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 provided a quantitative assessment of the entropies involved and showed 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.

I. INTRODUCTION

Daniel Styer recently addressed the claim that evolution requires a decrease in entropy and therefore is in conflict with the second law of thermodynamics. He correctly explained that this claim rests on misunderstandings about the nature of entropy and the second law. The second law states that the total entropy of a closed system must never decrease. However, the Earth is not a closed system and 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, but it is usually described in a general, qualitative way. Reference filled this gap with a quantitative argument.

In the following I present a more robust quantitative argument. We begin by identifying the appropriate closed system to which to apply the second law. We find that the second law requires that the rate of entropy increase due to the Earth’s absorption of sunlight, \( (dS/dt)_\text{sun} \), must be sufficient to account for the rate of entropy decrease required for the evolution of life, \( (dS/dt)_\text{life} \) (a negative quantity). As long as

\[
\left( \frac{dS}{dt} \right)_\text{sun} + \left( \frac{dS}{dt} \right)_\text{life} \geq 0,
\]

there is no conflict between evolution and the second law.

Styer estimated both \( (dS/dt)_\text{sun} \) and \( (dS/dt)_\text{life} \) to show that the inequality \( (1) \) is satisfied, but his argument rests on an unjustified and probably incorrect assumption about \( (dS/dt)_\text{life} \). I will present a modified version of the argument which does not depend on this assumption and which shows that the entropy decrease required for evolution is orders of magnitude too small to conflict with the second law of thermodynamics.

II. ENTROPY PROVIDED BY SUNLIGHT

Let us begin by justifying the inequality \( (1) \). The Earth maintains an approximately constant temperature by absorbing energy from the Sun and radiating energy at an almost equal rate. To consider the application of the second law of thermodynamics to these processes we first identify a closed system that is 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 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, because this process is 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, because this absorption represents energy 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 the rate \( P/T_\oplus \), and the Sun’s radiation field loses entropy at the rate \( -P/T_\odot \). The rate of entropy production is

\[
\left( \frac{dS}{dt} \right)_\text{sun} = \frac{P}{T_\odot} - \frac{P}{T_\oplus} \approx \frac{P}{T_\odot},
\]

where the last approximate equality reflects the fact that the Sun’s temperature is much larger than the Earth’s. If we assume that the evolution of life requires the entropy to decrease at the rate \( (dS/dt)_\text{life} \), the second law of thermodynamics applied to this system gives Eq. \( (1) \).
By using values for the solar constant and Earth’s albedo, Styer found that Earth absorbs solar radiation at a rate of \( P = 1.2 \times 10^{17} \text{ W} \). If we use \( T_\oplus = 300 \text{ K} \) as a rough estimate of Earth’s temperature, we find that

\[
\left( \frac{dS}{dt} \right)_{\text{sun}} = \frac{P}{T_\oplus} = 4 \times 10^{14} \text{ (J/K)/s} = (3 \times 10^{-6}k) \text{s}^{-1},
\]

where \( k \) is Boltzmann’s constant.

In this estimate we did not include any entropy increase due to thermalization of the radiant energy emitted by the Earth. If we assume that this radiation eventually thermalizes with the cosmic background (CMB) radiation in deep space, then an additional, much larger entropy increase results: \( (dS/dt)_{\text{CMB}} = P/T_{\text{CMB}} = 4 \times 10^{16} \text{ (J/K)/s} \). We may not include this entropy production in accounting for evolution, though. One reason is that this thermalization probably never occurs: the mean free path of a photon in intergalactic space is larger than the observable Universe and is probably infinite. 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. For this reason we may ignore the existence of distant thermalizing matter in defining the system to which we apply the second law. The argument in Sec. IV which concludes that inequality (1) is satisfied, would only be strengthened if this extra entropy were included.

### III. EVOLUTIONARY DECREASE IN ENTROPY

We now consider \( (dS/dt)_{\text{life}} \). Styer’s argument relies on the 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 \( \Omega_i \) is the number of microstates consistent with the specification of an organism 100 years ago, and \( \Omega_f \) 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. 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 (that is, the number of accessible microstates).

I will illustrate this idea by some order of magnitude estimates. First, let us address the precise meaning of the phrase “due to evolution.” If 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, and thus we might not count the associated multiplicity reduction in the factor \( \Omega_i/\Omega_f \). Instead we might count only changes such as the turning on of a new gene as being due to evolution. However, this narrow view would be incorrect. For this argument we should do our accounting in such a way that all biological changes are included. Even if a change like the increased size of an organism is not the direct result of evolution for this organism in this particular generation, it is still ultimately due to evolution in the broad sense that all life is due to evolution. All of the extra proteins, DNA molecules, and other complex structures that are present in the child are there because of evolution at some point in the past if not in the present, and they should be accounted for in our calculation.

To see that this broad sense of evolution is the correct one to apply, consider a 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 finding as proof that evolution is in conflict with the second law.

We now make some estimates of the required multiplicity reduction. We consider the case of an \( E. \text{ coli} \) bacterium. We will first consider the reduction in multiplicity 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 four 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 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. Because we will neglect other processes (such as the synthesis of the amino acids in the first place and the formation of other macromolecules), we will greatly underestimate the required multiplicity reduction.

