EVOLUTION, ENTROPY AND WORK

James Fournier

Ph.D. Candidate
California Institute of Integral Studies
1453 Mission Street, San Francisco CA 94103
jim@geoman.com

Research Paper

The discussion of the thermodynamics of evolution dates back at least to Schrodinger's (1945) seminal work, *What is Life?* which appeared long after an obscure but groundbreaking article by Lotka (1922). There has been a great deal of discussion of the thermodynamics of evolution over recent decades, and yet many issues remain unresolved, especially surrounding the question of entropy. The topic of this paper, involves the basic thermodynamic calculation of entropy, and specifically the relationship between energy, heat flow, entropy and work. It would appear that in their haste to develop a comprehensive theory explaining all of evolution, recent theorists have lost sight of the thermodynamic concept of work in their treatment of entropy (Swenson, 1989/1997). This is particularly ironic, as thermodynamics was originally developed in an effort to better understand the interrelationship among energy, heat flow, and work.

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1. A Review of Basic Thermodynamics

Thermodynamic entropy has units of energy over absolute temperature. If the term is to have any meaning this is where we must begin. There may be metaphors for entropy, which may be useful in information theory or in other approaches to understanding complex systems, but if we label these with the word "entropy," which has a very specific physical meaning, we lose sight of any real value of the term. Similarly, if we wish to engage in a thermodynamic analysis of a problem we must be careful to use words which have very specific technical meaning appropriately. A specific example of this is the word "efficiency." Efficiency has a very specific technical meaning in thermodynamics. It is intimately related to the concept of work. A brief review of basic thermodynamic concepts is in order.

From the First Law, the basic formula describing a simple thermodynamic system, or heat engine, is:

$$Q(h) - Q(c) - W = 0 \qquad \text{[eq. 1]}$$

where Q(h) is the heat flowing in, Q(C) is the heat flowing out, and W is the work done by the system.

or, in terms of Q(h):

$$Q(h) = Q(c) + W \qquad \text{[eq. 2]}$$

This says that the heat flowing in from the high temperature reservoir is equal to the heat flowing out to the low temperature reservoir, plus the work done by the heat engine. The key insight which led to the development of the Second Law is that W, the work done by the system, must always be less than Q(h), the heat flowing in from the high temperature reservoir. In other words, all of the heat flowing in cannot be converted to work, some heat must be discharged and flow out to the cold reservoir. It is the ratio of the work done by the system vs. the heat flowing in, which determines the efficiency of the system:

$$\text{Efficiency} = \frac{W}{Q(h)} \qquad \text{[eq. 3]}$$

The maximum theoretical efficiency for any system is:

$$\text{Efficiency}_{max} = \frac{T(h) - T(c)}{T(h)} \qquad \text{[eq. 4]}$$

For any designer of heat engines it is the amount of work, and therefore the efficiency, which are of greatest interest. It soon became obvious that some portion of the thermal energy, or any type of energy input, must be discharged in the form of heat to a colder reservoir, or sink, in order to extract any work at all from a high temperature reservoir or energy source. It was this observation which led to the articulation of the Second Law of Thermodynamics: For any irreversible process, entropy always increases.

In our system, a heat engine and two heat reservoirs, the change in entropy, delta S, in a complete cycle is:

$$\text{delta S} = \frac{Q(c)}{T(c)} - \frac{Q(h)}{T(h)} \qquad \text{[eq. 5]}$$

or substituting for Q(c):

$$\text{delta S} = \frac{Q(h) - W}{T(c)} - \frac{Q(h)}{T(h)} \qquad \text{[eq. 6]}$$

For a theoretical reversible cycle delta S = 0. In this case, the decrease of Q(h) by W in the numerator of the first term is exactly proportional to the smaller denominator represented by the lower temperature reservoir, T(c), and the terms cancel in Equation [6]. In a theoretical reversible cycle the work done, W, is a maximum, and the change in entropy is zero.

For the irreversible, and therefore real, case W is always less than the maximum reversible value. Therefore, the numerator of the first term is larger, and delta S > 0, as required by the Second Law. Reducing W increases the magnitude of the first term, thereby increasing the value of delta S. When W is zero, Q(c) is equal to Q(h), all of the heat is flowing out to the cold reservoir, and delta S is at a maximum, as shown in Equation [5].

