INSEAD The Business School for the World®

Working Paper

2022/08/EPS/TOM

The Economy as an "Island of Order" far from Equilibrium

Robert U. Ayres
Emeritus Professor of Economics, Political Science, and Technology Management and
The Novartis Chair in Management and the Environment
INSEAD, robert.ayres@insead.edu

This article makes three important arguments that need to be integrated into mainstream economic theory. The first argument is that energy is the substance of the universe, and everything in the universe is energy. Energy (exergy in modern terminology) is neither produced nor destroyed by human activity (the first law of thermodynamics) but it is transformed by activity, becoming less and less useful (the second or entropy law). The second argument arises from Schrodinger's observation (1944) that life is order is created from disorder, far from thermodynamic equilibrium. Prigogine has shown that cyclic physical and bio chemical systems, at all scales, can self-organize, inter-connect and can evolve by the dissipation of an exergy flux. This paper argues that the phenomenon of self-organization of cyclic structures applies also to human social and economic systems.The final argument of this paper concerns economic activity itself via markets, as places where surpluses and deficits of goods are balanced non-violently by exchange transactions and trade. Conventional economic theory still assumes that exchanges take place exclusively between individuals, in virtually perfect markets, and that the benefits and costs apply only to them. This ignores the fact that many – probably most – transactions involve benefits or costs to "third parties". Economists call them "externalities". One externality is the interconnected social system of families, communities, tribes, corporations and nations (the "social contract"). Another externality is the environment, which is the source of the exergy we utilize as a flux and also of useful mineral resources created by exergy fluxes in the past. None of these social structures are truly closed as they require and dissipate an energy flux from the sun to continue to exist and evolve. Through the input and dissipations of this energy flux living systems obey the laws of thermodynamics. Economic systems are examples of such living systems or "islands of order" .It is true that ecological economics has recognized that the economy is not closed, even though most models assume closure for convenience. However mainstream neoclassical economic theory mistakenly assumes that growth is driven by some combination of capital and labor and that "energy" (e.g. food or fuel) is an intermediate product. In reality, the driver of every activity on Earth (and beyond) is exergy flux originating from nuclear fusion taking place continuously in our sun. Economic theory still neglects the consequences of third party effects (externalities), such as pandemics (e.g. covid 19) and climate change that is reducing biodiversity and – in the extreme case -- could even make this planet uninhabitable by our species. Furthermore, standard economic theory still assumes that production and consumption occur according to an "optimal" equilibrium, in a closed system, where everything produced in the system is consumed in the system. This mathematical simplification dates to Walras. It has been central to the theory of economic growth ever since. But growth in equilibrium is thermodynamically impossible and neoclassical economic growth theory in particular has failed to adjust to this reality. This recognition also implies that prices at the Walrasian equilibrium are biased, as they do not take into account the contributions that the planet and the earth make (for free) to the economy, nor does such equilibrium consider the cost of externalities generated by energy dissipation at the output stage. In this paper we propose a conceptual way to integrate thermodynamic laws with neoclassical economics, thus aiming to contribute to an economic theory that recognizes the open nature of the economy and the thermodynamic implications of this openness. This is necessary for economic theory to contribute more meaningfully to the current climate crisis.

For this paper I wish to acknowledge especially the substantial editorial contributions by Jeroen van den Bergh and Ludo Van der Heyden, as well as many useful comments from Paul Brockway, Tiago Domingos, Paulo Frankl, Skip Laitner, Katalin Martinas, Philippe Pichat, Luk van Wassenhove, Geneviève Verbrugge, Gara Villalba-Mendez, Silvestre Voisin, and Benjamin Warr. I also would be remiss if I did not thank Anna McCavitt and Wikipedia for most valuable support.

1. Introduction

From before the time of Adam Smith and David Ricardo, and long afterward, economics has been primarily about trade. Money was not wealth, it was just a mechanism for enabling the exchange of material goods. The role of money grew considerably in the 18th century as credit and debt became more important. *(Ps money was important already in the Roman Empire)* With the creation of trusts in the Age of Morgan, the role of money took a big turn. It changed again in the 1980s. On Wall Street - or Silicon Valley on the speculative side - "making money" is seen as a financial game in which, it seems, nothing material needs to be produced to create and accumulate wealth.

That view is of course too partial and too simplistic. The flows of material goods result in waste residuals that have not "dematerialized" at all. They also show no signs of doing so. The oceans are increasingly full of plastics. Climate change is a consequence mainly of carbon dioxide accumulation in the atmosphere, due to the combustion of fossil fuels, and to methane emissions by animals producing food for human consumption. We are polluting the fresh water of the planet with our industrial wastes, and cutting the tropical forests to clear land to produce yet more red meat for high cholesterol fast foods. So, the production of wastes by humans is not decreasing.

Worse, some well-known economists using sophisticated models argue that global warming of a couple of degrees can be accommodated by the economy, modulo some acceptable cost. It is quite likely that these scholars underestimate the thermodynamic consequences of such warming, due to insufficiently accurate real implications of economic models that consider the economy as a closed system and rely unrealistically on equilibrium conditions.

We are now finally realizing that decarbonization is essential. Nuclear energy looked like a good alternative several decades ago, but the problem of disposing of radioactive waste has proved daunting. Now we hope to exploit wind power, hydroelectric power or photovoltaic power to electrify and energize the planet. All of that energy came from the sun in times past, or comes from it, mostly via machines. But sunshine cannot be produced by human activity, albeit controlled fusion is a future possibility. It is only borrowed and then transformed. Energy is a fundamental "factor of production", but it is more than that: it is the only substance that is fundamentally needed (in various material forms) to drive transformation of inputs into outputs.

