Critical Focus

Entropy and Evolution

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Abstract

It is widely argued that the spectacular local decreases in entropy that occurred on Earth as a result of the origin and evolution of life and the development of human intelligence are not inconsistent with the second law of thermodynamics, because the Earth is an open system and entropy can decrease in an open system, provided the decrease is compensated by entropy increases outside the system. I refer to this as the *compensation argument*, and I argue that it is without logical merit, amounting to little more than an attempt to avoid the extraordinary probabilistic difficulties posed by the assertion that life has originated and evolved by spontaneous processes. To claim that what has happened on Earth does not violate the fundamental natural principle behind the second law, one must instead make a more direct and difficult argument.

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INTRODUCTION

There is a long-standing debate over the apparent tension between the second law of thermodynamics, which restricts the circumstances under which order can increase spontaneously, and the origin and evolution of life, a process that seems to have involved a considerable increase in order. In very simple terms, the argument against spontaneous evolution is that the highly special arrangements of matter that constitute living things seem inexplicable as products of spontaneous processes, in view of the fact that, according to the second law, such processes always result in a loss of order.

Isaac Asimov, for example, recognizes the apparent problem:

> You can argue, of course, that the phenomenon of life may be an exception [to the second law]. Life on earth has steadily grown more complex, more versatile, more elaborate, more orderly, over the billions of years of the planet's existence. From no life at all, living molecules were developed, then living cells, then living conglomerates of cells, worms, vertebrates, mammals, finally Man. And in Man is a three-pound brain which, as far as we know, is the most complex and orderly arrangement of matter in the universe. How could the human brain develop out of the primeval slime? How could that vast increase in order (and therefore that vast decrease in entropy) have taken place? [1]

The popular response to this argument makes use of the fact that the common statements of the second law refer to systems that are *isolated* (i.e., not interacting in any way with anything outside the system). Consider, for example, three common statements of the second law from the textbook *Classical and Modern Physics* [2: p. 618]:

1. In an isolated system, thermal entropy cannot decrease.
2. In an isolated system, the direction of spontaneous change is from order to disorder.
3. In an isolated system, the direction of spontaneous change is from an arrangement of lesser probability to an arrangement of greater probability.

Statement 1 clearly has little relevance for evolution, and even the more general statements 2 and 3 also refer to isolated systems, so when the second law is described in these terms, one might be tempted to think that it has no bearing on open systems. And since the Earth is clearly an open system, receiving energy from the sun, that line of reasoning seems to provide a convenient response to the argument against spontaneous evolution.

Specifically, the defense of spontaneous evolution takes the form of what I refer to as the *compensation argument*, which posits that even spectacular reductions in local entropy (increases in order) are consistent with the second law if there are compensating entropy increases (decreases in order) elsewhere. (Although it has a more specific meaning in statement

1 above, "entropy" is most often used simply as a synonym for disorder). For example, Peter Urone makes a statement in *College Physics* [3], which is repeated in some form in many other general physics texts:

> Some people misuse the second law of thermodynamics, stated in terms of entropy, to say that the existence and evolution of life violate the law and thus require divine intervention.... It is true that the evolution of life from inert matter to its present forms represents a large decrease in entropy for living systems. But it is *always* possible for the entropy of one part of the universe to decrease, provided the total change in entropy of the universe increases.

Asimov uses this compensation argument in his above-quoted *Smithsonian* article:

> Remove the sun, and the human brain would not have developed.... And in the billions of years that it took for the human brain to develop, the increase in entropy that took place in the sun was far greater; far, far greater than the decrease that is represented by the evolution required to develop the human brain. [1]

Richard Dawkins [4] writes:

> When creationists say, as they frequently do, that the theory of evolution contradicts the Second Law of Thermodynamics, they are telling us no more than that they don't understand the Second Law... There is no contradiction, because of the sun!

Much of the confusion in applying the second law to evolution, and to other situations where entropy is difficult to define and quantify, comes from the idea that "entropy" is a single quantity which measures (in units of thermal entropy) disorder of all types. The *American Journal of Physics* papers by Daniel Styer [5] and Emory Bunn [6] illustrate the confusion that results from thinking of entropy as a single quantity when applying the second law to evolution, so let's look at these papers.