From the First Law, the heat flowing in, Q(h), must be equal to the heat flowing out, Q(c), plus any work, W, done by the system; as the energy flowing in as heat must be equal to the energy flowing out as some combination of heat and work. In addition, the Second Law says that some portion of the energy flowing out must be heat; the heat flowing in can't all be converted to work.

It becomes apparent from Equation [6] that the magnitude of the increase in entropy, delta S, is directly linked to the amount of work done by the heat engine on its environment. If it does no work, then Q(h) is equal to Q(c) and the entropy increase in maximal. However, if the system is as efficient as possible (in the thermodynamic sense of the word), and therefore does as much work as possible, then the increase in entropy is minimized. If the process could be truly reversible, then the increase in entropy could, in theory, be zero. In reality it is impossible for any actual macroscopic processes to be fully reversible. What is most important to focus on here, however, is the direct negative relationship between the magnitude of the increase in entropy, and work done by the system. Work most often represents that portion of the process which is reversible. Work can be used to de-disperse things, to put things back into a state of higher potential energy. Whether by lifting something with respect to gravity, or by making chemical bonds of a higher potential energy, it is work which can reverse the normal tendency of things to dissipate toward thermal equilibrium.

2. Thermodynamic Models of Evolution

Much of the recent theorizing about the thermodynamics of evolution attempts to build a model up from non-living systems.(Goerner, 1994) In the end this may prove to be fruitful, but it may be easier to first start from the other direction. When humans build machines we are mimicking what nature does, at least in so far as we are faced with the similar constraints as those facing any other organisms attempting to further their own survival. Therefore, we need only look at the most basic thermodynamics of the situation to see that the problem, both for humans and for other organisms, has always been how to extract as much useful work from a potential energy gradient as possible. There are two ways to do this. One is to increase the magnitude of energy flow across the gradient. The other is to increase the (thermodynamic) efficiency of its use, i.e. maximize the work extracted and therefore, by definition, minimize the entropy production. The first approach can lead to increased entropy production, if the thermodynamic efficiency of the process remains constant. But the second approach, which incidentally seems to be highly optimized in natural systems, may actually lead to a reduction in the entropy increase. In any case, the increase in entropy is an indicator after the fact, not a cause of the behavior of the system, which may be much better understood in terms of energy flows, work, and the overall thermodynamic efficiency.(Corning, 1997a) Indeed, it becomes plausible to hypothesize that in strictly thermodynamic terms living systems *are* the work extracted from the energy flux across the potential. However, it might be more correct to say that their structures are composed of the energy embodied by that work in matter. The following thought experiments may make this more understandable.

2. The Benard Cell Experiment

First, let us examine the now paradigmatic Benard cell. The Benard cell experiment is carried out in a flat circular dish filled with a thin layer of water, which is uniformly heated from below in a controlled manner. At a certain critical rate of thermal input, if the water layer is precisely the right thickness, the heat will be dissipated more rapidly through the formation of a coherent pattern of hexagonally arrayed convection cells than through turbulent boiling.(Benard, 1900) In this case we have a system in which energy moving across a potential gradient spontaneously gives rise to an ordered pattern or structure. While this may be a very useful critique of the 19th century idea that all physical systems tend toward a state of greater disorder, it really has very little to do with the thermodynamic behavior of living systems. Its repeated invocation seems to be an artifact of early thinking about dissipative structures.(Prigogine, 1984; Swenson, 1989/1997) The Benard cell does, however, also inadvertently illustrate a key distinction which should be recognized when comparing various types of systems. The question becomes one of whether or not the system does work which contributes to structures that endure in matter. This distinction is of pivotal importance to living systems. Living systems create structures that do endure. While perhaps so obvious as to be taken for granted, this distinction allows us to recognize why the Benard cell is not an appropriate example for describing the thermodynamic behavior of living systems. In order to create enduring structures in matter living systems must do work. Thus, if we are looking for thermodynamic examples of living system, we must look for systems that do work and create enduring structures. This appears to be a necessary, but not sufficient, condition for describing living systems. Thus, perhaps it might prove to be an interesting criterion to employ in pursuing an investigation into how non-living systems could have evolved into living systems. That question, however, is not the focus of this paper.