Philosophers and scientists from Francis Bacon, Rene Descartes, Galileo, Newton, and Leibnitz developed the scientific method of rational empiricism. Like the established Church, of that time, they were dualists. They believed in the simultaneous but independent existence of mind (or spirit) and matter. But Baruch Spinoza and Thomas Hobbes introduced the fundamental concept of *monism* -- in opposition to the matter/spirit of Descartes (and all established religious authorities to this day). Monism is the fundamental idea that there is only one essential physical substance in the universe, from which everything else is composed. It didn't have a name in the 17th century, but now it does: "energy". Today most scientists are monists, without necessarily knowing the meaning of the word.

The purpose of this paper is three-fold. Our first aim is to posit that the fundamental substance of the universe is energy, and that energy is required (consumed) for any material transformation, or information transmission, in it. Albert Einstein's 1905 formula, $E = mc^2$, attests that mass (m) and energy (E) are actually equivalent and inter-convertible. The second purpose of this paper is to argue one of the consequences of this first statement, as far as the economy is concerned, is to see the economy as an open system, fuelled by energy inputs, and emanating energy as an output in the form of degraded energy if not waste. This provides the opening to put economic theory on solid thermodynamic foundations. The third purpose of this paper is to see the economy as a living, dynamic system, in constant evolution seeking order at the expense of greater complexity and interconnexions. This leads us to describe it as an island of order – a living system – that exists far from both thermodynamic and economic equilibrium.

2. Foundation: Definition and Sources of Energy

The source of virtually all useful energy currently available to humans in the 21st century is (and will be) nuclear fusion in the center of our sun. That process drives all photosynthesis and all hydrological processes, including wind and ocean currents. A relatively tiny amount will come from nuclear fission or geothermal heat. You may ask: what has this to do with economics? We are trying to make the point – one that is too easily glossed over -- that energy is not just one among several – or many – intermediate resource inputs to materials transformation processes. It is the only fundamental resource input.

Allow me to start – figuratively – at the beginning of the universe, at the so-called "Big Bang" or BB, 16.87 billion years ago. Skipping over supposed -- but never seen -- sub-nuclear objects like "quarks", and "neutrinos" let me suppose that, just after that event there were only three kinds of elementary particles, all in a superheated plasma state. They were *electrons* (with a negative charge), *protons* (with a positive charge) and *neutrons* (with no charge). Apparently the negative and positive charges balance exactly because the universe as a whole is also electrically neutral.

The "couple" of one proton and one electron (no charge) is called a *Hydrogen atom*. When the plasma had cooled sufficiently – 370,000 years after the BB -- hydrogen atoms were formed as the electrons and protons combined. One could say that they were "married". The marriage yielded hydrogen atoms and photons (electromagnetic radiation), which are both forms of energy. We observe that radiation -- extremely "red-shifted" into the microwave range -- as background radiation at a temperature of 2.7 degrees K. This microwave radiation, coming from all directions, was discovered by Penzias and Wilson at Bell Telephone Laboratories in 1964). This seemed to confirm George Gamow's theory that the universe had an actual beginning, rather than the previous theory of continuous creation. Today it is regarded as clear evidence that the Big Bang (BB) actually occurred 13.787 billion years ago. (There are doubters. I am one of them).

When the positively charged nucleus of a hydrogen atom (a proton) encounters a free neutron, the proton and the neutron are attracted to each other, by short-range nuclear forces. They can decide to live together as a *heavy hydrogen* (deuterium) nucleus, consisting of 1 proton, 1 neutron, emitting an anti-electron plus an electron neutrino and 2 photons. (The anti-electron annihilates a passing electron, producing another high energy photon.) This marriage is called "fusion". With an electron to balance the positive charge, it yields an atom of "heavy hydrogen". The mass of the heayy hydrogen nucleus is less than the masses of the two "light" hydrogen nuclei from which it was made. The lost mass difference was converted into pure photon energy, according to Einstein's formula.

Two heavy hydrogen nuclei can combine with another proton, yielding a *Helium 3* nucleus plus another photon. Two of those Helium 3 nuclei can combine to form a *Helium 4* nucleus and 2 protons (Hydrogen nuclei) and another photon. Altogether it takes 9 fusions to produce a single Helium 4 nucleus, *yielding 15 photons along the way.* Those photons are electromagnetic fields acting like particles, that are pure energy, with no mass. The mass of the universe – consisting of all the shining stars – 370,000 years after the Big Bang (BB), when it became visible, was about 75 percent hydrogen and 25% helium, with no other elements yet in existence.

Helium atoms can also meet and combine spontaneously with Hydrogen, Deuterium, He 3 or He 4, with or without free neutrons to make heavier isotopes, like b*oron* and *beryllium* and *neon*, and more photons. Those heavier atoms can also combine by fusion to make still heavier atoms, like n*itrogen,* and still more photons, and so on. In other words, the mass of the universe keeps decreasing gradually, as the fusion process continues in stars. Each of these fusion reactions releases some energy (the technical term is *exergy*) to the environment in the form of a "photon" of electromagnetic radiation with a unique frequency characteristic of that reaction. This is the meta-process that made all the 26 elements with atomic weights up to and including iron (Fe). It also makes the stars shine and creates solar radiation (we see it as visible light) covering the whole range of frequencies.

Since the BB the mass of Hydrogen and Helium has declined by 2% and the mass of the 24 elements between helium and iron has risen to 2% of the total. The heavier atoms, from cobalt to uranium, were all made in exploding stars called supernovae, before the sun was formed. The total mass of the atoms heavier than Iron is infinitesimal, as a percentage, however important for technology. That 2% of the mass of the universe has combined and recombined and created enormous complexity: scores of simple chemical compounds, tens of thousands -- maybe millions -- of species of organic molecules and many millions of species of living organisms, on Earth, not to mention super-organisms, like corporations or universities, or the economy. Our planet Earth consists almost entirely of atoms from that 2% fraction. All living organisms and almost everything we humans have produced finds its origins in chemical combinations of hydrogen plus those heavier atoms.

