughput in the future. If the energy hypothesis is, indeed, relevant to our behaviour, in the co-evolutionary sense discussed here, and we canôt just abandon entropy debt ridden structures and migrate to another planet, there is a good chance that measures to use free energy in a way that promotes environmental sustainability will be enacted on a global scale. As Kaberger and Mansson (2001) point out, humans are quite capable of enacting such change and Gowdy (2006) provides a micro-scale island example in the South Pacific. However, there is also evidence that some great civilisations in the past have failed in this regard. Because the irreversibility inherent in dissipative structures is always strong and multi-faceted, adaptive change is not guaranteed ï in evolutionary processes, nothing is certain.

References

Abel, J. T. and Trevors, D.L., 2006. Self-organization vs. self-ordering events in life-origin models. Physics of Life Reviews, 3, 211ï 228.

Ariely, D., 2008. Predictably Irrational. New York: HarperCollins.

Allen, P.M., 1998. Evolving complexity in Social Science. In: Altman, G. and Koch, W.A. (Eds.). Systems ï New Paradigms for the Human Sciences. Berlin: De Gruyter.

Arnold, J.E., 1996. The Archaeology of Complex Hunter-Gatherers. Journal of Archaeological Method and Theory, 3, No. 1, 77-126

Arrow, K, Bolin, B., Costanza, R., Dasgupta, P., Folke, C., Holling, C.S., Jansson, B-O., Levin, S., Mäler, K-G., Perrings, C., Pimentel, D., 1995. Economic Growth, Carrying Capacity, and the Environment. Science, New Series, 268, No. 5210, 520-5.

Arrow, K.J and Dasgupta, P.S., 2009. Conspicuous consumption, inconspicuous leisure. Economic Journal, 119 Issue 541, F497 - F516.

Ayres, R.U., 1998. Eco-thermodynamics: economics and the second law. Ecological Economics, 26, 189ï 209.

Ayres, R.U., 2008. Sustainability economics: Where do we stand? Ecological Economics, 67, 218-310.

Ayres, R.U and Nair, I., 1984. Thermodynamics and economics. Physics Today, 37, 62-71.

Ayres, R.U. and Warr, B., 2005. Accounting for growth: the role of physical work. Structural Change and Economic Dynamics, 16, 181ï 209.

Baker, M.J., 2008. A structural model of the transition to agriculture. Journal of Economic Growth, 13, 257ï 292.

Beard, R. and Lozada, G.A. , 1999. Economics, Entropy and the Environment. Dodrecht: Springer.

Berndt, Ernest, 1978. Aggregate energy, efficiency, and productivity measurement. Annual Review of Energy, 9, 409-26.

Binswanger, M, 1993. From Microscopic to Macroscopic Theories: Entropic Aspects of Ecological and Economic Processes. Ecological Economics, 8, no.3, 209-34.

Boulding, K. E., 1978. Ecodynamics: A New Theory of Societal Evolution. Beverley Hills : Sage Publications.

Boulding, K. E., 1981. Evolutionary Economics. Beverley Hills: Sage Publications.

Boyd, R and Richerson, P.J., 2005. The Origin and Evolution of Cultures. Oxford: Oxford University Press.

Boettke, P. J., 1997. Where did economics go wrong? Modern economics as a flight from reality. Critical Review, 11, 11ï 64.

Brooks, D. and Wiley, E., 1986. Evolution as Entropy: Toward a Unified Theory of Biology, Chicago: University of Chicago Press.

Bryant, J., 1982. A thermodynamic approach to economics. Energy Economics, 4, 36-49.

Buenstorf, G., 2000. Self-organization and sustainability: energetics of evolution and implications for ecological economics. Ecological Economics, 33, 119ï 134.

Buenstorf, G., 2004. The Economics of Energy and the Production Process: An Evolutionary Approach**,** Cheltenham: Edward Elgar.

Burley, P. and Foster, J., 1994. Economics and Thermodynamics, Boston: Kluwer.

Chen, J. and Vinig, T.G., 2007, Entrepreneurship: An analytical thermodynamic theory. SSRN Working Paper Series (January). Available at http://ssrn.com/abstract=979858

Christensen, W. and Hooker, C., 1997. Selection Theory, Organization and the Development of Knowledge, Evolution and Cognition, 3, 44-48.

Corning, P. A., 2002. Thermoeconomics: Beyond the Second Law. Journal of Bioeconomics, 4, 57-88.