In the case of the Benard cell, one might be able to arrange a frame of reference in which it appears that work is being done to create, and temporarily maintain, the coherent pattern among the convective cells. This coherent pattern is, as has been pointed out repeatedly over the last few decades, what allows the system to dissipate the available thermal energy most rapidly (Swenson, 1989/1997). However, unlike a living system, this coherent pattern does not contribute to the establishment of any enduring structure in matter. As soon as the source of high energy potential is interrupted, the pattern immediately collapses, and any energy which had been contributing to maintaining the structure, is immediately converted to thermal dispersion and dissipated. Thus, the claim that the Benard cell creates increased entropy as rapidly as possible—often erroneously referred to as “efficiently”—appears to be a correct (Swenson, 1989/1997). But, while this is an interesting physical phenomenon, showing that macro scale ordered patterns can spontaneously emerge out of the dynamics of energy flow across a potential gradient, it has nothing to do with the thermodynamic behavior of living systems. Living systems, by contrast, use part of the energy flowing through them to do work. To the extent that this work is used to create structures in matter, that portion of the energy which does the work is sequestered in matter. That portion of the energy does not flow into a low temperature reservoir, and thus does not immediately contribute to entropy production. Thus, in many cases living systems actually create less entropy, than comparable non-living systems operating across the same potential gradient over a given period of time. It seems that the second law cannot be violated, but it can be stalled. In that sense life could be regarded as an energy "kiting" scheme.

3. Photosynthesis

This becomes particularly apparent when one examines the thermodynamic behavior of organisms engaging in photosynthesis. Here energy from photons coming from the high temperature source, namely the Sun, is converted to potential energy in the form of excited electrons and used to do work, namely creating higher energy molecules in the form of carbohydrates and molecular oxygen in the atmosphere. The energy represented by photons which are actually captured and used for photosynthesis, about twelve percent of those actually striking a leaf, are converted into chemical potential energy.(Corning, 1997b, p.5) This energy is bound up in the carbon compounds which make up the structure of the organism, i.e. organic material, and in the higher chemical potential energy state of the atmosphere. This portion of the incident solar energy is not immediately reradiated in the form of thermal dispersion, and thus does not immediately contribute to increased entropy. Therefore, it would appear that throughout the time when there have been photosynthesizing organisms on Earth, the overall rate of entropy production on Earth has in fact been less than it would otherwise have been without them. We can see the difference in the energy sequestered in the vast accumulation of biomass and fossil fuels on Earth. Energy which was chemically bound up on Earth rather than being disbursed into space as heat did not contribute to increased entropy over that period.

5. Respiration

It is only because of the long term accumulation of energy by photosynthesizing organisms, and the resultant slowing of entropy production, that a large energy reserve has been built up on Earth. It is the existence of this reserve that has made it possible for other organisms to consume and transform that energy more rapidly. It is only with the advent of aerobic organisms engaged in respiration that it becomes possible to burn up these reserves more rapidly, and therefore to increase the rate of entropy production. If one only examines the behavior of organisms engaged in respiration over the period following the onset of the increase in atmospheric oxygen levels, one might conclude that there is a pervasive trend toward increased entropy production in all of evolution (Swenson, 1989/1997). But, this is apparently a characteristic, not the cause, of a trend which has only existed over some portions of the evolutionary history of life on this planet. Moreover, in spite of this recent trend, wherein the oxidation rate associated with the respiration of ever more complex organisms has been steadily increasing, the overall rate of entropy production of the planet as a whole has still remained less than that of a comparable planet without life. The evidence for this observation is found in the overall tendency of the Earth to continue to accumulate carbon-based biomass, while maintaining a stable concentration of atmospheric oxygen. This represents the sequestering of energy which would otherwise have been reradiated into Space contributing to increased entropy, but which instead did not do so. A more interesting observation in this area concerns the steady increase in the oxidation rate per unit mass by ever more complex aerobic organisms. This trend toward increasing energy flux density in increasingly complex organisms is most interesting, but does not by itself lend any real support to the claim that entropy increases as rapidly as possible. There are two reasons why this is the case. In the first place, one would have to know how much work was performed by those organisms before one could make any meaningful calculation of entropy. Secondly, the trend itself is only valid over a portion of the evolutionary history, and as has previously been pointed out, was only made possible by a prior prolonged period of energy accumulation and collateral entropy rate reduction.