Styer estimated the rate of decrease in entropy associated with biological evolution as less than 302 Joules/degree Kelvin/second, noted that this rate is very small, and concluded, "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" [5]. To arrive at this estimate, Styer assumed that "each individual organism is 1000 times more improbable than the corresponding individual was 100 years ago," which, according to Styer, is a "very generous" assumption. He then used the Boltzmann formula to calculate that a 1000-fold decrease in probability corresponds to an entropy decrease of $k_B \times \log(1000)$, multiplied this by a generous overestimate for the number of organisms on Earth, and divided by the number of seconds in a century.

Bunn [6] later concluded that Styer's factor of 1000 was not really generous, that in fact organisms should be considered to be, on average, about 10^{25} times more improbable each century, but went on to show that, still, "the second law of thermodynamics is safe."

In full agreement with this, Bob Lloyd wrote in his *Mathematical Intelligencer* Viewpoint article [7]: "[A]lthough there is a local decrease in entropy associated with the appearance and evolution of life on Earth, this is very small in comparison with the very large entropy increase associated with the solar input to Earth. This qualitative idea has received quantitative backing from the calculations of Styer, and particularly as modified by Bunn, which show that the solar contribution is many orders of magnitude larger than any possible decrease associated with evolution."

But not everyone finds this line of argument convincing. Andy McIntosh offers this critique of the Styer [5] and Bunn [6] papers in a recent article [8]:

> Both Styer and Bunn calculate by slightly different routes a statistical upper bound on the total entropy reduction necessary to 'achieve' life on earth. This is then compared to the total entropy received by the Earth for a given period of time. However, all these authors are making the same assumption—viz. that all one needs is sufficient energy flow into a [non-isolated] system and this will be the means of increasing the probability of life developing in complexity and new machinery evolving. But as stated earlier this begs the question of *how* a local system can possibly reduce the entropy without existing machinery to do this.

Indeed, the compensation argument is predicated on the idea that there is no content to the second law *apart* from a prohibition of net entropy decreases in isolated systems, and moreover that the universal currency for entropy is *thermal* entropy. According to Styer, the Boltzmann formula, which relates the thermal entropy of an ideal gas state to the number of possible microstates, and thus to the probability of the state, can be used to compute the change in thermal entropy associated with any change in probability: not just the probability of an ideal gas state, but the probability of *anything*. This seems very much like finding a Texas State Lottery sheet that lists the probabilities of winning each monetary award and concluding that we now know how to convert the probability of *anything* into its dollar equivalent.

Extending my earlier arguments in [9] and [10: Appendix D], I argue here that there is actually more content to the second law of thermodynamics than proponents of the compensation argument are acknowledging, and that a fuller understanding of this law does indeed challenge the idea of spontaneous evolution.

FOUR TEST SCENARIOS

In order to clarify the connection between entropy, order and plausibility, let us consider four scenarios.

A. In an isolated steel object, the temperature distribution is initially non-uniform, and becomes more uniform with time, until the temperature is constant throughout. **Then**, the temperature distribution starts to become non-uniform again.

B. In an isolated steel object, the chromium distribution is initially non-uniform, and becomes more uniform with time, until the chromium concentration is constant throughout. **Then**, the chromium distribution starts to become non-uniform again. (In this scenario, you can replace chromium by anything else that diffuses, of course, and we are assuming nothing is going on but diffusion.)

C. A tornado hits a town, turning houses and cars into rubble. **Then**, another tornado hits, and turns the rubble back into houses and cars.

D. The atoms on a barren planet spontaneously rearrange themselves, with the help of solar energy and under the direction of four unintelligent forces of physics alone, into humans, cars, high-speed computers, libraries full of science texts and encyclopedias, TV sets, airplanes and spaceships. **Then**, the sun explodes into a supernova, and, with the help of solar energy, all of these things turn back into dust.

