Evolution and the second law of thermodynamics

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Skeptics of biological evolution often claim that evolution requires a decrease in entropy, giving rise to a conflict with the second law of thermodynamics. This argument is fallacious, because it neglects the large increase in entropy provided by sunlight striking the Earth. A recent article in this journal provides a quantitative assessment of the entropies involved in order to show explicitly that there is no conflict. That article rests on an unjustified assumption about the amount of entropy reduction involved in evolution. I present a refinement of the argument that does not rely on this assumption and that shows rigorously that there is no conflict between evolution and thermodynamics.

I. INTRODUCTION

In a recent article in this journal,[1] Daniel Styer addresses the claim, often made by creationists, that evolution requires a decrease in entropy and therefore is in conflict with the second law of thermodynamics. He correctly explains that this claim rests on misunderstandings about the nature of entropy and the second law. In particular, the second law says that the total entropy of a closed system must never decrease, but the Earth is not a closed system. It is constantly absorbing sunlight, resulting in an enormous increase in entropy, which can counteract the decrease presumed to be required for evolution. This argument is known to those who defend evolution in evolution-creationism debates,[2] but it is invariably described only in a general, qualitative way. Styer's article attempts to fill this gap with a quantitative argument. Because the incorrect claim is widespread among creationists, a robust, quantitative rebuttal is an extremely good idea.

To formulate a precise argument on this subject, we must begin by identifying the appropriate closed system to which to apply the second law. As we will see below, once we have done this we find that the second law requires that the rate of entropy increase due to the Earth's absorption of sunlight, $(dS/dt)_{\text{sunlight}}$, must be sufficient to account for the rate of entropy decrease required for the evolution of life, $(dS/dt)_{\text{life}}$ (a negative quantity). To be specific, as long as

$$\left(\frac{dS}{dt}\right)_{\text{sunlight}} + \left(\frac{dS}{dt}\right)_{\text{life}} \geq 0, \tag{1}$$

there is no conflict between evolution and the second law.

Styer estimates both $(dS/dt)_{\rm sunlight}$ and $(dS/dt)_{\rm life}$ in order to show that inequality (1) is satisfied. Unfortunately, his argument rests on an unjustified and probably incorrect assumption about the latter quantity. I will present a modified version of the argument, which does not depend on this assumption and which shows that the final conclusion remains valid: the entropy decrease required for evolution is orders of magnitude too small to conflict with the second law of thermodynamics.

In Section II, I will discuss the system to which the second law should be applied and compute the entropy available to drive evolution. Section III discusses the problematic assumption made in Styer's estimate of $(dS/dt)_{\rm life}$, and Section IV provides an alternative argument that does not rely on this assumption.

II. ENTROPY PROVIDED BY SUNLIGHT

Let us begin by justifying equation (1) above. The Earth maintains an approximately constant temperature by absorbing energy from the Sun and radiating energy at an almost exactly equal rate into deep space. To consider the application of the second law of thermodynamics to these processes, we should first identify a closed system large enough that these energy flows may be considered to be internal to the system. Let us take our system to be the Earth, the Sun, and the outgoing thermal radiation emitted by both of these bodies. We will ignore interactions of this radiation with bodies other than Earth and Sun and consider the outgoing radiation from each to form an ever-expanding spherical halo. In this system, no entropy is produced by emission of radiation from the Sun, since this process is simply a flow of energy from the Sun to its radiation field at the same temperature. The same applies to radiation emitted by the Earth. Entropy production occurs only when radiation from the Sun is absorbed on the Earth, since this absorption represents heat flow between parts of the system at different temperatures.

Let $T_\odot$ and $T_\oplus$ be the temperatures of Sun and Earth respectively, and let P be the solar power absorbed by Earth. (To be precise, P is the *net* flow from Sun to Earth, including the backward flow of energy from Earthshine being absorbed on the Sun, but the latter contribution is negligible.) The Earth gains entropy at a rate $P/T_\oplus$, while the Sun's radiation field loses entropy at a rate $-P/T_\odot$. The rate of entropy production is therefore

$$\left(\frac{dS}{dt}\right)_{\rm sunlight} = \frac{P}{T_\oplus} - \frac{P}{T_\odot} \approx \frac{P}{T_\oplus}, \tag{2}$$

where the last approximate equality simply reflects the fact that the Sun's temperature is much larger than the Earth's. Assuming that the evolution of life requires entropy decrease at a rate

$(dS/dt)_{\rm life}$, the second law of thermodynamics applied to this system gives inequality (1).