6. The Planet as a Whole

The question of the overall thermodynamic behavior of the planet as a whole is also worth considering in greater detail. The maximum possible increase in entropy for a given system is found when all of the thermal energy flowing in as heat from the high temperature source, is also flowing out as heat to the low temperature sink. This is essentially the case for a dead planet such as the Moon, or as far as we can tell Venus or Mars. In this case all of the solar radiation which strikes the planet is reradiated out into Space within a relatively brief period. The only other possibility is that some of the energy flowing in could go into heating the planet. But the dead planet appears to be pretty much at equilibrium, or perhaps more accurately at a stable steady state, as there may also be some residual thermal energy being radiated as heat from volcanic activity by the planet as it cools very slowly. The source of this heat is largely nuclear decay within the core of the planet, although it is possible that there may also be some leftover thermal energy from mechanical collisions when it was formed, or even conversion of a small amount of gravitational energy to heat in movements of its crust.(Cloud, 1988) But the rate of heat flow from all of these sources is stable enough that as a practical matter the dead planet is at a stable equilibrium temperature averaged over any representative period.

It is also important to understand that changing the relative position of the temperature of the planet within the temperature gradient between the Sun and Space has no effect on the ongoing change in entropy. Any increase on one side is exactly offset by a decrease on the other, i.e. if the planet were colder and there was therefore more entropy increase associated with photons from the Sun being absorbed by it, then that increase would be offset by the reduced increase in entropy when photons were radiated from the colder planet back out into Space. The overall rate of entropy production is entirely determined by the temperature difference between the source, the Sun, and the sink, cold dark Space, and has nothing to do with the relative intermediate temperature of the planet. The rate of entropy production is therefore already pegged at a maximum for any dead planet. There is simply nothing for any incident energy to do other than to be reradiated out into space, and therefore all of the energy leaving the Sun and striking the planet is already contributing to the maximum possible rate of entropy production.

7. The Transition to Life

Once a planet has evolved photosynthesizing organisms, it is clearly operating at an overall rate of entropy production which is less than that of a dead planet. This is the case because, as has already been outlined, photosynthesizing organisms use some of the energy to do work to create higher energy compounds, which sequester a portion of the energy rather than allowing it to be reradiated out into space. If a portion of the energy striking the planet is not immediately contributing to the increase in entropy then the overall rate of entropy production must be less than the theoretical maximum for any given period of time. What is more interesting is the question of what happened during the earlier period before photosynthesis starts. More interesting still is the question of what happened before there was really life *per se*, but after autocatalytic chemical reactions start occurring. It would seem that as soon as such reactions begin to sequester significant amounts of incident energy in the form of chemical compounds at higher than equilibrium potential energy, the process has started. Indeed, most hypotheses for the spontaneous emergence of life out of some mixture of multiple autocatalytic reaction cycles depend upon the existence of some sort of high-energy soup. The ultimate energy source for the creation of such a soup might be some combination of thermal radiation from the Earth and/or photons from the Sun. Even if this energy were converted into a hydrologic cycle giving rise to lightening, or some other form, the key transition point in this model would be when some portion of that energy began to be sequestered as complex chemical compounds, proteins or other chemical precursors to life. From a thermodynamic standpoint it is impossible to say where in this sequence life actually begins, even though from a biochemical, or at least from a biological standpoint it might be clear that such a system could not yet be said to contain life. This begs the question of whether a living system or pre-living system must contain life, or rather living entities. Indeed, as Gaia theory begins to suggest the whole system might in some sense be said to be living, even before individual entities could be said to be alive.(Lovelock, 1987; 1995) The key observation appears to be that living, and perhaps even pre-living, systems tend to drive the planet away from its previous condition of maximum entropy.