In scenarios A and B, everyone agrees that the second law is being obeyed during the first stage, and violated during the last stage. In the case of scenario A, "thermal entropy" can be defined in a precise, quantitative manner, and it can be shown that thermal entropy is increasing during the first stage, and decreasing during the last stage. In scenario B, the "chromium entropy" can be defined in a similar and equally precise manner, and the same equations that are used to show that thermal entropy cannot decrease in an isolated system can be used to show that chromium entropy cannot decrease in an isolated system (see for example, [10: Appendix D]). But note that now "entropy" measures disorder in the chromium distribution, not the temperature distribution, and "entropy" does not even have the same units in the two scenarios. Thus we see that there are different kinds of entropy, even where entropy can be precisely, quantitatively defined.[1]

Scenarios A and B are both straightforward applications of statement 1 of the second law, as given in the Introduction, except that what is diffusing in scenario B is not heat. Statement 1 is one of the first formulations of the second law, and only later was it realized that the reason heat (or chromium, or anything else that diffuses) distributes itself more and more uniformly in an isolated system (causing the associated entropy to increase) is that uniformness is a more probable state in these simple scenarios. So statement 1 is essentially just one application of the later, more general, statements 2 and 3.

In the last two scenarios, entropy is difficult to define and measure, with the result that there is much more controversy and confusion in applying the second law. In scenario C, despite the difficulty in defining an associated entropy in a precise manner (and the entropy here has very little to do with either the temperature or the chromium distribution), most scientists would agree that the first tornado, which turns houses and cars into rubble, increases the "entropy" of the town, and what it does is consistent with the second law, while the second tornado, which turns rubble into houses and cars, decreases the entropy, and violates the second law, at least the more general statements 2 and 3. Although most general physics textbooks give examples of entropy increases that are difficult to quantify, such as wine glasses breaking or books burning, because it is more difficult to define an associated entropy precisely in scenario C, some scientists are reluctant to apply the second law to things like tornados. But although sometimes it is difficult to say what the second law predicts, sometimes it is easy, even if what is happening is difficult to quantify. If we saw a video of a tornado turning rubble into houses and cars, the difficulty in defining and measuring entropy would not prevent us from immediately realizing that the video must be running backward, because what we were seeing was completely implausible.

In scenario D, it is again very difficult to define an associated entropy precisely, but again most general physics texts that discuss the matter agree that entropy is decreasing during the first stage, when atoms are spontaneously rearranging themselves into computers and books and airplanes, but would increase during the second stage, when computers and books and airplanes are being turned back into dust. The common sense conclusion would be that the second law is being violated during the first stage of this scenario, and obeyed during the second stage. However, as noted, every general physics textbook that discusses evolution and the second law employs the compensation argument as a refutation of this common sense conclusion.

Notice that the compensation argument could just as well be applied to scenario C by saying that since tornados receive their energy from the sun, and the Earth is an open system, tornados turning rubble into houses and cars would not violate the second law. In fact, the compensation argument does not even require an open system: one could argue that the second law is not violated during the second stage of scenario B either, as long as the decrease in chromium entropy is compensated by an increase in some other form of entropy in the isolated steel object. In other words, the compensation argument can be used to justify scenarios that all scientists would recognize to be entropically implausible, and this means that it does a poor job of representing the actual content of the second law.

To see how flawed the compensation argument is, let's extend Styer's calculations (see Introduction) to the second tornado of scenario C. Let us "generously" estimate that a house is $10^{1,000,000,000}$ times more improbable than the corresponding pile of rubble, and use the Boltzmann formula to calculate that the decrease in entropy resulting from the construction of one house is about $k_B \times \log(10^{1,000,000,000}) = 1.38 \times 10^{-23} \times$

[1] "There are many thermodynamic entropies, corresponding to different degrees of experimental discrimination and different choices of parameters. For example, there will be an increase of entropy by mixing samples of ^{16}O and ^{18}O only if isotopes are experimentally distinguished." R. Carnap, T*wo Essays on Entropy* [11].

