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Article

Bumps on the Road to Here (from Eternity)

Eric Winsberg

Department of Philosophy, The University of South Florida, 4202 E. Fowler Avenue, FAO226, Tampa, FL 33620, USA; E-Mail: eric.winsberg@gmail.com

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Abstract: In his recent book, *From Eternity to Here*, and in other more technical papers, Sean Carroll (partly in collaboration with Jennifer Chen) has put forward an intriguing new way to think about the origin of the Universe. His approach, in a nutshell, is to raise certain worries about a standard Boltzmannian picture of statistical mechanics, and to present certain commitments that he thinks we ought to hold—commitments that the standard picture doesn't share. He then proposes a cosmological model—one that purports to give us insight into what sort of process brought about the "initial state" of the universe—that can uniquely accommodate those commitments. The conclusion of Carroll's argument is that statistical mechanical reasoning provides grounds for provisionally accepting that cosmological model. My goal in this paper is to reconstruct and critically assess this proposal. I argue that "statistical cosmology" requires a careful balance of philosophical intuitions and commitments against technical, scientific considerations; how much stock we ought to place in these intuitions and commitments should depend on where they lead us—those that lead us astray scientifically might well be in need of philosophical re-examination.

Keywords: time; statistical mechanics; cosmology; Boltzmann; entropy; reversibility

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1. Introduction

Can statistical-mechanical reasoning—reasoning about the origin of the thermodynamic arrow of time—help us to learn about the origin of the Universe? How could it do so? Here is one way that some think that it could: Statistical mechanics—at least in its Bolzmannian varieties—involves assigning measures of probability to regions of the space of the possible microstates of the Universe. On some versions of this assignment, Boltzmannian reasoning can lead us to conclude that the initial macrostate of the Universe was extremely improbable. And so perhaps, the would-be Boltzmannian cosmologist reasons, by finding an explanation for why the Universe began in such an ostensibly low-probability state—an explanation that satisfies various constraints—we might find some clues about what sort of process brought about the "initial state" of the Universe. In short, statistical-mechanical reasoning might help us to make some useful inferences about what occurred prior to the big bang.

In his recent book, *From Eternity to Here* [1], and in other more technical papers ([2,3] and also a popular exposition in [4]), Sean Carroll (partly in collaboration with Jennifer Chen) has put forward an intriguing new way to advance this program. His approach, in a nutshell, is to raise certain worries about a standard Boltzmannian picture of statistical mechanics, and to present certain commitments that he thinks we ought to hold—commitments that the standard picture doesn't share. He then proposes a cosmological model—one that purports to give us insight into what sort of process brought about the "initial state" of the Universe—that can uniquely accommodate those commitments. The conclusion of Carroll's argument is that statistical mechanical reasoning provides grounds for provisionally accepting that cosmological model. My goal in this paper is to reconstruct and critically assess this proposal. I worry, in the end, that Carroll creates more problems than he solves. More generally, I argue that "statistical cosmology" requires a careful balance of philosophical intuitions and commitments against technical, scientific considerations; how much stock we ought to place in these intuitions and commitments should depend on where they lead us—those that lead us astray scientifically might well be in need of philosophical re-examination.

2. The Boltzmannian Picture

To understand how statistical mechanical cosmology is supposed to work, it will be helpful to have an overview of the Boltzmannian picture—one that makes perspicuous the worries that motivate a program like Carroll's. The Boltzmannian approach to statistical-mechanical foundations can be divided into two main components: a state space and dynamics for the Universe; and a specification—partly statistical—of where in that dynamical space the Universe actually lives.

2.1. The Dynamics

The picture of the dynamics of the Universe that the Boltzmannian offers is rather abstract. It does not, in other words, actually specify a dynamics for the Universe. Rather, it seeks to characterize that dynamics in terms of certain qualitative features. These include at least the following three:

1. A state space that represents the possible states that the Universe can be in.
2. A deterministic dynamics that determines how the Universe's state evolves—that determines, in other words, how a point in that state space moves around over time.
3. Time reversibility: (a) the dynamics not only tells us how the system evolves forward in time, but also how it evolves backwards in time; (b) the state space, moreover, has a natural-looking time-reversal operator [5], such that if the dynamics takes the Universe from point a to point b after time t, then it also takes the time-reverse of the point b to the time-reverse of the point a in the same amount of time.