Corning, P. A. and Kline, S.J., 1998. Thermodynamics, information and life revisited, part I. Systems Research and Behavioral Science. 15, 453-482.

Costanza, R., 1980. Embodied energy and economic valuation. Science, 210, 1219-1224.

Daly, H. E., 1996. Beyond Growth: The Economics of Sustainable Development, Boston: Beacon Press.

Dawkins, R., 2009. The Greatest Show on Earth: The Evidence for Evolution. London: Bantam Books.

De Fraja, G., 2009. The origin of utility: Sexual selection and conspicuous consumption.ò Journal of Economic Behavior & Organization, 72, 51ï 69.

Diamond, J., 2005. Collapse: How Societies Choose to Fail or Succeed. New York: Viking Books.

Dopfer, K., 2005. The Evolutionary Foundations of Economics. Cambridge: Cambridge University Press.

Dutton, D., 2009. The Art Instinct. Oxford: Oxford University Press.

Dyke, C., 1990. Cities as dissipative structures, In: Weber, B., Depew, D.J. and Smith, J.D. Entropy, Information, and Evolution: New Perspectives on Physical and Biological Evolution, Cambridge, Mass. : MIT Press.

Faber, M. and Proops, J.L.R., 1990. Evolution, Time, Production and the Environment, Berlin: Springer-Verlag.
.
Fromm, E., 1978, To Have or to Be? London: Cape.

Fisk, D.J. and Kerhervé, J., 2006. Complexity as a caiuse of unsustainability. Ecological Complexity, 3, 336-343.

Foster, J., 1987. Evolutionary Macroeconomics. London: Unwin Hyman.

Foster, J., 2000. Competitive Selection, Self-Organization and Joseph A. Schumpeter. Journal of Evolutionary Economics, 10, 311-328.

Foster J., 2005. From simplistic to complex adaptive systems in economics. Cambridge Journal of Economics, 29, 873-892.

Foster, J. and Potts, J., 2009. A micro-meso-macro perspective on the methodology of evolutionary economics: integrating history, simulation and econometrics. In: Gaffard, J-L, Nesta, L. and Cantner U., Schumpeterian Perspectives on Innovation, Competition and Growth, Berlin: Springer/Physica, 53-70.

Galor, O., & Moav, O., 2002. Natural selection and the origin of economic growth. Quarterly Journal of

Economics, 117, 1133ï 1191.

Georgescu-Roegen, N., 1971. The Entropy Law and the Economic Process, Boston: Harvard University Press.

Georgescu-Roegen, N., 1976. Energy and Economic Myths: Institutional and Analytical Economic Essays. New York: Pergamon Press.

Georgescu-Roegen, N., 1977a. Bioeconomics: A new look at the nature of economic activity. In: L. Junker (Ed.) The Political Economy of Food and Energy, Ann Arbor: The University of Michigan Press, 105-134.

Georgescu-Roegen, N., 1977b. The steady state and ecological salvation: a thermodynamic analysis. Bioscience, 27, 266-270.

Georgescu-Roegen, N., 1977c. Inequality, limits and growth from a bioeconomic viewpoint. Review of Social Economy, 35, 361-375.

Georgescu-Roegen, N., 1979. Energy analysis and economic valuation. Southern Economic Journal, 45, 1023-1058.

Giampietro, M., Bukkens, S.G.F. and Pimentel, D., 1993. Labor productivity: a biophysical definition and assessment. Human Ecology, 21, 229-259.

Gillett, S. L., 2005. Entropy and its misuse, I. Energy, free and otherwise. Ecological Economics, 56, 58ï 70.

Gilliland, M.W., 1975. Energy analysis and public policy. Science, 189, 1051-1056.

Gintis, H., 2009. The Bounds of Reason: Game Theory and the Unification of the Behavioural Sciences. New Jersey: Princeton University Press.

Gowdy, J.M., 2006. Darwinian selection and cultural incentives for resource use: Tikopia as a case study of sustainability. International. Journal of Global Environmental Issues, 6, 348-61.

Hannon, B. M., 1973. An energy standard of value. Annals of the American Academy of Political Science, 410, 139-153.

Hanusch, H. and Pyka, A., 2007. Elgar Companion to Neo-Schumpeterian Economics, Cheltenham: Edward Elgar Publishing.

Hartmann, T., 2000. The Last Hours of Ancient Sunlight: Waking Up to Personal and Global Transformation. New York: Three Rivers Press.

