Entropy and evolution

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Quantitative estimates of the entropy involved in biological evolution demonstrate that there is no conflict between evolution and the second law of thermodynamics. The calculations are elementary and could be used to enliven the thermodynamics portion of a high school or introductory college physics course. © *2008 American Association of Physics Teachers.*
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I. INTRODUCTION

Does the second law of thermodynamics prohibit biological evolution?

The erroneous answer "yes" is sometimes presented in the creationist literature,[1,2] and more often in creationist web sites. Henry Morris, for example, finds it "obvious that the Second Law of Thermodynamics constitutes a serious problem to the evolution model" because "every system left to its own devices always tends to move from order to disorder."[1]

The creationist argument is that advanced organisms are more orderly than primitive organisms, and hence as evolution proceeds living things become more ordered, that is less disordered, that is less entropic. Because the second law of thermodynamics prohibits a decrease in entropy, it therefore prohibits biological evolution.

This argument rests upon two misconceptions about entropy.

- Disorder is a metaphor for entropy, not a definition for entropy.[3,4] Metaphors are valuable only when they are *not* identical in all respects to their targets. (For example, a map of Caracas is a metaphor for the surface of the Earth at Caracas, in that the map has a similar arrangement but a dissimilar scale. If the map had the same arrangement *and* scale as Caracas, it would be no easier to navigate using the map than it would be to navigate by going directly to Caracas and wandering the streets.) The metaphor of disorder for entropy is valuable and thus imperfect. For example, take some ice cubes out of your freezer, smash them, toss the shards into a bowl, and then allow the ice to melt. The jumble of ice shards certainly seems more disorderly than the bowl of smooth liquid water, yet the liquid water has the greater entropy.[5]
- Although the entropy of the universe increases with time, the entropy of any part of the universe can decrease with time, so long as that decrease is compensated by an even larger increase in some other part of the universe.[6] For example, any hot cup of coffee left to its own devices on a tabletop *decreases* in entropy.

(This creationist argument also rests upon the misconception that evolution acts always to produce more complex organisms. In fact evolution acts to produce more highly adapted organisms, which might or might not be more complex than their ancestors, depending upon their environment. For example, most cave organisms and parasites are qualitatively simpler than their ancestors.[7] This biological misconception will not be discussed in this article.)

These misconceptions have been pointed out numerous times,[8] but here we explicitly and quantitatively answer questions such as "What entropy changes accompany evolution?" and "If the entropy here on Earth is decreasing due to evolution, where is the other piece of the universe where the entropy is increasing?"

II. ENTROPY FLUX THROUGH THE EARTH

The Sun heats the Earth through electromagnetic radiation (largely in the visible and near-infrared bands). The Earth radiates electromagnetic radiation (largely in the far-infrared band) into outer space, where it eventually joins the cosmic microwave background.[9] The Earth itself remains almost constant in temperature, so the incoming radiant energy from the Sun must balance almost exactly the outgoing radiant energy into space. In short, the Sun heats the Earth and to a nearly equal extent the Earth heats outer space.

Each of these "heatings" is accompanied by an entropy change. The change of entropy for a system at constant (absolute) temperature T, gaining heat Q quasistatically, is

$$\Delta S = \frac{Q}{T}. \tag{1}$$

(If the heat transfer is not quasistatic, then the associated entropy change is greater than this quotient.) The Sun emits heat and hence decreases in entropy, while outer space absorbs heat and hence increases in entropy. Meanwhile, the Earth is nearly constant in entropy.

To make this argument quantitative,[10] we use the data in the first four lines of Table I. From these, we calculate the lower-bound entropy changes due to the "Sun heats Earth, Earth heats outer space" process under discussion here. The last three lines of Table I show that each second the Sun decreases in entropy while outer space increases in entropy. Meanwhile, the Earth doesn't change its entropy, but has the throughput shown. As required by the second law of thermodynamics, the increase in entropy of outer space far exceeds the decrease in entropy of the Sun. (These are the entropy changes due to energy flow via the Earth. There are also entropy changes due to energy flow directly from the Sun to outer space, and flow via the Moon, and flow via Jupiter, etc.)