Using values for the solar constant[3] and Earth's albedo[4], Styer[1] finds that the Earth absorbs solar radiation at a rate of $P = 1.2 \times 10^{17}$ W. Using $T_\oplus = 300$ K as a rough estimate of Earth's temperature, we find that

$$\left(\frac{dS}{dt}\right)_{\rm sunlight} = \frac{P}{T_\oplus} = 4 \times 10^{14}\,({\rm J/K})/{\rm s} = (3 \times 10^{37} k)\,{\rm s}^{-1}, \tag{3}$$

where k is Boltzmann's constant.

In the above calculation we did not include any entropy increase due to thermalization of the radiant energy emitted by the Earth. If we assumed that this radiation eventually thermalized with the cosmic background (CMB) radiation in deep space, then an additional, far larger entropy increase would result: $(dS/dt)_{\rm CMB} = P/T_{\rm CMB} = 4 \times 10^{16}\,({\rm J/K})/{\rm s}$. We are not entitled to include this entropy production in accounting for evolution, however. For one thing, this thermalization probably never occurs: the mean free path of a photon in deep space is larger than the observable Universe and in fact is probably infinite.[5] In any case, even if thermalization does occur, it happens far in the future and at great distances from Earth and so is not available to drive evolution on Earth. (This is why we were able to ignore the existence of distant thermalizing matter in defining the system to which we applied the second law.) Of course, the argument in Section IV, which concludes that equation (1) is satisfied, would only be strengthened if this extra entropy were included.[6]

III. EVOLUTIONARY DECREASE IN ENTROPY

We now proceed to consider $(dS/dt)_{\rm life}$. Styer's argument relies on the following assumption:

> Suppose that, due to evolution, each individual organism is 1000 times "more improbable" than the corresponding individual was 100 years ago. In other words, if Ω_i is the number of microstates consistent with the specification of an organism 100 years ago, and Ω_f is the number of microstates consistent with the specification of today's "improved and less probable" organism, then $\Omega_f = 10^{-3}\Omega_i$. I regard this as a very generous rate of evolution, but you may make your own assumption.

The fact that no justification is provided for this assumption undermines the persuasive power of the argument. Moreover, far from being generous, a "probability ratio" of $\Omega_i/\Omega_f = 10^3$ is probably much too low. After all, one of the central ideas of statistical mechanics is that even tiny changes in a macroscopic object (say, one as large as a cell) result in exponentially large changes in the multiplicity (i.e., the number of accessible microstates).

I will illustrate this with some order-of-magnitude estimates below. Before we begin, though, let us address one question of interpretation of the passage above, namely the precise meaning of the phrase "due to evolution." If, say, a child grows up to be slightly larger than her mother due to improved nutrition, we do not describe this change as "due to evolution," so we might be tempted not to count the associated multiplicity reduction in the factor above. In fact, we might be tempted to count only changes such as the turning on of a new gene as being "due to evolution." However, this would be incorrect. For the argument at hand, we should do our accounting in such a way that *all* biological changes are included. After all, even if a change like the increased size of an organism is not the direct result of evolution within this organism in this particular generation, it is still ultimately due to evolution, in the very broad sense that all life is due to evolution. All of the extra proteins, DNA molecules, etc. that are present in the child are there because of evolution at some point in the past if not in the present, and they therefore deserve to be accounted for in our calculation.

To see that this broad sense of evolution is the correct one to apply in the present context, consider the following thought experiment. Suppose that the entropy reduction due to life in this broad sense were computed and found to be greater than the entropy provided by sunlight. Creationists would justifiably cite this as proof of the claim that evolution is in conflict with the second law.

We will now proceed with some estimates of the required multiplicity reduction. For definiteness, let us consider the case of an *E. coli* bacterium. We will first consider the reduction in multiplicity (or equivalently in entropy) associated with building this organism "from scratch." Following Styer, we will then imagine a series of ever-simpler ancestors of this organism at 100 year intervals, stretching back over the 4-billion-year history of evolution. Each organism is somewhat more improbable than its ancestor from the previous century, and the product of all of these multiplicity reductions must be sufficient to account for the total required multiplicity reduction.