Finally, the Boltzmannian of the kind we envision in this paper will assume that, whatever other characteristics the dynamics has, it must be "friendly" to statistical mechanical reasoning. Being "friendly" is a somewhat loose notion, but it presumably entails at least a few things. In order to describe this feature of the dynamics more carefully, we need to assume that the state space mentioned above is partitioned into a set of *macrostates*—a set of mutually disjoint subsets of the entire space. The idea, in particular, of the partition being into *macrostates* is that we partition the space in such a way that by knowing what macrostate a system is in, we know some physically relevant information about the system, but only in a relatively coarse-grained way. Intuitively, to know that a system is in some particular macrostate is to know how macroscopic physics would characterize it *vis a vis* a small number of macroscopic variables, such as temperature, density, pressure, magnetization, composition, *etc.*

So, once we have available a macropartition, what does it mean for the dynamics to be "friendly"? Minimally, it entails that systems will have an equilibrium macrostate (generally one that is very large relative to the entire accessible volume of the space), and that almost all of the points in the state space will be lead by the dynamics, after a sufficient period of time, into the equilibrium state. More generally, it also entails that given a macrostate with a relatively small volume, the dynamics will take most of the points in that macrostate into successively larger macrostates. Most stringently, being friendly entails that if M_1 and M_2 are two macrostates of any system—whether that system is the entire dynamical system in question [6] or some energetically isolated subsystem—and it is an observable law of macroscopic physics that systems of type M_1 tend to evolve into systems of type M_2, then it will necessarily be a feature of the microdynamics that it takes the overwhelming majority of the points compatible with M_1 towards points compatible with M_2, and it will do it in about the amount of time that macroscopic physics says that it will take for the above to happen [7].

2.2. Probability and Reversibility

Let us call everything we have assumed so far the *Boltzmannian dynamical picture*. The dynamical picture tells us everything we need to know about the different ways the Universe could possibly behave. If we want our picture to be capable of making predictions, on the other hand, we need to say something about where, in the space of possibility that the dynamic picture provides, our own Universe actually lives. But we have only described the dynamics qualitatively. And even if we had an exact dynamics for the Universe, it would be impractical to specify the initial state exactly as well. So, what we do is describe where, in the space of possibility, our Universe lives by establishing a connection between volumes in the statespace and probability. Instead of saying where exactly it lives, we try to say where it is *likely* to live. This is where many of the puzzles arise.

The ordinary Lebesgue measure provides us with a natural notion of volume in the state space. What we would like to do is to connect up that natural notion of volume with a measure of probability. But as we will see, there are a variety of ways we could try to do this. And some of them lead to problems. Perhaps the most obvious way to do it is to directly identify *relative volumes* with *conditional probabilities*—anywhere and everywhere. So, e.g., if a system is in some macrostate, then the probability that the system is in some subregion of that macrostate (conditional on it being in the macrostate itself) would be equal to the volume of the subregion relative to the volume of the macrostate. Then, if the dynamics is "friendly" in the most stringent sense above, and all we know about a system is that it is in a macrostate M_1, it will be very likely to evolve into a macrostate M_2 whenever a macroscopic law of physics says that macrostates of type M_1 evolve into macrostates of type M_2.

The problem, famously, with this intuitive idea is reversibility. If, as we supposed above was the case, the dynamical laws are time reversible, then the identification of volume with probability that we proposed in the last paragraph will lead to all the right predictions about the future, but all the wrong retrodictions about the past. In fact, of course, it will make exactly the same macroscopic predictions about the past as it will about the future. But now we have lost the thermodynamic arrow of time. So this is no good.

The identification of volume with probability will have to take a different form. For our purposes here, it is worth examining two different proposals—both of which can originally be attributed, in some form or other, to Boltzmann. Above we assumed that volume was a guide to conditional probability anywhere and everywhere. This helped make the right predictions, but was subject to reversibility objections. Boltzmann realized that this assumption could not lead to bad retrodictions if it only applied at the very beginning of time. So let us suppose that volumes in state space are proportional to probabilities *for the initial state of the Universe*. That is, given any region of state space, the probability that the universe began in that region is equal to its normalized volume.

On its own, this assumption is clearly problematic. It is problematic because it makes it overwhelmingly likely that the Universe began in a maximum-entropy state. And this at least *seems* to be contradicted by observation. The universe looks to be in a medium entropy state, and it looks like its overall entropy is always steadily increasing.