III. ENTROPY REQUIRED FOR EVOLUTION

What is the change in the entropy of living things on Earth due to evolution?

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 or-

Table I. Temperature, heat, and lower-bound entropy values.

Quantity	Value
Mean temperature of the Sun's surface[a]	5778 K
Mean temperature of the Earth's surface[b]	288 K
Mean temperature of the cosmic microwave background[c]	2.728 ± 0.004 K
Solar energy absorbed by the Earth each second[d]	$(1.21 \pm 0.01) \times 10^{17}$ J
Sun's entropy decrease each second	$(20.9 \pm 0.1) \times 10^{12}$ J/K
Cosmic microwave background's entropy increase each second	$(44\,400 \pm 400) \times 10^{12}$ J/K
Earth's entropy throughput each second	$(420 \pm 4) \times 10^{12}$ J/K

[a]Reference 11.
[b]Reference 12.
[c]Reference 13.
[d]Reference 14.

ganism 100 years ago, and Ω_f is the number of microstates consistent with the specification of today's "improved and less probable" organism, then

$$\Omega_f = 10^{-3}\Omega_i. \qquad (2)$$

I regard this as a very generous rate of evolution, but you may make your own assumption.

The statistical definition of entropy (in the microcanonical ensemble) is

$$S = k_B \ln \Omega, \qquad (3)$$

where the Boltzmann constant is $k_B = 1.38 \times 10^{-23}$ J/K. If the assumption in Eq. (2) is used, then the corresponding difference in entropy of the organism of today versus the organism of a century ago is

$$S_f - S_i = k_B \ln \Omega_f - k_B \ln \Omega_i = k_B \ln(\Omega_f/\Omega_i) \qquad (4a)$$

$$= k_B \ln(10^{-3}) = k_B(-6.91) \qquad (4b)$$

$$= -9.53 \times 10^{-23} \text{ J/K}. \qquad (4c)$$

That's the entropy change over 100 years. The entropy change per second is -3.02×10^{-30} J/K.

How many individual organisms are there on Earth? The number of eukaryotic species[15] on Earth is unknown, but has been estimated at 5–15 million. We will be generous and estimate the number of species as 10^8. The number of individuals of each species is also unknown, but the human population is about 6×10^9. If every species were so numerous, there would be about 10^{18} eukaryotic individuals on Earth. By contrast, the Earth's population of prokaryotes has been estimated[16] at $4-6 \times 10^{30}$. We adopt 10^{32} as a generous overestimate for the number of organisms on Earth.

If each of these organisms were evolving at the rate assumed in Eq. (2), the change in entropy of the biosphere each second would be

$$-302 \text{ J/K}. \qquad (5)$$

In contrast we found earlier that a lower bound for the Earth's entropy throughput each second is about

$$420 \times 10^{12} \text{ J/K}. \qquad (6)$$

In other words, at a minimum the Earth is bathed in about one trillion times the amount of entropy flux required to support the rate of evolution assumed here.

Presumably the entropy of the Earth's biosphere is indeed decreasing by a tiny amount due to evolution, and the entropy of the cosmic microwave background is increasing by an even greater amount to compensate for that decrease. But the decrease in entropy required for evolution is so small compared to the entropy throughput that would occur even if the Earth were a dead planet, or if life on Earth were not evolving, that no measurement would ever detect it.

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APPENDIX: SUGGESTED PROBLEMS

The following problems can be assigned to students to drive home the points made in this article.

1. *Inverse problem.* Suppose that the Earth's entropy output were increased by one part per million due to the evolution of living things on Earth. (Such an increase would have no measurable effect on the Earth's energy balance.) After 100 years, how many times more "improved and less probable" would each individual organism be? (That is, what is the ratio Ω_i/Ω_f?) (Answer: $10^{4.17 \times 10^{12}}$ times.)