$10^9 \times \log(10) = 3.2 \times 10^{-14}$ Joules/degree Kelvin. If we make the generous assumption that 10,000 houses were turned into rubble by the first tornado, and back into houses by the second tornado, and that the second tornado took about five minutes to make its improvements, we calculate that this tornado caused the entropy of the universe to decrease at the rate of about $3.2 \times 10^{-14} \times 10{,}000 / 300 = 10^{-12}$ Joules/degree Kelvin/second, about 14 orders of magnitude less than the rate of decrease due to evolution, and about 26 orders of magnitude less than the "Earth's entropy throughput" rate given in Styer's Table 1. So by the logic of the compensation argument, the second law is safe even in scenario C, despite its obvious implausibility. It is not clear why entropy decreases associated with the construction of houses or cars should be measured in Joules/degree Kelvin (chromium entropy isn't), or how these entropy decreases could be compensated by thermal entropy increases in the cosmic microwave background, and of course our probability estimates are just wild guesses,[2] but we could raise all of the same objections to Styer's application of the Boltzmann formula to evolution.

Since about five million centuries have passed since the beginning of the Cambrian era, if organisms are, on average, a thousand times more improbable every century, that would mean that today's organisms are, on average, about $10^{15,000,000}$ times more improbable ($10^{125,000,000}$ times, if we use Bunn's estimate) than those at the beginning of the Cambrian. But, according to Styer, there is no conflict with the second law because the Earth is an open system, and entropy increases outside the Earth compensate the entropy decrease due to evolution. In other words, using Styer's understanding of entropy, the fact that evolution is astronomically improbable is not a problem as long as something (*anything*, apparently) is happening elsewhere which, if reversed, would be even more improbable.

EXTENDING THE SECOND LAW TO OPEN SYSTEMS

Although all current statements of the second law apply only to isolated systems, the principle underlying the second law can actually be stated in a way that applies to open systems. In Appendix D of my 2005 book *The Numerical Solution of Ordinary and Partial Differential Equations* [10], and earlier in [9], and more recently in an *Applied Mathematics Letters* article,[3] I showed that in scenario A, if the object is no longer isolated, then the thermal entropy can decrease, but no faster than it is exported. Stated another way, the thermal order (defined as the negative of thermal entropy) can increase, but no faster than it is imported. And in scenario B, if the object is not isolated, the "chromium order" can increase, but no faster than chromium order is imported. Thus statement 1 of the second law can be generalized to:

> 1b. In an open system, thermal order (or "X-order," where X is any diffusing component) cannot increase faster than it is imported through the boundary.[4]

Just as statement 1 is one application of the more general statement 2, statement 1b is one application of the following tautology ([9] and [10]), which generalizes statement 2 to open systems:

> 2b. If an increase in order is extremely improbable when a system is isolated, it is still extremely improbable when the system is open, unless something is entering (or leaving), which makes it *not* extremely improbable.

Applying this tautology to the less quantifiable scenarios C and D, we conclude that the fact that order can increase in an open system does not mean that tornados can turn rubble into houses and cars without violating the second law. And it does not mean that computers can appear on a barren planet as long as the planet receives solar energy. Something must be entering from outside which makes the appearance of computers *not* extremely improbable, for example, computers.

Bob Lloyd's primary criticism [7] of my approach was that my "X-entropies" (e.g., "chromium entropy") are not always independent of each other. He showed that in certain experiments in liquids, thermal entropy changes can cause changes in the other X-entropies. Therefore, he concluded, "the separation of total entropy into different entropies ... is invalid." He wrote that the idea that my X-entropies are always independent of each other was "central to all of the versions of his argument." Actually, I never claimed that: in scenarios A and B, using the standard models for diffusion and heat conduction, and assuming nothing else is going on, the thermal and chromium entropies *are* independent, and then statement 1b nicely illustrates the general statement 2b (though I'm not sure a tautology needs illustrating). But even in solids, the different X-entropies can affect each other under more general assumptions. Simple definitions of entropy are only useful in simple contexts. But my basic arguments in [9] and [10] and in my *Applied Mathematics Letters* paper do not depend on any definition of entropy, as seen in the next section.

THE FUNDAMENTAL PRINCIPLE BEHIND THE SECOND LAW

Statements 2 and 2b of the second law are more general than statements 1 and 1b, but often difficult to apply, because "order" (or "entropy") can mean different things in different contexts, and it may be very hard to define an associated order or entropy in others. It is especially confusing if you insist on

[2] To say that a house is N times more improbable than the corresponding pile of rubble presumably means there are N times as many "rubble" microstates as "house" microstates, but it is not clear how one could count these microstates.