Boltzmann realized that he had to deal with this problem. In the very same paper [8], Boltzmann proposed two distinct ways to do just that.

Proposal 1: add what Boltzmann called "Assumption A", which is now well known in the literature as the "Past Hypothesis". This is the hypothesis that the universe started in a very low-entropy state.

> The second law will be explained mechanically by means of assumption A (which is of course unprovable) that the Universe, considered as a mechanical system—or at least a very large part of it which surrounds us—started from a very improbable state, and is still in an improbable state… Hence, it turns out that entropy always increases, temperature and concentration differences are always equalized [9].

Once "Assumption A" is made about the original macrostate of the Universe, the identification of probability (with regard to the initial state of the Universe) with volume needs to be modified, lest it contradict assumption A. Boltzmann is not entirely clear about this, but the standard view is to suppose that it takes the following form: whatever low-entropy state the Universe did begin in, the probability that it began in some subregion of that state is proportional to the subregion's volume. Let us call this the low-entropy probabilistic postulate (LEPP). It is the combination of these two suggestions, the Past Hypothesis ("Assumption A"), and the LEPP, that form the basis of what I take to be the standard contemporary approach to statistical mechanics. It is, in any case, the approach championed by David Albert in his highly influential *Time and Chance* [10] and it is the one Carroll has in mind as he raises his worries.

Proposal 2: Boltzmann's second suggestion was to embrace the consequences of the hypothesis that volumes in state space are proportional to probabilities for the initial state of the Universe—that the Universe *began in thermodynamic equilibrium*—despite the seeming observational evidence to the contrary.

But how could he reconcile the idea that the Universe began in thermodynamic equilibrium with what we see in front of our eyes, and with our belief, enshrined in the second law, that entropy is always increasing? How could entropy always have been increasing if the Universe began in the highest entropy state? Especially given that the Universe now looks to be in a medium entropy state? Boltzmann himself is worth quoting at length here:

> There must then be in the Universe, which is in thermal equilibrium as a whole and therefore dead, here and there relatively small regions of the size of our galaxy (which we call worlds), which during the relatively short time of eons deviate significantly from the thermal equilibrium. Among these worlds the state probability [entropy] increases as often as it decreases. For the Universe as a whole the two directions of time are indistinguishable, just as in space there is no up or down. However, just as at a certain place on the Earth's surface we can call "down" the direction toward the center of the Earth, so a living being that finds itself in such a world at a certain period of time can define the time direction as going from less probable to more probable states…and by virtue of this definition he will find that this small region, isolated from the rest of the universe, is "initially" always in an improbable state [11].

In Proposal 2, in other words, Boltzmann is suggesting that the Universe really is in thermal equilibrium and that *globally*, there really is no direction of time. Occasionally, however, local regions of the Universe will undergo fluctuations away from equilibrium. During these fluctuations, entropy will locally decrease for a while, and then turn around and increase. Since we are living beings (who cannot live in a bath of thermal equilibrium), we obviously inhabit one of these fluctuated regions during one of these periods. Whichever side of that see-saw that we live on, we will call the direction from lower to higher entropy "moving forward in time" and the other direction "going backwards in time".

3. Boltzmann Brains

The problem with this scenario, famously, is that it leads to a skeptical paradox. The underlying problem is that in a Universe fluctuating around equilibrium, large fluctuations into *extremely low entropy states* are much more rare and unlikely than small fluctuations into *less extreme states*. So no *medium entropy state* can ever be evidence of a previous, *lower entropy state*. But using medium entropy states as evidence of lower entropy states is what we do all the time when we make ordinary macroscopic inferences about what the past was like.