2. *Cambrian explosion.* It is generally agreed that the greatest rate of evolution ever witnessed by Earth occurred during the Cambrian period, from 542 million years ago to 488 million years ago. During this "Cambrian explosion" multicellular organisms diversified into remarkable variety.[17] Suppose that during the Cambrian period the biosphere's entropy decreased due to evolution at the rate calculated in Eq. (5). And suppose that at the end of the Cambrian there were 10^{18} multicellular individuals. How much "improved and less probable" would each organism be, relative to its (possibly single-celled) ancestor at the beginning of the Cambrian period? (Answer: $10^{1.80 \times 10^{22}}$ times.)

3. *The probability of life.* The famous bacterium *Escherichia coli* contains a strand of DNA consisting of 4 639 221 base pairs,[18] each of which can be in any of four states (denoted A, C, G, or T).

(a) How many DNA configurations are possible in a strand of this length? (Answer: $4^{4\,639\,221} \approx 10^{2\,790\,000}$).

Some of these configurations correspond to living bacteria, but most do not. To estimate the number of configurations corresponding to living things, note that there are at least 12992 known strains[19] of *E. coli* and about 10^9 bacterial species,[20] each with a strand of DNA about the size of the strand in *E. coli*. Adopt the estimate that only 10^{13} of the configurations counted in part (a) correspond to living things.

(b)   Calculate the ratio of total configurations to living configurations, and compare to the results of problems 1 and 2. (Answer: The ratio is $10^{2\,790\,000}$, which is a large number in most contexts but minute compared to ratios like $10^{4.17\times10^{12}}$ or $10^{1.80\times10^{22}}$.)

4. *Rejoinder.* A creationist confronted with the estimates in this article might respond by saying "an open system and an adequate outside source of energy are necessary *but not sufficient* conditions for the complexity, structure, and organization of a system to increase."[21] How would you reply? (First possible answer: The second law of thermodynamics *permits* but does not *require* evolution. For example, the second law of thermodynamics holds on the Moon, yet biological evolution doesn't occur there. Second possible answer: This article establishes that evolution is *consistent* with the second law of thermodynamics. Whether or not biological evolution *actually happens* is a different question, which has been investigated thoroughly.[22–24] In exactly the same way it is consistent with the second law of thermodynamics for my salary to exceed $1000 annually, and for it to exceed $1 000 000 annually. Whether or not either salary actually happens is a different question.)

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[1] Henry M. Morris, *Scientific Creationism* (Master Books, Green Forest, AR, 1974).

[2] Harun Yahya, *The Evolution Deceit: The Scientific Collapse of Darwinism and its Ideological Background* (Ta-Ha, London, 2001).

[3] Daniel F. Styer, "Insight into entropy," Am. J. Phys. **68**, 1090–1096 (2000).

[4] Frank L. Lambert, "Disorder—A cracked crutch for supporting entropy discussions," J. Chem. Educ. **79**, 187–192 (2002); "Configurational entropy revisited," *ibid.* **84**, 1548–1550 (2007).

[5] Thomas A. Moore and Daniel V. Schroeder, "A different approach to introducing statistical mechanics," Am. J. Phys. **65**, 26–36 (1997); Brian B. Laird, "Entropy, disorder and freezing," J. Chem. Educ. **76**, 1388–1390 (1999).

[6] John W. Patterson, "Thermodynamics and evolution," in *Scientists Confront Creationism*, edited by Laurie R. Godfrey (W. W. Norton, New York, 1983), pp. 99–116.

[7] Stephen Jay Gould, *Full House: The Spread of Excellence from Plato to Darwin* (Harmony Books, New York, 1996), especially pp. 135–136; David C. Culver, Thomas C. Kane, and Daniel W. Fong, *Adaptation and Natural Selection in Caves* (Harvard U.P., Cambridge, MA, 1995).

[8] Other creationist misconceptions concerning entropy are even more distressing. For example, in a public address titled "Why evolution fails" (Oberlin College, Oberlin, Ohio, 14 November 2007), Professor John Sanford referred to entropy as a type of force, despite the fact that entropy is a scalar measured in joules/kelvin and force is a vector measured in newtons.