From those chemical elements a number of very stable inorganic chemical "building blocks" have been self-created, either in interstellar space, or on Earth. They include H_2O, H_2S, HNO_3, CH_4, CO_2, SO_2, SiO_2, PO_4, NaCL, KCl, $CaCl_2$, simple amines, etc. It is from these (plus hydrogen) that the nuclide bases -- adenine, thymine, cytosine, and guanine -- are constructed. In turn, DNA and proteins are constructed from these nuclide bases.

All transformations on earth thus require energy (exergy) to be "activated". This energy comes directly from the sun, or from the transformation of materials (e.g., fossil fuels, nuclear energy, hydropower …). According to the first law of thermodynamics, materials transform, but do not disappear. Hence, transformations produce energy for useful work (called *exergy*), the rest being degraded energy (which can be used again, like in regeneration), or pure waste (called *anergy).*

The primary sources of useful energy or exergy available to us humans on Earth are photosynthesis (including fossil fuels), the hydrological cycle (wind and flowing water), and nuclear heat from radioactive decay in the Earth's core. All of these are elements of "natural or nature's capital". Fossil fuels are stores of chemical exergy from photosynthesis that occurred in the distant geological past. This reservoir is gradually being exhausted, although there is still enough left, as some witty journalist has noted, "to fry us all". The same is true of the Earth's geological reservoir of radio-nuclides, and its store of useful chemical combinations, such as metallic sulfides. Minerals and ores are valued because they are anomalous concentrations of useful elements. But the elements, themselves, do not disappear, they just transform.

The solar furnace that drives photosynthesis and the hydrological cycle will run out of hydrogen fuel several, billion years in the future (Morris 1980). According to current cosmological theory, this will be followed by the "red giant" phase, as the sun starts burning its accumulated helium "ash" – and swallows up the inner planets - followed by the "white dwarf" stage when the helium is also used up by creating carbon, oxygen and iron. When fusion gradually slows down to a stop, billions of years from now, the sun will become a "black dwarf".

That of course is not our concern. For the present, and the foreseeable future, what matters is that there is plenty of useful energy available for human purposes, and that this will be true for a very long time to come. The question is thus not whether we will run out of energy, the question is one of technological choices and bottlenecks when nature's capital is running out of particular stocks of materials, or when anergy, in the form of poorly managed heat and particle emissions, is radically transforming life on the planet. Technological choices are, of course, where economics currently dominate the debate, in an unbalanced way. For this we need to do a little excursion into thermodynamics, the old and the newer version.

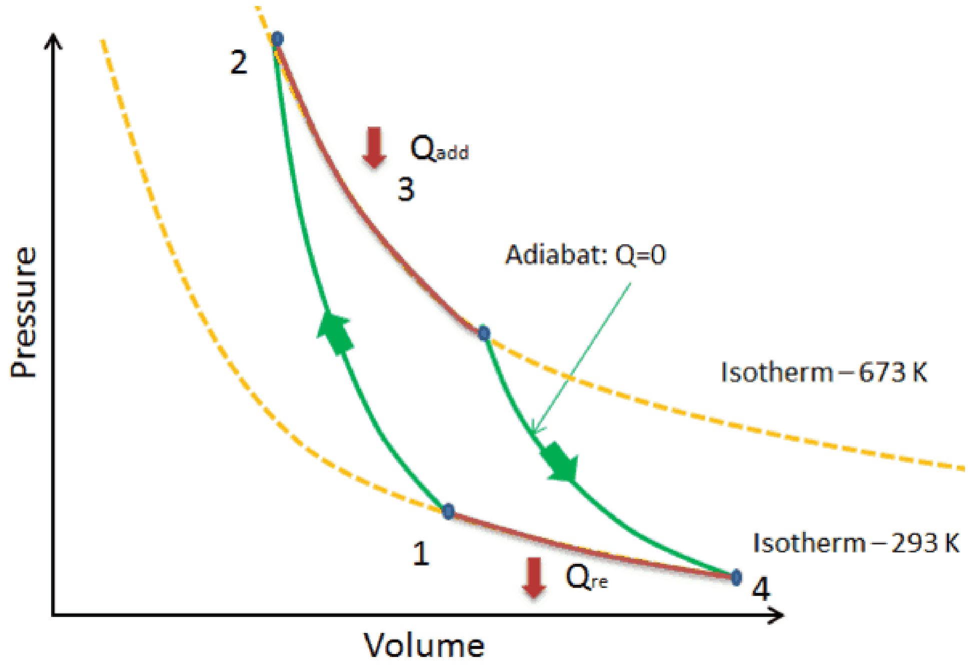
3. Heat engines and thermodynamics

A brief history of thermodynamics is relevant to economics because even physical scientists, let alone economists, didn't fully understand energy or the laws of thermodynamics until quite recently. The importance of the "new" thermodynamics far from equilibrium can't be appreciated without a little history about how these ideas emerged. The key point is that standard thermodynamics, which is what is still taught in physics, chemistry, and chemical engineering, is still focused on "thermal engines" using heat to do mechanical work. At a deeper level it was about approaches to equilibrium, which is the state where nothing can happen because everything that could happen spontaneously has happened. The idea that there was anything interesting happening far from equilibrium did not occur to any of the 19th century pioneers of thermodynamics. And the fact that social systems, and economics in particular, are also governed by the laws of thermodynamics far from equilibrium, did not occur to anybody until the 1970s.