The entropy reduction associated with the evolution of life comes in many forms, consisting in general of the construction of complex structures from simpler building blocks. For simplicity, we will consider just one portion of this process, namely the construction of proteins from their constituent amino acids. Since we will neglect other processes (the synthesis of the amino acids in the first place, the formation of other macromolecules, etc.), we will underestimate the required multiplicity reduction.

An *E. coli* bacterium has about 4×10^6 protein molecules.[7] (Note that this number refers not to the number of distinct *types* of protein, but to the total number of protein molecules in the cell.) We will find the multiplicity cost of assembling all of these molecules by first considering the multiplicity cost of assembling a single protein molecule. Imagining assembling the protein one amino acid at a time. At each step, we must take an amino acid that was freely moving through the cell and place it in a specific position relative to the others that have already been assembled. If the amino acids were previously in a dilute solution in the cell, then the multiplicity loss due to each such step is approximately n_Q/n, where n is the number density of amino acids and n_Q is the density at which the amino acids would reach quantum degeneracy.[8] This is certainly a large factor: amino acids in a cell are far from degenerate. To assemble a protein with N_a amino acids, we would repeat this process $N_a - 1$ times, resulting in the exponentially large number $\Omega_i/\Omega_f \sim (n_Q/n)^{N_a - 1}$. For instance, if $n_Q/n = 10$ (surely far too low) and $N_a = 300$ (about the average size of a protein[7]), the multiplicity ratio is $\sim 10^{299}$ for the production of a single protein molecule.

Using this conservative estimate for the multiplicity change associated with the formation of a single protein molecule, we estimate the multiplicity reduction required to assemble all of the proteins in the bacterium to be $\sim (10^{299})^{4\times 10^6} \sim 10^{10^9}$. Assuming that the entire 4 billion years (or 4×10^7 centuries) of biological evolution were required to achieve this, we would require a multiplicity reduction of $(10^{10^9})^{1/(4\times 10^7)} = 10^{25}$ each century, not 10^3.

The above estimates are of course extremely rough. For example, they neglect the internal degrees of freedom of the protein (which are surely far fewer than those of the free amino acids), and entropy changes due to the energy absorbed or emitted during the formation of chemical bonds. To include the latter, we can simply note that the multiplicity change associated with a chemical reaction is $e^{\mu/kT}$. The chemical potential μ (also known as the Gibbs free energy per particle) in a chemical reaction is generically of order 1 eV ($\sim 10^{-19}$ J) or more, implying multiplicity changes of order $e^{40} \approx 10^{17}$ for each chemical bond formed or broken at biological temperatures. Since hundreds of chemical bonds must be formed in assembling each protein molecule, the resulting factor will once again be exponentially large as above. This sort of number is the ante to enter this particular game.

Of course, since bacteria appeared very early in evolution, we should really assume a shorter time period, and hence a still larger factor would be required. Similarly, if we considered more than just the formation of proteins, or if we considered a large multicellular organism, the required factor would be much greater.

Rough as the above arguments are, they establish that there is reason to doubt the factor 10^3 that plays an essential role in Styer's argument, rendering the argument unpersuasive.[9] To fix the problem, we should set a robust upper limit on $|(dS/dt)_{\mathrm{life}}|$, or equivalently on the total entropy reduction $|\Delta S_{\mathrm{life}}|$, in a way that does not depend on such an assumption. I will provide such an argument in the next section.

IV. A ROBUST ARGUMENT

Let us establish an upper limit on $|\Delta S_{\mathrm{life}}|$ by estimating the relevant quantities in a way that is certain to overestimate the final result. Consider the entropy difference between two systems: Earth as it actually is at the present moment, and a hypothetical Dead-Earth on which life never evolved. We will assume Dead-Earth and Earth are identical, except that every atom in Earth's biomass is located in Dead-Earth's atmosphere in its simplest molecular form. Furthermore, when considering the entropy of Earth, we will assign *zero* entropy to the biomass. That is, we will imagine that, in order to turn Dead-Earth into Earth, it is necessary to pluck every every atom required for the biomass from the atmosphere and place it into its exact present-day quantum state. These assumptions maximize the entropy of Dead-Earth and minimize that of Earth, so the difference between the two entropies grossly overestimates the required entropy reduction for the production of life in its present form.