8. Human Intervention

It is only with the advent of human use of fire that the overall rate of entropy actually begins to increase on Earth. The first indications of this might have been when hunting and gathering peoples began to manage large areas of forest by regularly burning the undergrowth more extensively and frequently than had been the case due to lightening strikes. From there humans eventually moved on to slash and burn agriculture, and eventually to larger and larger scale deforestation. The desire for wood, both as fuel and building material, combined with the need for more grazing area for cattle and sheep has driven a steady pattern of deforestation wherever human populations have spread. Especially in Europe and the Middle East, the spread of human civilization has been basically synonymous with the spread of deforestation for at least four thousand years. Yet, throughout this period, while the rate of entropy production due to human activity was steadily increasing, total combustion still did not even come close to approaching the point where the biosphere could no longer sequester far more energy than was being dissipated as heat due to combustion. It has only been since the industrial revolution that the overall rate of entropy increase on the Earth may have for the first time approached, or even exceeded, that of the planet before life began. For it was only when humans began to tap, and burn, the fossil hydrocarbon reserves of the planet, disbursing a large portion of that energy as heat, that the rate of entropy production on Earth spiked upward. In this act of essentially hyper-respiration human technology at once mimicked, and surpassed, the behavior of all other aerobic organisms including ourselves. Prior to this point the biosphere, in combination with the hydrologic and geologic systems of the planet, has apparently always been capable of maintaining a net positive balance in the current account of energy flow, always sequestering a net surplus.(Cloud, 1988) Now, in a relative flash on the scale of geologic time we are literally burning through those reserves, massively accelerating the rate of entropy production, and indeed the rate of increase of the rate of entropy production. This resembles more a rip, or tear, in the fabric of the energetic net life has so carefully woven, than an extension of life's natural functioning. This situation will most likely only make sense in retrospect, as a necessary and even inevitable stage in our evolution, if we are able to recognize the implications of the situation now and very rapidly adapt our technology and behavior.

9. Technological Analogs of Organisms

From the point of view of the energy flow and entropy analysis, which we have so far been applying primarily to biological organisms, current fossil-fuel energy technology functions like a hyper-animal. Human-made machines oxidize hydrocarbons to extract the embodied energy, while remaining dependent upon photosynthesizing organisms to maintain atmospheric equilibrium. Biological respiration is essentially combustion, but carried out in a controlled manner to yield the maximum thermodynamic efficiency. It seems clear, given the preceding analysis, that we as a species are now facing a fundamental point of inflection in a very long-term oscillation in the thermodynamics of the biosphere. This point is no less profound than when organisms capable of aerobic respiration first emerged in response to the build up of oxygen in the atmosphere. We now face the symmetrical point. This time, hyper-animals, i.e. our machines, threaten to exceed the capacity of the atmosphere to absorb the CO_2 they give off without adversely destabilizing the narrow range of climatic temperature we require to support our vast population. The current situation is in many ways exactly the opposite of the one which gave rise to our predecessors, and launched the whole lineage of ever more complex organisms extracting ever greater amounts of energy with oxygen from the atmosphere. Now, having made technological extensions of ourselves, which have pushed that process further, we must implement technology which will bring the system back into balance.

The key insight may be to discern the fundamental difference between plants, which engage in photosynthesis, and animals, which engage in respiration, and to recognize that there is potentially a parallel classification system between animal-like technologies which engage in combustion, or more precisely oxidation, and plant-like technologies which represent a technological analog of photosynthesis. The obvious technological parallel will be with photovoltaic cells. Yet, photovoltaics by themselves cannot really be described as meta-plants. Like plants, they do convert sunlight into available energy, but they do not directly affect the atmospheric balance between CO_2 and O_2. If, however, their electrical output is used to perform electrolysis, splitting water into hydrogen and oxygen, then photovoltaics might represent plants on one side of a potentially balanced energetic cycle, analogous to the carbon cycle in nature. A human-made closed-loop analog of nature might even work without carbon, instead using only H_2, O_2 and water. Energy technology may actually be headed in this direction already. The chemical composition of fuels have moved steadily from wood, to charcoal, to peat, to coal and then through the sequence of successively smaller and lighter fossil hydrocarbons from crude oil, to natural gas. This sequence inevitably converges on pure hydrogen, H_2, as the smallest lightest energy storage and transport medium. Hydrogen can be highly problematic as a fuel for combustion, but the optimal technology for the use of H_2 does not involve atmospheric combustion. Oxidation is instead carried out in a controlled manner in a fuel cell. This is the technological analog of respiration. Fuel cells combine H_2 and O_2 to yield an electric current and water. These technological analogs of photosynthesis and respiration are based on silicon instead of carbon. Silicon, the basis of rock, is essentially the higher octave of carbon in the periodic table. Thus, it might be appropriate to describe such a new closed-loop cycle as an octave of nature, or even as "Meta-Nature."