The first "engine" to obtain mechanical work from heat (actually fire) was a piston in a cylinder invented by Denis Papin (c. 1689). An "atmospheric" version (with no moving parts) was patented by Thomas Savery in 1698. A combination of Papin's idea with Savery's ideas was finally put to work pumping water from coal mines by Thomas Newcomen in 1712. James Watt's improvement (the separate condenser) in 1776 made it practical for other purposes, including boring cannons and weaving cloth. During those years Joseph Black, a friend of James Watt, was discovering latent heat and heat capacity, as well as learning how to measure the quantity of heat. The high-pressure steam engine by Richard Trevithick and Oliver Evans (independent contributions) came in the years 1810-1811. From that came the first steamship and railroad trains. A new transportation industry was about to crack its shell.

In 1798 Benjamin Thompson established that heat can not only do work (by means of a steam engine) but that work also produces heat (e.g., by friction, as for instance, by boring cannons, as he was doing). What nobody, at the time, understood quantitatively was that the common factor between work and heat was *energy (*actually *exergy*) consumption and that it was a one-way conversion.

The next question for science became: is there a general law to explain this conversion process? In 1824 Nicolas Sadi-Carnot conceived a repetitive "cycle" (for a gas) of compression, heating (from a hot reservoir), expansion – while doing work -- and cooling (by a cold reservoir). He proved that his idealized cycle maximized the amount of mechanical work obtainable from a given amount of heat (during the expansion phase). He furthermore established that the efficiency in terms of work per unit of heat input depends only on the temperature difference between the hot and cold reservoirs. He pointed out that the cycle is unidirectional (irreversible), viz. heat flows from higher to lower temperatures and not the reverse ("Carnot's principle"). Carnot thus lay the foundations for thermodynamics.



An idealized Carnot cycle in pressure-volume space

A few years later, Julius Robert Mayer wrote (1841) that "energy is conserved" which became the *First Law of thermodynamics*. Energy cannot be either created nor destroyed, but only transformed. He also noted (1842) that energy in biological organisms is obtained by metabolic oxidation of carbohydrates – which is called *respiration* -- and (1844) that those carbohydrates are produced by some kind of *photosynthesis.* We now know how those two metabolic processes work at the molecular level. Both are one-way cycles, named for their discoverers (Melvin Calvin and Hans Krebs).

Rudolf Clausius' most famous paper, *Ueber die bewegende Kraft der Wärme* ("*On the Moving Force of Heat and the Laws of Heat which may be Deduced Therefrom*") was published in 1850. It showed that there was a contradiction between Carnot's principle and the concept of conservation of energy. Clausius stated the Second Law of Thermodynamics in order to overcome this contradiction: "*Heat can never pass from a colder to a warmer body without some other change, connected therewith, occurring at the same time*." In other words, all spontaneous processes are unidirectional. His mathematical derivation of the second law and the definition of *entropy* was published in 1865. The discovery of the mechanical equivalent of heat was attributed to James Joule in 1853.

Josiah Willard Gibbs extended the theory of thermodynamics to include chemical energy, and refined the theory in its current near-equilibrium version. Albert Einstein's famous formula, $E = mc^2$ (published in 1905) brought atomic energy into thermodynamics. Einstein's formula is a kind of addendum to the First Law, because it says that mass is also energy: they are equivalent, but the it didn't say that the conversion is irreversible.

4. Integrating the Second Law with Darwin's Evolutionary Paradigm

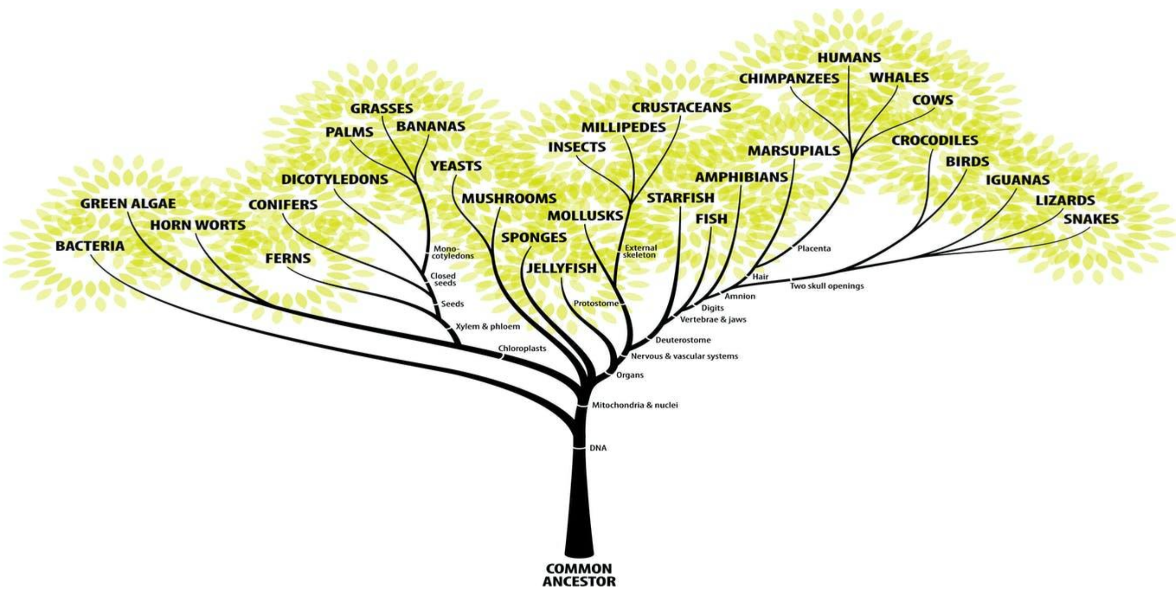
The Second Law, also called the Entropy Law, as interpreted probabilistically by Ludwig Boltzmann, implies that natural systems (actually ideal gases) move always toward increasing disorder, meaning increasing homogenization and disappearance of gradients. It seems inconsistent with the evolutionary paradigm associated with Charles Darwin (Darwin 1859) and Alfred Russell Wallace (Wallace 1902). We here aim for a reconciliation.