An \( E. \text{ coli} \) bacterium has about \( 4 \times 10^9 \) protein molecules (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. This ratio is large: 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 large number $\Omega_f/\Omega_i \sim (n_Q/n)^{N_a-1}$. For instance, if $n_Q/n = 10$ (much too low) and $N_a = 300$ (about the average size of a protein), the multiplicity ratio is $\sim 10^{299}$ for the production of a single protein molecule.

If we use 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 $\sim (10^{299})^{4 \times 10^8} \sim 10^{6.5 \times 10^9}$. If the entire 4 billion years ($4 \times 10^7$ centuries) of biological evolution were required to achieve this number, we would require a multiplicity reduction of $10^{(10^9)/(4 \times 10^7)} = 10^{23}$ in each century, not $10^3$.

These estimates are extremely rough. For example, they neglect the internal degrees of freedom of the protein (which are 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 note that the multiplicity change associated with a chemical reaction is $e^{\mu/kT}$. The chemical potential $\mu$ in a chemical reaction is of order $1 \text{ eV} \sim 10^{-19} \text{ J}$ or more, implying multiplicity changes of order $e^{\mu} \sim 10^{17}$ for each chemical bond formed or broken at biological temperatures. Because hundreds of chemical bonds must be formed in assembling each protein molecule, the resulting factor will again be exponentially large. This sort of number is the antithesis to entering this particular game.

Because bacteria appeared very early in evolution, we should assume a time period much shorter than four billion years, and hence a still larger multiplicity reduction per century 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 these arguments are, they establish that there is reason to doubt the factor $10^3$ that plays an important role in Styer’s argument, rendering his argument unpersuasive. To strengthen the argument we should set a robust upper limit on $|(dS/dt)_{\text{life}}|$, or equivalently on the total entropy reduction $|\Delta S_{\text{life}}|$, in a way that does not depend on such an assumption.

### IV. A ROBUST ARGUMENT

Let us establish an upper limit on $|\Delta S_{\text{life}}|$ 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 is at present, and a hypothetical Dead-Earth on which life never evolved. We will assume that 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. When considering the entropy of Earth, we will assign zero entropy to the biomass. That is, we will imagine that to turn Dead-Earth into Earth, it is necessary to pluck 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 use the standard thermodynamic result $\mu/T = -\partial S/\partial N$, which implies $\Delta S = -N \mu/T$, to estimate the entropy difference as

$$|\Delta S_{\text{life}}| = S_{\text{earth}} - S_{\text{dead-earth}} \approx \frac{N_b \mu}{T},$$  

(4)

where $N_b$ is the number of molecules required to make up the biomass and $\mu$ is a typical chemical potential for a molecule in the atmosphere of Dead-Earth. If we use standard relations for an ideal gas, we find $\mu/kT \sim -10$, so that $|\Delta S_{\text{life}}| < 0$ as expected. We can obtain a value for $N_b$ from the estimate that the total carbon biomass of Earth is $\sim 10^{15}$ kg. Even if we increase this value 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

$$|\Delta S_{\text{life}}| \sim 10^{44} k.$$  

(5)

If we compare this value with the rate of entropy production due to sunlight in Eq. (2), we find that the second law, in the form of Eq. (1), is satisfied as long as the time required for life to evolve on Earth is at least

$$\Delta t = \frac{|\Delta S_{\text{life}}|}{(dS/dt)_{\text{sun}}} \sim 10^7 \text{ s},$$  

(6)

or less than a year. Life on Earth took four billion years to evolve, so the second law of thermodynamics is safe.
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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 [www.talkorigins.org/faqs/thermo.html](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 (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 Ref. 1 calculates both \((dS/dt)_\text{sun}\) and \((dS/dt)_\text{CMB}\). In the quantitative conclusion [Eqs. (5) and (6)], Ref. 1 correctly uses \((dS/dt)_\text{sun}\), 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 (Garland, New York, 1994), 3rd ed., p. 90, an *E. coli* bacterium has a volume of $2 \times 10^{-12}$ cm$^3$ and is about 15% protein by mass. If we assume that the density of the bacterium is that of water, the total mass of protein is $3 \times 10^{-13}$ g. The molecular weights of amino acids are about 150 g/mol, and thus the total number of amino acids in these proteins is $\approx 1.2 \times 10^9$. An average protein contains 300 amino acids per protein (p. 118), yielding $4 \times 10^6$ proteins in the bacterium.
8 Imagine that there are $n_a$ amino acids in solution, with $N$ available quantum states. Nondegeneracy means that $N \gg n_a$.
9 The multiplicity is $\Omega(n_a) = \binom{N}{n_a}$. Taking one molecule out of solution causes the multiplicity to decrease by a factor $\Omega(n_a)/\Omega(n_a - 1) = (N - n_a + 1)/n_a \approx N/n_a = n_Q/n$.
10 If we adopt a much narrower view of which changes are due to evolution, these estimates would not apply. Even in this case, the factor of $10^3$ would still lack justification.
11 See for example, Eq. (3.63) in D. V. Schroeder, An Introduction to Thermal Physics (Addison-Wesley Longman, Reading, MA, 2000).
12 W. B. Whitman, D. C. Coleman, and W. J. Wiebe, “Prokaryotes: The unseen majority,” Proc. Natl. Acad. Sci. USA 95, 6578–6583 (1998).
13 Creating all of life in six days might be thermodynamically problematic, however.