Hill, K., Barton, A. and Hurtado, M., 2009. The emergence of human uniqueness: Characters underlying behavioral modernity. Evolutionary Anthropology: Issues, News, and Reviews, 18, Issue 5, 187-200

Horan, R.D., Bulte, E.H. and Shogren, J.F., 2008. Co-evolution of human speech and trade. Journal of Economic Growth, 13, 293ï 313.

Huettner, D.A., 1976. Net energy analysis: an economic assessment. Science, 192, 101-4.

Kaberger, T. and Mansson, B., 2001. Entropy and economic processes ð physics perspectives. Ecological Economics, 36, 165ï 179.

Kauffman S., 1993. Origins of Order: Self-Organization and Selection in Evolution, Oxford: Oxford University Press.

Keynes, J.M., 1936. The General Theory of Employment, Interest and Money. London: Macmillan.

Kiala, Ville R. I. and Annila, A.. 2008. Natural selection for least action. Proceedings of The Royal Society, A. doi:10.1098/rspa.2008.0178.

Kuran, T., 2009. Explaining the economic trajectories of civilizations: the systemic approach. Journal of Economic Behavior & Organization, 71, 593ï 605.

*Lehrer, J., 2009. How We Decide. New York: Houghton Mifflin Harcourt.

Li, J. and Ayres, R.U., 2008. Economic Growth and Development: Towards a Catch-up Model. Environmental and Resource Economics , 40, 1ï 36.

Lineweaver, C.A. and Egan, C.H., 2008. Life, gravity and the second law of thermodynamics. Physics of Life Reviews, 5, 225ï 242.

Lipsey, R., 2009. Economic growth related to mutually interdependent institutions and technology. Journal of Institutional Economics, 5, No. 3, 259-288.

Loasby, B.J., 2002. Knowledge, Institutions and Evolution in Economics. London: Routledge.

Loasby, B. J., 2007. A cognitive perspective on entrepreneurship and the firm. Journal of Management Studies, 44, No. 7, 1078-1106.

Loasby, B., 2009. Motivation, innovation and coordination. In: Cantner, U., Gaffard, J-L and Nesta, L. (Eds.) Schumpeterian Perspectives on Innovation, Competition and Growth. Dordrecht: Springer.

Lotka, A., 1922. Contribution to the energetics of evolution and Natural selection as a physical principle. Proceedings of the National Academy of Science, 8(6), 147-154.

Lozada, G. A., 1999. The role of entropy and energy in natural resource economics. In: Gowdy, J.M., Mayumi, Kozo (Eds.), Bioeconomics and Sustainability: Essays in Honor of Nicholas Georgescu-Roegen. Cheltenham: Edward Elgar, 251ï 326.

Lozada, G.A., 2006. Entropy, free energy, work, and other thermodynamic variables in economics. Ecological Economics, 56, 71ï 78.

McKelvey, B., 2004, Toward a 0^{th} law of thermodynamics: order-creation complexity dynamics from physics and biology to bioeconomics. Journal of Bioeconomics, 6, 65-96.

Metcalfe, J.S., 1998. Evolutionary Economics and Creative Destruction. London: Routledge.

Metcalfe, J. S., 2009. Technology and economic theory. Cambridge Journal of Economics, 33, No. 7 (in press).

Mokyr, J., 1990, The Lever of Riches: Technological Creativity and Economic Progress. New York: Oxford University Press.

Mokyr, J., 2002. The Gifts of Athena: Historical Origins of the Knowledge Economy, Princeton: Princeton University Press.

Nelson, R.R. and Winter, S.G., 1982. An Evolutionary Theory of Economic Change, Cambridge, Mass., Belknap Press.

Newell, R.G., Jaffe, A.B. and Stavins, R.N., 1998. The Induced Innovation Hypothesis and Energy-Saving Technological Change. NBER Working Paper No. 6437, March.

Odum, H. T., 1988. Self-organization, transformity and information. Science, 242, 1132-1139.

OôConnor, M., 1994. Entropy, liberty and catastrophe: the physics and metaphysics of waste disposal. In: Burley, P and Foster, J. (Eds.), Economics and Thermodynamics: New Perspectives on Economic Analysis, Boston: Kluwer.

Parsons, T. R., and Harrison, B., 1981. Energy utilization and evaluation. Journal of Social and Biological Structures, 4, 1-15.

Popper, K. R., 1990. A World of Propensities. Bristol: Thoemmes Antiquarian Book

Potts, J., Foster, J. and Straton, A., 2009. An entrepreneurial model of economic and environmental co-evolution. Mimeo available from j.potts@uq.edu.au.