Biological evolution generates increasing complexity, specialization and organization of biological systems through time. The natural world consists of coherent structures, ranging from convection cells to autocatalytic chemical reactions, to molecular reproduction, cellular reproduction, species reproduction and ecosystem reproduction. These natural systems exist far from equilibrium, and yet they dissipate free energy to function and evolve. The essential feature of these systems is that they are *open*, not closed. As Nicolas Georgescu-Roegen and Herman Daly have both pointed out, the real global economy receives low entropy inputs (resources) from "outside", processes them, extracts utility from them, and finally discards high entropy wastes back to the environment. A closed system would violate the First Law.

Ludwig Boltzmann attempted to reduce the entropy law to a law of probability, following from the random collisions of atomic particles. With Maxwell, he conceived gas molecules as tiny "billiard balls" colliding in a box of fixed volume, noting that with each collision the velocity distributions would become increasingly *disorderly* (random). Boltzmann's statistical theory correctly explained the observed relationship between the density, temperature, pressure and heat capacity of ideal gases. (His billiard-ball model is not a very good model of real gases that are not tiny hard billiard-balls.) The idea that the second law of thermodynamics or "entropy law" is a *law of increasing disorder* is due to Boltzmann's interpretation of the second law of thermodynamics. If the universe consisted of empty space and tiny billiard balls the limiting case of maximum entropy would, indeed, be "heat death".

Before Darwin, most Christians (and other religions) believed that the creation of Adam – the first man -- occurred a mere few thousand years ago. The most plausible date was 4004 BCE, as calculated by an Irish bishop named James Ussher. There were many other such estimates. Most of them equated the creation of Adam with the creation of the earth itself. We now know that the earth is several billion years old, and that life on Earth also began more than one billion years ago, but Adam (and Eve) came much later.

The diversity of life was hard to explain. It was finally explained as a process of selection on the basis of genetic advantage ("fitness"). Even so, the Mendelian laws of genetic inheritance were not understood until chromosome theory was established in the 20th century (c. 1915). Now we know (thanks to the discovery of radioactivity and the invention of radio-metrics) that all life on Earth shares a last universal common ancestor (LUCA) that lived approximately 3.5–3.8 billion years ago.



The Tree of Life.

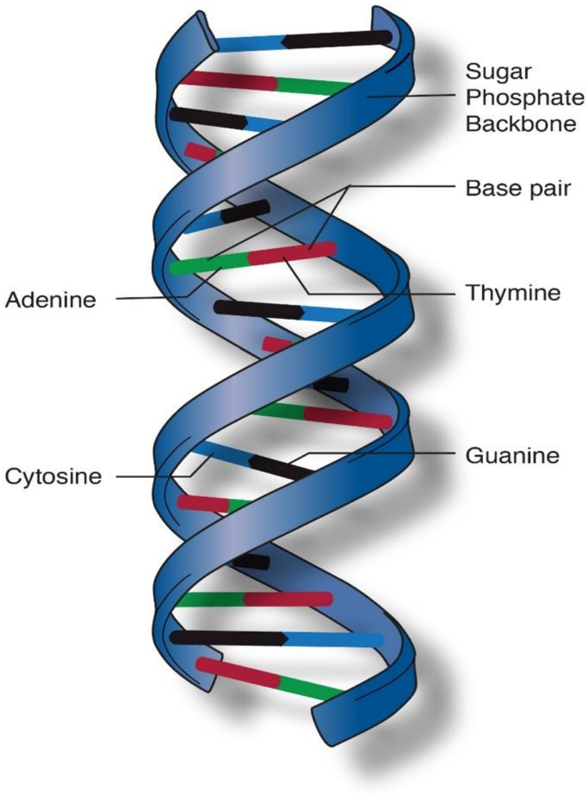
This evolutionary process has not led to increasing disorder, randomness, homogeneity or disappearance of species. It has given rise to biodiversity at every level of biological organisation, including the levels of phyla, species, individual organisms and molecules. In a joint publication with Alfred Russel Wallace, in 1858, Darwin explained that the branching pattern of evolution resulted from a process that they called natural selection, in which the struggle for existence has a similar effect to the artificial selection involved in selective breeding of animals and plants.

Existing patterns of biodiversity have been shaped by repeated formations of new species (*speciation*), changes within species (*anagenesis*) and loss of species (*extinction*) throughout the evolutionary history of life on Earth. The evolutionary process of natural selection has also resulted in a vast increase in the complexity of the organisms, starting from the first cells and resulting in the human brain and our DNA. The activities of the human brain have, with time, produced an even higher order of complexity: this is the world of products, structures, and organizations that we know today. The brain is the most energy consuming function of our bodies.

5. The two basic life processes: Order from Order and Order from Disorder

Erwin Schrödinger was one of the fathers of quantum mechanics, as well as a refugee (in Ireland) from Nazi Germany. In his Dublin lectures (1944) and the resulting book "What is Life?" he attempted to draw together the fundamental processes of biology and the sciences of physics and chemistry (Schrödinger 1945). He noted that life exemplifies two fundamentally different processes: one is "order from order" and the other is "order from disorder".