Suppose, for example, I see a glass of water with some partially melted ice cubes in it. If I have followed Proposal 2, then it becomes much more likely that this state represents the farthest from equilibrium the glass has ever been, than it does that the glass used to contain intact ice cubes in it. A fluctuation out of equilibrium into half-melted ice is much more likely than a fluctuation into unmelted ice followed by some melting. More troublingly, perhaps, if I see a picture of Napoleon, it is much more likely that this picture is a fluctuation out of equilibrium than it is that it is a genuine record of the history of France. Under the assumptions of Proposal 2, in fact, nothing I see will ever be normal evidence of any past history. It is much more likely, after all, that the universe fluctuated into a state that includes a room that looks just like mine does (complete with light waves hitting my eyes that look like they bounced off a city outside my window)—but which is actually surrounded by thermal chaos—then that it fluctuated into a world out there with roads and trees. And it is much more likely that the book on my desk, *The History of the Decline and Fall of the Roman Empire* [12], is a spontaneous fluctuation than it is that there was actually a Roman Empire. Indeed, no matter what I think I see, it is most likely not a genuine perception, but overwhelmingly more likely that it is a spontaneous fluctuation of my brain into a state that accidentally simulates a perceptual state or memory.

And so it becomes overwhelmingly likely that any apparent "records" I have are nothing but spontaneous fluctuations, and hence are not veridical. If we figure, moreover, that the only thing we are ever directly aware of are our own mental states, then the assumption that we are in a universe undergoing fluctuations around equilibrium leads to the conclusion that it is overwhelmingly likely that we are nothing but disembodied brains surrounded by a thermal equilibrium, whose memories and perceptions are not veridical: they are nothing but spontaneous fluctuations out of chaos.

Such entities—these disembodied brains with spontaneously generated "memories" of past events and "records" of a Universe with a real history—have been called "*Boltzmann Brains*" (See, for example [1,2,13,14]) after the author of the scenario that gives rise to them.

4. Two Problems with the Past Hypothesis

We will return to Boltzmann Brains later, because they have implications beyond that of refuting Boltzmann's Proposal 2. But for now, let us return to Boltzmann's Proposal 1, the one involving "Assumption A": the "Past Hypothesis". Let us start calling Proposal 1 the standard proposal, since I think it has that status at least in philosophical circles. Recall that this proposal involves making two basic assumptions (over and above what I called the Boltzmannian dynamical picture.) The first is the Past Hypothesis, according to which the Universe began in a suitable low entropy macrostate. The second is the low-entropy probabilistic postulate (LEPP), according to which the probability that the Universe began in some subregion of that macrostate is proportional to that subregion's volume.

Carroll has two problems with the standard proposal. The first problem that he has with it is that he thinks the Past Hypothesis, as a brute empirical conjecture, is unnatural. He argues that we should always assume that the Universe began in whatever state is "most probable", and that, by definition, this is the state with the highest possible entropy. But the Past Hypothesis says that the Universe began in a very low entropy state. So by Carroll's logic, to posit the Past Hypothesis is to conjecture something extremely unlikely without any explanation.

Notice, right off the bat, that this critique of the Past Hypothesis violates the Past Hypothesis' usual traveling companion, the LEPP. The reason is that on the standard proposal, the LEPP is the only measure of probability in town. Probabilities, on the standard proposal, are defined only conditional on the Past Hypothesis, and so talking about the probability of the Past Hypothesis itself is ill-defined. Of course, this defense of the standard proposal is somewhat question begging. Carroll is following a school of thought with a fairly long tradition which is committed to the principle that, regardless of what you postulate, the probability measure that is uniform on the whole state space is *a priori natural*, and that any initial state of the Universe that is unlikely on *that measure* requires explanation. A lot of ink has been spilled on the question of whether or not the initial state of the universe requires explanation [15–17]; I don't want to weigh in on that debate here. For now, I just want to note that Carroll rejects the Past Hypothesis on the above grounds. I want to see whether doing so leads us anywhere useful, from a cosmological perspective. If it does, then that alone might be good reason for siding with Carroll on this issue.

Carroll's second problem with the standard picture is that, in fact, it brings us right back to the "Boltzmann Brain" paradox. The reason that it does has to do with Poincaré's recurrence theorem, which tells us that certain kinds of systems (including the kinds of classical systems Boltzmann had in mind) will, after a sufficiently long time, return to a state arbitrarily close to any state that they have previously passed into. It follows that if I follow the standard proposal, that is, if I try to make predictions and retrodictions using a package consisting of only the Past Hypothesis, the LEPP, and the Boltzmannian dynamical picture, then it is overwhelmingly likely that the macrocondition I am presently "observing" is not the one that evolved directly out of the big bang, but is one of the infinitely many fluctuations out of equilibrium that will occur after the universe relaxes. This follows from the very same reasoning that we followed before: fluctuations out of equilibrium into Boltzmann Brain states (which contain brains that think they have records of a big bang) will happen much more often than fluctuations into actual big bangs.