Baring the sudden advent of nuclear fusion or zero-point energy, the rapid deployment of such technology will be necessary for human civilization to continue. While this is already obvious to many, it may shed new light on the problem if we are able to understand it within the framework of the very long-term behavior of energy flows in nature. Such analysis may illustrate, more clearly than previous approaches, that what we must now do is essentially create meta-plants, systems which are capable of an analog of photosynthesis, in order to initiate a new sustainable balance with the vast amount of human technology which already behaves like essentially meta-animals. It may also be helpful to recognize that in general, living systems tend to maximize their access to available energy, while striving to be as efficient as possible, in the true thermodynamic sense of the word. We would do well to follow their example.

References

Benard, H. 1900. "Les Tourbillons Cellulaires dans une Nappe Liquide," *Rev. General Science Pur. Appl.* Vol. 11:1261-1271.

Cloud, P. 1988. *Oasis in Space,* W.W. Norton & Co.

Corning, P. A. & Kline, S.J. 1997a. "Thermodynamics, Information and Life Revisited, Part I To Be or Entropy" *Syst. Res. Behav. Sci.* Vol. 14:0:1-22 John Wiley & Sons, Ltd.

Corning, P. A. & Kline, S.J. 1997b. "Thermodynamics, Information and Life Revisited, Part II 'Thermoeconomics' and 'Control Information'" *Syst. Res. Behav. Sci.* Vol. 14:0:1-29 John Wiley & Sons.

Corning, P.A. in press. "On the Concept of Synergy and its Role in the Evolution of Complex Systems," *Journal of Social and Evolutionary Systems*

Goerner, S. J. 1994. *Chaos and the Evolving Ecological Universe* Gordon & Breach.

Lotka, A. J. 1922. "Contribution to the Energetics of Evolution," *Proceedings of the National Academy of Sciences* Vol. 8:147-151.

Lovelock, J. E. 1987. *Gaia : A New Look at Life on Earth* Oxford University Press

Lovelock, J. E. 1995. *The Ages of Gaia : A Biography of Our Living Earth* W.W. Norton & Company

Prigogine, I. 1984. *Order Out of Chaos* Bantam.

Schrodinger, E. 1945. *What is life?* New York: Macmillan.

Swenson, R. 1989a. "Emergent Attractors and the Law of Maximum Entropy Production: Foundations to a Theory of General Evolution," *International Federation for Systems Research* Pergamon Press.

Swenson, R. 1989b. "Emergent Evolution and the Global Attractor: The Evolutionary Epistemology of Entropy Production Maximization," *Proc. 33rd Annual Meeting, ISSS, 2-7 July, Edinburgh* Vol. 3:46-53.

Swenson, R. 1989c. "The Earth as an Incommensurate Field at the Geo-Cosmic Interface: Fundamentals to a Theory of Emergent Evolution," *Proc. 1st Int. Congress on Geo-Cosmic Relations* Amsterdam: PUDOC Science Publishers.

Swenson, R. & Turvey, M.T. 1991. "Thermodynamic reasons for Perception-Action Cycles," *Ecological Psychology* Vol.3(4):317-348 Lawrence Erlbam Associates, Inc.

Swenson, R. 1997a. "Autocatakinetics, Evolution, and the Law of Maximum Entropy Production: A Principled Foundation Toward the Study of Human Ecology" *Advances in Human Ecology* Vol. 6:1-47

Swenson, R. 1997b. "Thermodynamics and Evolution," *The Encyclopedia of Comparative Psychology* New York: Garland Publishers, Inc.