Schrödinger observed that the gene – it was not yet understood as a coded molecular message -- generates *order from order* in a species: that is, the progeny inherit the traits of the parent. This observation, the basis of plant and animal breeding, is central to genetic theory. A decade after Schrödinger, in 1953, James Watson and Francis Crick discovered the exact mechanism for intergenerational transmission of genetic information via genes. The coded message -- predicted by Schrödinger -- is DNA, the double helix of chains of nuclide-pairs connected by sugar-phosphate bonds. This genetic substance contains all the information needed to reproduce the complete organism, at the atomic and molecular levels. The menstrual cycle enables reproduction that passes information from generation to generation: order from order.



The double helix (DNA molecule) (actually a polymer) that carries information from generation to generation. The five nuclide bases are adenine, thymine, cytosine, guanine, uracil, all based on five or six elements H,C,N,O, S and P.

The menstrual cycle of ovulation is perhaps the best illustration of life as a system of dynamic interactive bio-chemical cycles. It is a series of natural changes in hormone production and the structures of the uterus and ovaries of the female reproductive system. These changes make pregnancy possible, i.e. they enable the female to accommodate a foetus and enable it to grow large enough to survive outside the mother's body. It is a very complex process, but its details are not our topic.

Schrödinger's other equally important, observation in 1944 was his "order from disorder" premise. This was an effort to link biological evolution with the second law of thermodynamics. Schrödinger noted that living systems seem to defy the second law of thermodynamics. The Second Law insists that, within closed systems, the entropy – meaning Boltzmann's disorder (randomness or improbability) – will be maximized. Living systems, including economic systems, being open, do not obey this principle: they are the antithesis of disorder. They are highly ordered structures, synthesized from atoms and simple chemical molecules that are capable of capturing and storing energy, both from photons and from molecular "batteries", to create still more order.

The second law of thermodynamics says that every spontaneous materials transformation process (like combustion) is irreversible. To sustain they therefore need a continuous input of energy. These irreversible transformations can, nevertheless, do "useful (productive) work" in the economic sense. Doing work can produce complex long-lived artifacts i.e., create order out of disorder in a subsystem of the overall system. The Second Law can be seen to say that while the total energy in a system remains constant, the usable fraction of it (we call it *exergy*) declines with every action or transaction. The *exergy* (useful energy) is converted to *anergy* (useless energy or waste heat), keeping the total unchanged. And, while the usable fraction (*exergy*) declines, the local order (complexity) increases, as does the overall level of disorder (*entropy*). The second law insists that, within closed systems, the entropy of a system should be maximized. Living systems, however, are the antithesis of such disorder. They display high degrees of order created from disorder. For instance, plants are highly ordered structures, which are synthesized from disordered atoms and molecules found in atmospheric gases and soils.

Schrödinger's insight about order from disorder was developed into a full-fledged theory of non-equilibrium thermodynamics, by Ilya Prigogine and his colleagues at the Free University in Brussels (Nicolis and Prigogine 1977), (Prigogine et al. 1979) (Prigogine and Stengers 1984) (Gunzig, Gehenian, and Prigogine 1987). The Second Law allows for the existence of cyclic subsystems, at every level of complexity, including simple cycles within larger cycles, contained in still larger cycles, from simple cells to multi-cellular organisms, and beyond that to social and economic systems. All of them are maintained by continuous input of exergy from external sources, as well as dissipation of energy. Being physically active, they are far from general thermodynamic equilibrium (where nothing changes). As their complexity grows, we expect local entropy to grow as well.

I argue that the human economic system is the latest evolutionary example of a "super-cyclic" system driven by exergy dissipation. It generates information, as well as increasingly complex physical artifacts, from anthills, to beaver colonies to institutions like organizations, churches, universities, and cities. The next important idea is that cycles can work together in larger systems. The Calvin cycle (named for its discoverer) underlies the photochemical process in green plants, which converts water and carbon dioxide into carbohydrates with help from exergy from sunlight. The by-product of photosynthesis is molecular oxygen, one of the main components of our planetary atmosphere. But oxygen is toxic to plants and too much oxygen kills.

Another biochemical cycle solved the surplus oxygen problem. This Krebs cycle allows organisms to metabolize stored carbohydrates more efficiently to increase mobility. Some species became hunter-killers (predators) while others specialized in escape or protection by shells. These two interacting cyclic subsystems are crucial for the existence of life on Earth (and the future of Mankind, not to mention your pension fund). The two cycles work together. Without the Krebs cycle, the build-up of oxygen in the atmosphere by photosynthesis would have killed all living organisms. The combination has led to the evolution of the so-called balanced carbon-oxygen cycle.

All of the other primary nutrients of living organisms (nitrogen, phosphorus and, sulfur) also now have their own individual cycles to reverse some decay processes that would otherwise make that nutrient chemically unavailable (Elzen 1995). Phosphorus is a possible exception. It is an element that is geologically rare, and yet essential to life. Its use in synthetic fertilizers is currently dependent on mining "phosphate rock" deposited geologically in the past, and "reducing it" by means of sulfuric acid. The mineral supply is limited while current agricultural practices are considerably reducing its availability. Yet phosphorus rich water is continuously upwelling in several parts of the ocean, most notably off the coast of Peru. It raises a question: is there an organism in the deep ocean that biologically reduces inert calcium phosphates -- in teeth and shells -- and makes it reactive again?

What the Second Law, in its primitive form, does not say (but does not deny) is that an isolated system – such as the universe as a whole, or a solar system, or a planet - can exploit a flux of exergy to "self-organize" into stable subsystems, many of which are contained within other ones. An example of this "Russian doll" type of construction is the menstrual cycle in mammals, itself contained in the grand nutrient cycles in the ecosystem.