With these assumptions, we can estimate the entropy difference as

$$\Delta S_{\mathrm{life}} = S_{\mathrm{Earth}} - S_{\mathrm{Dead\text{-}Earth}} \approx \frac{N_b \mu}{T}, \tag{4}$$

where N_b is the number of molecules in the biomass and μ is a typical chemical potential for a molecule in the atmosphere. Using standard formulae for an ideal gas (e.g., equation 3.63 of the book by Schroeder[10]), we find $\mu/kT \sim -10$, so that $\Delta S_{\mathrm{life}} < 0$ as expected. We can obtain a value for N_b from an estimate[11] that the total carbon biomass of Earth is $\sim 10^{15}$ kg. Even if we scale this value up by a generous factor of 100 to account for other elements, we still have fewer than 10^{43} molecules. We conclude that the entropy reduction required for life on Earth is (far) less than

$$|\Delta S_{\mathrm{life}}| \sim 10^{44} k. \tag{5}$$

Comparing this with the rate of entropy production due to sunlight in equation (3), we find that the second law, in the form of inequality (1), is satisfied as long as the time required for life to evolve on Earth is at least

$$\Delta t = \frac{|\Delta S_{\rm life}|}{(dS/dt)_{\rm sunlight}} \sim 10^7\,{\rm s}, \tag{6}$$

or less than a year. Life on Earth actually took four billion years to evolve, so the second law of thermodynamics is safe.[12]

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[1] D. F. Styer, "Entropy and evolution," Am. J. Phys **76**, 1031–1033 (2008).

[2] The TalkOrigins Archive has a list of resources on the subject at `http://www.talkorigins.org/faqs/thermo.html`.

[3] D. Labs and H. Neckel, "The solar constant (A compilation of recent measurements)," Solar Phys. **19**, 3–15 (1971).

[4] P. R. Goode, J. Qiu, V. Yurchyshyn, J. Hickey, M.-C. Chu, E. Kolbe, C. T. Brown, and S. E. Koonin, "Earthshine observations of the earth's reflectance," Geophys. Res. Lett. **28**, 1671–1674 (2001).

[5] E. W. Kolb and M. S. Turner, *The Early Universe* (Frontiers in Physics, Addison-Wesley, Reading, MA, 1990). P. 354.

[6] The reader who wishes to compare this article with that of ref. 1 may find it helpful to note that that paper computes both $(dS/dt)_{\rm sunlight}$ and $(dS/dt)_{\rm CMB}$. In the quantitative conclusion [equations (5) and (6)], the paper correctly uses $(dS/dt)_{\rm sunlight}$, referring to this quantity as the "entropy throughput".

[7] According to B. Alberts, D. Bray, J. Lewis, M. Raff, K. Roberts, and J. D. Watson, *Molecular Biology of the Cell*, 3rd edition (Garland, New York, 1994), p. 90, an *E. coli* bacterium has a volume of 2×10^{-12} cm^3 and is about 15% protein by mass. Assuming that the density of the bacterium is that of water, the total mass of protein is 3×10^{-13} g. The molecular weights of amino acids are about 150 g/mol, so the total number of amino acids in these proteins is about 1.2×10^9. An average protein contains 300 amino acids per protein (Alberts et al., op. cit., p. 118), yielding 4×10^6 proteins in the bacterium.

[8] To see this, imagine that there are k amino acids in solution, with N available quantum states. Nondegeneracy means that $N \gg k$. The multiplicity is $\Omega(k) = \begin{pmatrix} N \\ k \end{pmatrix}$. Taking one molecule out of solution causes the multiplicity to go down by a factor $\Omega(k)/\Omega(k-1) = (N-k+1)/k \approx N/k = n_Q/n$.

[9] If we adopted a much narrower view of which changes are "due to evolution," then the estimates above would not apply. Even in this case, the factor 10^3 would still lack justification, rendering the argument as a whole unpersuasive. Furthermore, the conclusion that there is no conflict between evolution and the second law would be a much weaker one, applying only to the narrower sense of this phrase.

[10] D. V. Schroeder, *An Introduction to Thermal Physics* (Addison Wesley Longman, 2000).

[11] W. B. Whitman, D. C. Coleman, and W. J. Wiebe, "Prokaryotes: the unseen majority," Proc. Natl. Acad. Sci. USA **95**, 6578–6583 (1998).

[12] Creating all of life in six days, on the other hand, might be thermodynamically problematic.