And so it follows that, according to the standard proposal, it is overwhelmingly likely that I am a Boltzmann Brain, and no one will ever read this paper, which exists only in my mind. It is also, then, overwhelmingly likely that none of my records are veridical. More importantly, it is overwhelmingly likely that all the records (including memories) I have of the experiments that made me believe in modern physics in the first place are not veridical. And hence the standard proposal leads to a skepticism about its own components; it is epistemologically unstable. Let us call this state of affairs—the state of affairs where the set of assumptions we make about the universe lead us to conclude that it is very likely that we are BBs that have fluctuated out of the heat death of the Universe—a Poincare Boltzmann Brain (PBB) scenario.

This version of the problem, with its reliance on Poincare recurrence, is the classical version. Carroll and others are more concerned with a more modern, quantum-gravitational version of the paradox. On this version, we are to take the recent evidence of the presence of dark energy in the Universe to be reason to believe that we are headed toward a future Universe that is a de Sitter space [18]. In such a universe, vacuum fluctuations would give rise to behavior that was, for all intents and purposes, just like classical Poincare recurrence. And so in fact the details might not really matter. As long as we have a dynamical picture that leads to equilibrium with subsequent fluctuations of roughly the right kind, we get a version of the problem. What seems to matter is that the standard proposal—the Boltzmannian dynamical picture plus the past hypothesis plus the LEPP—is epistemologically unstable. So, we can call of these results PBB scenarios.

Strangely, Carroll and others take any cosmological model that leads to PBB scenarios to be a case of "direct disagreement between theory and observation" [19]. But this is incorrect. In fact, no observation is ever inconsistent with the result that I am a BB. A BB is precisely the sort of disembodied brain-in-a-thermal-equilibrium-vat that has exactly the same "perceptions" and "memories" that you do. Indeed, that is the problem. It makes the package of postulates that I have called the standard picture epistemologically unstable. That's because if we assume that package, then it becomes overwhelmingly unlikely that the experiments that we have records of having taken place—the very ones that provide us with the evidence for the postulates—have actually taken place. Unfortunately, Carroll seems confused about this. He writes:

> [A scenario where the Universe will reach a de Sitter state followed by fluctuations of the right kind] makes a strong prediction, namely, that we (under any possible definition of we) should be the smallest fluctuation away from thermal equilibrium consistent with our existence. In the most extreme version, we should be disembodied Boltzmann Brains, surrounded by a gas with uniform temperature and density. But we're not, and further experiments continue to reveal more evidence that the rest of the universe is not anywhere near equilibrium, so *this scenario seems to be ruled out experimentally* [20].
>
> In de Sitter space, we can reliably predict the number of times in the history of the Universe (including the infinite future) that observers will appear surrounded by cold and forbidding emptiness, and compare them to the observers who will find themselves in comfortable surroundings full of stars and galaxies, and the cold and forbidding emptiness is overwhelmingly likely. This is more than just an uncomfortable fine-tuning; *it's a direct disagreement between theory and observation* [19].

But the simple point about Boltzmann brains is that no amount of evidence, and no number of experiments (or a least not records of experiments—which is all we ever have), cosmological or otherwise, can ever show that I am not a Boltzmann Brain. Only a simple and straightforward desire to avoid insanity can argue against the PBB scenario once we go down the statistical mechanical road [21].

So the real PBB scenario isn't refuted. It can't be. It is, by definition, empirically indistinguishable from what we take to be the facts that we normally observe. Of course, this is no different from the fact that no observation, and no record of an experiment, is ever inconsistent with the possibility that the universe is presently in the lowest entropy condition it will or ever has been in. That is why, in order to avoid a virtually identical skeptical paradox, we need to postulate the Past Hypothesis. The Past Hypothesis, we might say, is a condition for the possibility of our having knowledge of the past, and hence for the possibility of having knowledge of physics at all—once we have adopted the rest of the standard package. The standard picture without the Past Hypothesis is consistent with my present observational base, but it is epistemologically unstable.