To summarize: "self-organization", in Prigogine's sense (op cit) can occur by dissipating an exergy flux, which means converting exergy into anergy, while doing "useful work" or – in the language of economics - increasing utility. It is possible, if the right ingredients are present, to maintain an "island of stability and increasing order" (negative entropy) far from Boltzmann's general thermodynamic equilibrium. These self-organized subsystems, from as simple cells to higher animals, human communities and human institutions, can survive and grow – and evolve -- for a very long time, provided only that there is a continuous stream of exergy (fuel) from another part of the system, available to "feed" the local exergy dissipation. *Self-organization can thus enable the creation and preservation of order*, both as complex material structures and also as useful information or knowledge (Ayres 1994).

The increase of complexity in our world has engendered a new science about complexity itself focused on self-organization and far-from-equilibrium dynamics e.g. (Kaufmann 1993). The mechanism for spontaneous creation of auto-catalysis in chemicals is still unexplained, but that may change at any moment with further research advances. We don't yet understand how to measure complexity or how to attach an economic value to it. But I think it is clear that there is a correlation between complexity and value-added and this is a promising avenue for both systems theory and economic theory.

6. Let us conclude with Economics

It is worth emphasizing that environmental economics and ecological economics study the relationships of humans with the ecosystem. The global environment is, to a large extent, composed of the four interacting global "nutrient cycles": the carbon-oxygen cycle, the nitrogen cycle, the phosphorus cycle, and the sulfur cycle. (They are essential because all life systems are composed of those five elements.) Human industrial activity is not only capable of disrupting those cycles but is doing so on an increasing scale. Geological scarcity will again become a factor in the case of phosphorus, because accumulation of phosphates in the ocean sediments seems -- for now -- to be a one-way process. There is no known biological mechanism to bring phosphorus from the sediments back to the land.

Meanwhile human economic activity has engendered other material cycles. These include the "industrial metals" : chromium, copper, lead, manganese, nickel, tin, and zinc , all mined, refined on a large scale, recovered, and re-used on a significant scale. The "precious metals" -- gold, silver, and the platinum group -- are kept in circulation – or in storage – because their properties are economically valuable. In addition, there are several "electronic metals", including gallium, germanium, indium, lithium, neodymium, selenium, tantalum and zirconium, that may become economically viable candidates for recovery from waste and recycling in the near future, as natural sources are depleted (Ayres 2013, 2014).

To complicate matters further, the human economic system has engendered two other "substance flows" complementing the material flows: these concern money and information. *Money* has several distinct economic functions: first, as a mechanism for enabling non-violent and efficient exchange of goods in markets; secondly, as portable wealth, and thirdly as a measure of economic input (investment) and output value (trade). Monetary flows are sometimes presented in economic textbooks as though they are closed circular flows (wages, expenditures, savings). In recent decades credit and debt have become increasingly important. So has gambling, based on information asymmetries and leverage, which has become an important source of making money from money without any physical product (Ayres~~,~~ 2014).

The other product of economic activity is *information*, which is also physical, but not material (in the sense of mass). Technology has made it possible to create, transmit, and store information (e.g., in "the cloud"), almost without limit, albeit not without energy (exergy) consumption and at considerable cost, as we now realize in the case of data centres. This is one of the kinds of complexity generated by human self-organization, far from economic equilibrium. Most of these complexities are motivated and driven by disequilibrium.

The positive conclusion then of this article is that there is no contradiction between the laws of physics and the laws of biology, and, in particular, Darwinian evolution. However, some "laws " of neoclassical economics are inconsistent with the laws of physics. The main inconsistency, to be blunt, is the idea, dating back to the 18th century physiocrats, and emphasized by Adam Smith, David Ricardo, and the marginalists -- virtually everybody at the time -- that agricultural land (later including capital goods produced from primary products) is the primary source of all wealth.

That dominance of human labor as the key "factor of production" was accepted in the 18th century. It has become axiomatic that all wealth is actually created by human labor, plus capital services, also requiring human labor as input (including labor performed in the past). This very human-centred paradigm is still embodied in neoclassical economics today, despite the fact that most work converting raw materials into useful products is done by machines driven by exogenous power sources.

Since 1895 the "production function" – especially the mathematical form introduced by Charles Cobb and Paul Douglas in 1928 -- has been widely adopted (despite some criticism) by the economics profession. It is central to the growth model introduced by Robert Solow (Solow 1956, 1957). The model is simple

$$Y = A(t)K^{\alpha} L^{\beta},$$

where Y is output (GDP), A(t) is a function of time (connoting technical progress), K^{α} is the productivity of capital, L^{β} is the productivity of labor, with $\alpha + \beta = 1$. The latter condition ~~is~~ states that there are no negative nor positive returns to scale (i.e. big is not more productive than small).

The core of the problem that needs to be addressed by economic theory was clearly expressed to me in a 2008 letter I received from Robert Solow. I had sent him a paper for comment (Ayres 2005). I quote only a few of his lines: "*I have a lot of sympathy with the impulse that lies behind the paper: to understand and estimate the limitations on growth arising from the (possibly) increasing real cost of a ubiquitous factor of production like energy… It seems to me that the right and direct way to go at this is to recognize that energy (or "useful work") is an intermediate good, and to treat it as such explicitly*." Solow goes on to suggest a multi-equation scheme treating L_i and energy E_i as independent variables required for economic sector i : "*This could be done, using the input-output model of the economy, introduced by Wassily Leontief and treating energy E_i for the ith sector as a sectoral product, depending on inputs from other sectors, including the annual flow R of "natural resources*". The argument of this paper is that R is the energy (exergy) input into economic activity and that L and K are the intermediates, which energy is not.