[9] Thermodynamics, most often applied to fluids, crystals, and magnets, also applies to radiation in thermal equilibrium. An excellent treatment is by Robert E. Kelly, "Thermodynamics of blackbody radiation," Am. J. Phys. **49**, 714–719 (1981).

[10] The calculations in this article, like all calculations, are not exact. In the words of one great scientist, "As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality." (Albert Einstein, *Geometry and Experience*, address to the Prussian Academy of Sciences, Berlin, 27 January 1921, Methuen & Co., London, 1922.) For example, these calculations neglect temperature variation over the Earth's surface. Improved calculations such as those of D. M. O'Brien, "A yardstick for global entropy-flux," Q. J. R. Meteorol. Soc. **123**, 243–260 (1997), take additional details into account and show that the numbers generated in this article are accurate enough to prove their point.

[11] Charles F. Yoder, "Astrometric and geodetic properties of Earth and the Solar System," in *Global Earth Physics: A Handbook of Physical Constants*, edited by Thomas J. Ahrens (American Geophysical Union, Washington, DC, 1995), Table 19.

[12] David R. Williams, NASA Goddard Space Flight Center, "Earth fact sheet," 19 April 2007, ⟨nssdc.gsfc.nasa.gov/planetary/factsheet/earthfact.html⟩.

[13] D. J. Fixsen, E. S. Cheng, J. M. Gales, J. C. Mather, R. A. Shafer, and E. L. Wright, "The cosmic microwave background spectrum from the full COBE FIRAS data set," Astrophys. J. **473**, 576–587 (1996).

[14] The solar energy incident on the Earth each second is $(1.732\pm0.005)\times10^{17}$ J: Dietrich Labs and Heinz Neckel, "The solar constant," Solar Physics **19**, 3–15 (1971). However, the average terrestrial albedo is 0.297 ± 0.005: 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).

[15] Nigel E. Stork, "Measuring global biodiversity and its decline," in *Biodiversity II: Understanding and Protecting our Biological Resources*, edited by Marjorie L. Reaka-Kudla, Don E. Wilson, and Edward O. Wilson (Joseph Henry, Washington, DC, 1997), pp. 27–40. A eukaryote is an organism whose cells contain nuclei. Mammals, insects, plants, fungi, and amoebae are all eukaryotes.

[16] William B. Whitman, David C. Coleman, and William J. Wiebe, "Prokaryotes: The unseen majority," Proc. Natl. Acad. Sci. U.S.A. **95**, 6578–6583 (1998). A prokaryote is an organism whose cells lack nuclei. Bacteria are prokaryotes.

[17] Stephen Jay Gould, *Wonderful Life: The Burgess Shale and the Nature of History* (W. W. Norton, New York, 1989).

[18] Frederick R. Blattner *et al.*, "The complete genome sequence of *Escherichia coli* K-12," Science **277**, 1453–1462 (1997).

[19] This is the number of strains listed on 21 December 2007 in the National BioResource Project, ⟨www.shigen.nig.ac.jp/ecoli/strain/top/top.jsp⟩.

[20] H.-J. Bach, J. Tomanova, M. Schloter, and J. C. Munch, "Enumeration of total bacteria and bacteria with genes for proteolytic activity in pure cultures and in environmental samples by quantitative PCR mediated amplification," J. Microbiol. Methods **49**(5), 235–245 (2002).

[21] Duane T. Gish, *Creation Scientists Answer their Critics* (Institute for Creation Research, El Cajon, CA, 1993), p. 175.

[22] Bruce Wallace, *Chromosomes, Giant Molecules, and Evolution* (Norton, New York, 1966).

[23] Ernst Mayr, *What Evolution Is* (Basic Books, New York, 2001).

[24] Douglas J. Futuyma, *Evolution* (Sinauer Associates, Sunderland, MA, 2005).