5. Modest Responses

Just as Boltzmann added "Assumption A" to his package to avoid this problem, we could simply do something similar with the PBB problem. We simply add another postulate to the package of the standard picture. In addition to the Boltzmannian Dynamical Picture, the Past Hypothesis, and the LEPP, we would need to add something like a "Near Past Hypothesis", which says that our present state lies between the time of the initial state and the time when the Universe first relaxes—or in the modern version: the time when the Universe first reaches a de Sitter state. The epistemological status of such a principle would be exactly like the one that Albert attributes to the Past Hypothesis in Time and Chance—it is not something which is empirically observable, it is a principle that we reason to trancendentally, as it were–it is a condition for the possibility of our having the very knowledge base that forms the empirical evidence base for the physics we were doing in the first place [22]. There is, in other words, a relatively simple response available to us for this worry.

So before we go any further in discussing Carroll's positive proposal it is worth noting that his negative points are far from decisive. More precisely, both of Carroll's worries, the worry about the unnaturalness of the Past Hypothesis, and the worry about PBB scenarios, present possible conventional [23] solutions to us if we need them. To the first worry, we can simply reject that that there is any coherent notion of probability in the Boltzmannian picture beyond the one offered up in the LEPP. We can simply argue, in other words, that probability measures are only ever justified empirically, and reject the a priori reasoning that leads to the conclusion that the Past Hypothesis is unlikely. And in response to the second worry, we can simply add the Near Past Hypothesis (NPH) to the package that makes up the standard picture. And like for the Past Hypothesis itself, the justification for the NPH would be a kind of transcendental reasoning. They are both conditions for the possibility of doing genuine physics.

What I really want to insist on at this point, therefore, is simply that how seriously we take Carroll's two problems with the standard picture really ought to depend on how much hay can be made out of them—and not entirely on how strong the initial motivation is for them—because the initial motivation is not that strong. They are not, in other words, insurmountable problems that *require* radical cosmological solutions. The attitude we really ought to have is to follow Carroll in his desire to take these two problems seriously, and to see if, by trying to address them by making more detailed cosmological conjectures, we can come up with a coherent picture that is compelling, and that tells us something interesting about the history of the cosmos.

6. Some Commitments

In that vein, we can begin by making a list of commitments to which Carroll wants to adhere. And we can start with these two.

C1. Given the Botlzmannian dynamical picture, there is well defined Boltzmann entropy for the Universe as a whole; since volumes in state space are proportional to probabilities for the initial state of the Universe, whatever macrostate of the Universe has the highest possible entropy is the state that we should expect the universe to have begun in.

- A raw postulate like the Past Hypothesis is illegitimate. Considerations of entropy and probability allow us to calculate, rather than postulate, the likely original macrostate of the Universe.

C2. Once we determine what state we should expect the Universe to have begun in, it should come out as extremely unlikely that we are in a PBB scenario. And the unlikelyhood of the PBB scenario should just come out in the wash—there should be no need for anything like a "Near Past Hypothesis" to be put in by hand.

These two commitments, as we have seen, come out of Carroll's worries about the standard picture. We can also add the following ones. Some of them are common to any Boltzmannian, and some of them Carroll brings to the table independently. In any case, Carroll believes that any proper account of the origin of the thermodynamic asymmetry in time needs to accommodate all of the following principles, and that doing so will help us to make inroads into understanding the origin of the Universe. I take it, also, that the following three are much less controversial than the first two.

C3. The second law of thermodynamics is universal.

- In other words, the tendency of systems to increase in entropy over time is not a tendency that is potentially limited to particular systems or to the Universe during a particular period of its history. Whatever the sum-total of the Universe consists in, its entropy (of some kind) is well defined, and is always on the increase (until, presumably, it reaches its maximum).

C4. The microdynamics are reversible and conserve information: "...the dynamics of our observable universe are *reversible*—they conserve information...There is a space of states that is fixed once and for all—in particular, it is the same at early times as at late times—and the evolution within that space takes different starting states to different ending states," [24].

C5. There is only one notion of time; there can be no external time parameter.

- "The weirdest thing about the idea that the space of states changes with time is that it requires an *external* time parameter—a concept of "time" that lives outside of the actual universe, and through which the universe evolves." [25].