I argue that the output Y(t) over time for a country should be explained almost entirely by the flux of useful energy (exergy) from the sources summarized above (section 2), captured and "consumed" by the economic system. There is some contribution, of course, from capital services, capital goods themselves being the products of exergy flows in the past. In other words, the "Solow residual", meaning the fraction of historical economic growth not explained by increasing capital stock or labor supply, should be explained quite well by past aggregate energy (exergy) consumption (Ayres 2021).

Unfortunately, knowing that energy (exergy) was the driver of past economic growth -- in the few countries for which detailed exergy consumption by sector was available – does not tell us much about the future. It is helpful to know how much is used for space heating, how much for mining and manufacturing, how much for transportation and distribution, how much for agriculture, how much for health services, education, entertainment, defense, law enforcement, IT and so on. We can then estimate the future rates of change of exergy consumption per dollar of output, in each sector, in each country. These time series need to be compiled in exergy terms. So far this has only been done for a few countries (mainly the US and Japan)

We know that cutting Greenhouse gas (GHG) emissions is important, for climate reasons, and increasingly so. Exergy efficiency is perhaps the central strategy for economic growth in the future. We can see that space heating and transport are obvious opportunities for increasing efficiency, which has much greater potential for contributing to the climate change equation as current efficiencies are overestimated by accounting for energy rather than its fundamental substance, exergy. What are the limits of substituting public for private transportation? How would that change with income? What are the limits of demand for red meat vs. other sources of protein and how does that vary with income, in different countries? What are the limits of electricity storage capacity, and at what cost? What are the technical limits of metals re-use, recovery, and recycling? Is there a long-term limit to the daily exergy consumption requirement for human health and happiness?

There are plenty of interesting questions for the next generation of students to answer. This paper just intends to open the door.

7. References

Ayres, Robert U. 1994. *Information, Entropy and Progress: a new evolutionary paradigm*. New York: American Institute of Physics (AIP).

Ayres, Robert U., Ivan Savin, Hao Lu, and Jeroen van den Bergh. 2021. "Exergy vs Labor in aggregate production functions: Estimates for ten large economies." *International Journal of Exergy*.

Ayres, Robert U., and Benjamin S. Warr. 2005. "Accounting for growth: The role of physical work." *Structural Change & Economic Dynamics* 16 (2):181-209.

Ayres, Robert U., and Benjamin S. Warr. 2008. "Accounting for growth; The role of physical work." In *Recent Developments in Ecological Economics*, edited by Joan Martinez-Alier and Inge Røpke. Cheltenham UK and Lyme MA: Edward Elgar.

Ayres, Robert U., and Benjamin S. Warr. 2009a. *The economic growth engine: How energy and work drive material prosperity'*. Cheltenham, UK and Northampton MA, US: Edward Elgar Publishing.

Ayres, Robert U., and Benjamin S. Warr. 2009b. "Energy efficiency and economic growth: The "rebound effect" as a driver." In *Energy Efficiency and Sustainable Consumption*, edited by Horace Herring and Steve Sorrell, 121-137. London: Palgrave Macmillan.

Cobb, Charles W., and Paul A. Douglas. 1928. "A theory of production." *The American Economic Review* (supplement).

Darwin, Charles. 1859. *On the origin of species*. London: J. Murray.

Gunzig, Edgard, Jules Gehenian, and Ilya Prigogine. 1987. "Entropy and Cosmology." *Nature* 330:621-24.

Jevons, William Stanley. 1865 [1974]. "The coal question: Can Britain survive?" *Environment and Change* (extracts from 1865 original).

Kaufmann, Stuart. 1993. *The Origin of Order: Self-organization and selection in evolution*. Oxford: Oxford University Press

Kuemmel, Reiner. 1989. "Energy as a factor of production and entropy as a pollution indicator in macroeconomic modeling." *Ecological Economics* 1:161-180.

Kuemmel, Reiner. 2011. *The Second Law of Economics: Energy, entropy and the origins of wealth*, *The Frontiers Collection*. New York; Dordrecht; Heidelberg; London: Springer.

Kuemmel, Reiner, Robert U. Ayres, and Dietmar Lindenberger. 2010. "Thermodynamic laws, economic methods and the productive power of energy." *Journal of Non-Equilibrium Thermodynamics* 35 (2):145-181. doi: DOI: https://doi.org/10.1515/jnetdy.2010.009.

Morris, Richard. 1980. *The End of the World*. New York: Anchor Press/Doubleday.

Nicolis, Gregoire, and Ilya Prigogine. 1977. *Self-organization in non-equilibrium systems*. New York: Wiley-Interscience.

Prigogine, Ilya, Gregoire Nicolis, Robert Herman, and T. Lain. 1979. "Stability, Fluctuations and Complexity." *Collective Phenomena* 2:103-09.

Prigogine, Ilya, and I. Stengers. 1984. *Order out of chaos: Man's new dialogue with nature*. London: Bantam Books.

Schrödinger, Erwin. 1945. *What is life? The physical aspects of the living cell*. London: Cambridge University Press.

Sedlacek, Tomas. 2011. *Economics of Good and Evil*. New york: Oxford University Press.

Solow, Robert M. 1956. "A contribution to the theory of economic growth." *Quarterly Journal of Economics* 70:65-94.

Swan, Trevor. 1956. "Economic growth and capital accumulation." *The Economic Record* 32 (68):334-361.

Wallace, Alfred Russell. 1902. "From mail coach to telephone." In *Men of Achievement: Inventors and Scientists*, edited by Alfred Russell Wallace, 45-50. New York: The University Society.

Wicksteed, Philip Henry. 1894. Essay on the coordination of the laws of distribution. unknown.