Prigogine, I., 1978. Time, structure and fluctuations. Science, 777-84.

Prigogine, I and Stengers, I., 1997. The End of Certainty: Time, Chaos and the New Laws of Nature, New York: Free Press.

Proops, J. L. R., 1983. Organization and dissipation in economic systems. Journal of Social and Biological Structures, 6, 353-366.

Proops, J. L. R., 1985. Thermodynamics and economics: from analogy to physical functioning. In: W. van Gool & J. J. C. Bruggink (Eds.) Energy and Time in Economic and Physical Sciences. New York: Elsevier Science Publishers, 155-175.

Proops, J. L. R., 1987. Entropy, information and confusion in the social sciences. The Journal of Interdisciplinary Economics, 1, 225-242.

Raine, A., Foster, J and Potts, J., 2006. The new entropy law and the economic process, Ecological Complexity, 3, 354-360.

Roberts, P. C., 1982. Energy and value. Energy Policy, 10, 171-80.

Salins, M., 1998. The original affluent society. In: J. Gowdy (Ed.) Limited Wants, Unlimited Means. Washington, DC: Island Press.

Shackle, G.L.S., 1966. The Years of High Theory: Invention and Tradition in Economic Thought. Cambridge: Cambridge University Press.

Shackle, G.L.S., 1972. Epistemics and Economics. Cambridge: Cambridge University Press.

Schneider, E and Kay, J., 1994. Life as a manifestation of the Second Law of Thermodynamics,. Mathematical and Computer Modelling, 19, 25-48.

Schneider E. and Sagan, D., 2005. Into The Cool: Energy Flow, Thermodynamics and Life. Chicago: Chicago University Press.

Slesser, M., 1975. Accounting for energy. Nature, 254, 170-72.

Smith, V., 2008. Rationality in Economics: Constructivist and Ecological Forms. Cambridge: Cambridge University Press.

Soddy, F., 1912. Matter and Energy. London: Butterworth.

Steedman, I., 2004). On ómeasuringô knowledge in new (endogenous) growth theory. In: N. Salvatori (Ed.) Old and New Growth Theories, Cheltenham: Edward Elgar.

Tainter, J.A., 1988. The Collapse of Complex Societies. Cambridge: Cambridge University Press.

Van den Bergh, J. C. J. M. and Gowdy, J.M., 2000. Evolutionary Theories in Environmental and Resource Economics: Approaches and Applications, Environmental and Resource Economics, 17, 37-57.

Van den Bergh, J.C.J.M. and Gowdy, J.M., 2009. A group selection perspective on economic behavior, institutions and organizations. Journal of Economic Behavior & Organization, 72 , 1ï 20.

Veblen, T., 1898. Why is Economics Not an Evolutionary Science? The Quarterly Journal of Economics, 12, 373-97.

Veblen, T., 1899a. The Barbarian Status of Women. American Journal of Sociology, 4, 503-34.

Veblen, T., 1899b. The Theory of the Leisure Class. New York: Macmillan.

Veblen, T., 1909. The Limitations of Marginal Utility. Journal of Political Economy, 17, 235-45.

Veblen, T., 1914. The Instincts of Worksmanship and the State of the Industrial Arts, New York: Augustus M Kelley.

Warr, B., Schandl, H. and Ayres, R.U., 2008. Long term trends in resource exergy consumption and useful work supplies in the UK, 1900 to 2000. Ecological Economics, 68, 126-140.

Weisdorf, J.L., 2005. From foraging to farming: explaining the neolithic revolution. Journal of Economic Surveys., 19, No.4, 561-86.

Wicken, J.S., 1987. Evolution, Thermodynamics, and Information: Extending the Darwinian Program. Oxford: Oxford University Press

Winiarski, L., 1899. Lôéquilibre Esthétiqueò (Aesthetic Equilibrium). Review of Philosophy, xivii, 569-605.

Witt, U., 1991. Economics, sociobiology, and behavioural psychology on preferences. Journal of Economic Psychology, 12, 557-573.

Witt, U., 2005. Production' in nature and production in the economy--second thoughts about some basic economic concepts. Structural Change and Economic Dynamics, 16, 165-179.
.
Witt, U., 2007. Novelty and the bounds of unknowledge in economics. Papers on Economics and Evolution, No. 07, Max Planck Institute of Economics, Evolutionary Economics Group.

Woodburn, J., 1998. Egalitarian societies. In: J. Gowdy (Ed.) Limited Wants, Unlimited Means. Washington, DC: Island Press.