7. More Aggressive Response: Reconciling C1–C5

Once we lay the commitments out, it becomes fairly obvious where some of the problems are going to arise. Read literally and naively, C1 and C3 are mutually incompatible with the presently observable state of the Universe—especially when we consider C2. C1 tells us that the Universe began in its maximum entropy state, and C3 tells us that its entropy keeps increasing until it reaches its maximum. But the presently observable state of the Universe clearly shows that it is not in its maximum entropy state, and C2 closes the one possible loophole: that the non-maximal entropy we can observe is just a local fluctuation. So, we seem to have an impossible set of commitments. C2 by itself, furthermore, seems to present a challenge, since insofar as we have evidence that the conditions for eternal recurrence are met, it's hard to see how we could avoid reaching the conclusion that a PBB scenario is overwhelmingly likely without, on transcendental grounds, rejecting it *by hand*.

Commitments C1–C5 thus raise two obvious challenges: (1) reconciling C1 and C3 without resorting to a simple fluctuation model; and (2) eliminating the high likelihood of a PBB scenario without eliminating it by hand.

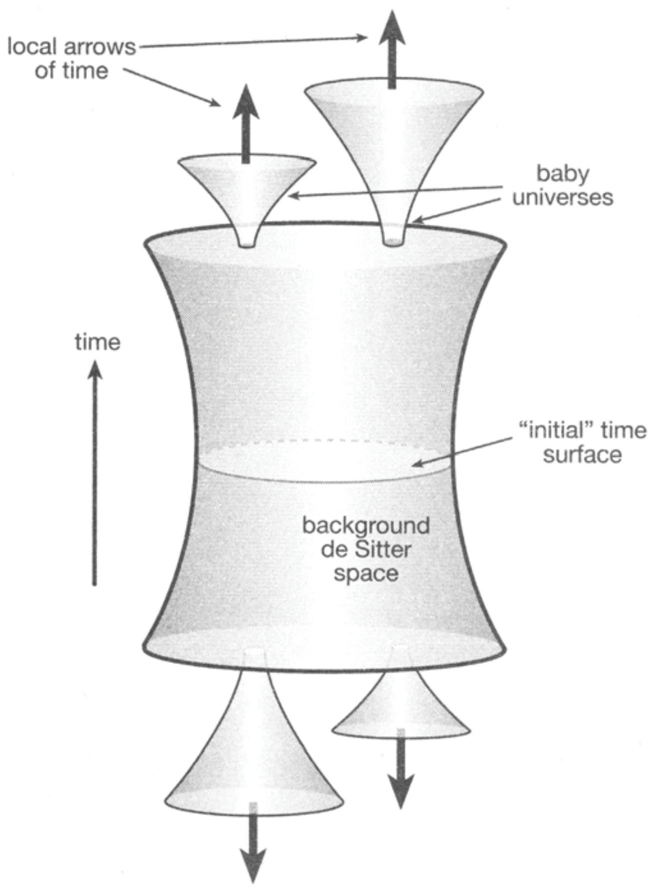
Despite these obvious difficulties, Carroll thinks that these two challenges can be met. To do so, however, requires some creative thinking about what counts as a Universe, and what counts as its "maximum entropy state".

7.1. Response to Challenge 1

Carroll imagines that the world starts out as a single Universe whose initial state arises in accord with the uniform probability distribution described in C1. Such a Universe would be overwhelmingly likely to begin in its highest entropy state. In his model, that highest entropy state would be a pure de Sitter space. But now C2 implies that our Universe has much lower entropy than it might have, and C3 implies that its entropy has always been increasing. We have a seeming logical inconsistency. Carroll breaks the logical stalemate by supposing that *our Universe* is not the same Universe as the one mentioned in the first sentence of this paragraph.

What we are meant to suppose, instead, is that our Universe is an offspring of some temporally prior Universe, which together make up a part of a large set of universes with a shared history—the multiverse. The model looks something like Figure 1.

Figure 1. Baby universes created in background of de Sitter space [26].



The basic idea is that at some arbitrary point in the history of time, a Universe is created, and the state in which it is created accords with C1. Thus, we have every reason to suppose that it was created in the form of pure de Sitter space. This Universe, being governed by the appropriate laws, will, going in both directions of time, eventually give rise to fluctuations in the vacuum that will give birth to offspring Universes. While the details of the mechanism are beyond the scope of this paper, Carroll argues that our current best guesses about the nature of the fundamental laws that describe the quantum evolution of spacetime make it plausible to suppose that a Universe in the de Sitter state will occasionally give rise to such offspring baby Universes, which begin their lives in *very low entropy states*. Thus, while the original Universe begins in the highest entropy state, by creating offspring Universes, the potential arises for the Universe to create new Universes that are not in their own respective maximum entropy states. While we have reason to suppose that the original mother Universe began at maximum entropy, we also have good reason to suppose that *our Universe*, so long as it is not the *original Universe*, would have begun in a very low entropy state.