[3] "A Second Look at the Second Law" (http://www.math.utep.edu/Faculty/sewell/AML_3497.pdf) was accepted by *Applied Mathematics Letters* in 2011, then withdrawn by the editor at the last minute, "not because of any errors or technical problems found by the reviewers or editors, but because the Editor-in-Chief subsequently concluded that the content was more philosophical than mathematical," according to the apology [12] that was later published in this journal.

[4] Here, as before, we are assuming nothing is going on but diffusion or heat conduction (diffusion of heat).

thinking of "entropy" as a single number that measures all types of disorder, as Urone, Asimov, Styer, and Lloyd do above.

Statement 3 is much clearer and easier to apply: "In an isolated system, the direction of spontaneous change is from an arrangement of lesser probability to an arrangement of greater probability." A highly non-uniform arrangement of chromium atoms is a less probable state than a uniform arrangement, so diffusion produces a more uniform chromium distribution. The reason that natural forces can turn a computer into scrap metal in an isolated system, but not vice-versa, is that of all the arrangements that atoms could take, only an extremely small percentage would be able to do mathematical computations. Rust, fire, tornados, crashes and supernovae can destroy airplanes, but not create them, because of all the arrangements atoms could take, only an extremely small percentage would be capable of long-distance air travel. A computer or an airplane obviously represents an arrangement of lesser probability than a pile of scrap metal, even if it is difficult to define an associated entropy to measure the probabilities involved. But the laws of probability do *not* apply only to isolated systems, so statement 3 can also be generalized to open systems:

> 3b. Natural (unintelligent) forces do not do macroscopically describable things that are extremely improbable from the microscopic point of view.

In an open system you just have to take into account what is entering (and leaving) the system when deciding what is extremely improbable and what is not. When thermal entropy decreases in an open system, there is not anything macroscopically describable happening that is extremely improbable from the microscopic point of view; rather, something is crossing the boundary that makes the decrease not extremely improbable.

Of course we have to define "extremely improbable" events using a very low probability threshold. If we repeat an experiment 2^k times, and define an event to be "simply describable" (macroscopically describable) if it can be described in m or fewer bits (so that there are 2^m or fewer such events), and "extremely improbable" when it has probability $1/2^n$ or less, then the probability that any extremely improbable, simply describable event will ever occur is less than $2^{k+m}/2^n$. Thus we see that it is possible to define "extremely improbable" events using a threshold probability so low ($n >> k + m$) that we can safely assume that *no* extremely improbable, macroscopically describable event will *ever* occur. If we flip a billion fair coins, any outcome we get can be said to be extremely improbable, but we only have cause for astonishment if something extremely improbable and simply describable happens, such as "all heads" or "every third coin is tails." Note the similarity between (3b) and William Dembski's argument [13] that unintelligent forces do not do things that are "specified" (simply or macroscopically describable) and "complex" (extremely improbable).

This basic principle is the *only* thing the four applications in the second section, and all other applications of the second law, have in common. The second law is all about using probability at the microscopic level to predict macroscopic change. The confusion in applying it to less quantifiable applications such as evolution is the result of trying to base it on something else, such as "entropy cannot decrease," when entropy may be difficult or impossible to define.

This statement of the second law, or at least of the fundamental principle behind the second law, is the one that should be applied to evolution. Those wanting to claim that the basic principle behind the second law is not violated in scenario D need to argue that, under the right conditions, macroscopically describable things such as the spontaneous rearrangement of atoms into machines capable of mathematical computations, or of long-distance air travel, or of receiving pictures and sounds transmitted from the other side of the planet, or of interplanetary space travel, are not really astronomically improbable from the microscopic point of view, thanks to the influx of solar energy and to natural selection or whatever theory they use to explain the evolution of life and of human intelligence. And those wanting to claim that the second law is not violated in scenario C cannot argue that what the second tornado does is compensated by entropy increases outside the Earth; they likewise must argue that, under the right conditions, tornados turning rubble into houses and cars are not really astronomically improbable, thanks to the influx of solar energy that causes tornados, and to whatever theory they may have to explain constructive tornados.

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