What Carroll has effectively devised is a mechanism for the multiverse as a whole to have unbounded entropy. If, as Carroll's picture supposes, the multiverse has potentially unbounded entropy, then it can begin in as high an entropy state as one likes, and still continue to grow in entropy. That is another way to think about why the seemingly obvious conflict between C1 and C3 can be avoided.

7.2. Assessing the Response to Challenge 1

There is a sense in which Carroll is cheating here—indeed there are a couple of them. First, C1 is not exactly being met. C1, after all, demanded that the Universe begin in the highest entropy state possible, but now it turns out that the multiverse has potentially unbounded entropy. And so there is a sense in which C1 is made incoherent, rather than being met. It is a bit like claiming to have solved the problem of evil by arguing that the amount of possible good in the world is unbounded. But so it goes. Something has to give if C1 and C3 are to be reconciled.

One might worry that a deeper problem is lurking here. The thing that is making C1 even logically compatible with C3 (given the background constraints that I mentioned above) is an equivocation on "Universe". The "Universe" that has to begin in its highest entropy state (C1) is whatever original mothership Universe the world begins with. But the "Universe" whose entropy keeps increasing (C3) is the multiverse. This is a crude way to make the point. But it highlights that the notion of a "natural" probability distribution is coming under pressure here. What motivates C1 in the first place is a conviction that a uniform probability distribution over the entire set of possible initial states of the Universe is "natural"; it has *a priori* justification; it has to be respected. But once we acknowledge the possibilities of multiple Universes, what is it that remains that is special about a distribution that is uniform over the ways that one single Universe could be created? Once we countenance the possibility of multiple Universes, it would seem that all of the standard objections to indifferentist interpretations of probability rear their ugly head in particularly acute fashion, and we are left wondering why there should be a uniform probability distribution over the set of initial conditions for one Universe, rather than over some other set, which might look equally natural.

For the moment, though, let's set those more "philosophical" problems aside and focus on the technical details of the multiverse, and the proliferation of Universes.

Here we find deeper though more technical problems. The first problem has to do with the orientation of the time parameter *vis a vis* the multiverse. In the figure above (reproduced from FETH), it is clear that Carroll envisions a scenario in which the proliferation of Universes allows entropy to increase in time. The time axis is labeled on the left, and as time marches on, there are more and more Universes—creating the possibility of more and more entropy. But it is not clear why it is legitimate to envision this as a process occurring in time, as the label on the left would indicate, and as C3 and C5 would seem to demand. This is because in the Carroll scenario, when a baby Universe pinches off from its mother Universe, it is the entirety of space-time that is pinched off. Thus, there is no temporal metric, nor even any space-time interval at all, that relates events in the baby Universe to events in the mother Universe, or to other baby Universes. Thus, unless there is an external time parameter, something Carroll explicitly, and correctly, rejects (in C5), there can be no clear sense in which entropy is increasing, "in time".

The second problem has to do with interpretations of quantum mechanics. Recall that C4 requires that the microdynamics be reversible and information conserving. Thus, Carroll favors an Everett-style "consistent histories" interpretation of quantum mechanics. Recall that Everett style interpretations of QM are those in which the Schrödinger equation is never violated. They are interpretations in which superpositions of states, no matter how macroscopic, continue to be preserved—the cat is both alive and dead even after the box is opened. But Carroll claims that on his model, baby Universes arise as a result of quantum fluctuations. "Every once in a while, we could get lucky," he says, and a new universe could form. But there is controversy, at least in the philosophy of science, about whether or not Everett style QM can recover probabilities. If the state vector provides some amplitude for the state vector |baby-Universe-gets-formed> and some amplitude for the state vector |baby-Universe-doesn't-get-formed>, then the actual state of the world will be to remain in a superposition of those states. Philosophers are divided about whether, in such a situation, it makes any sense to say that a baby Universe is "likely" to be formed. Settling that debate is beyond the scope of this paper, but it worth noting that, beyond whatever other problems the Carroll and Chen proposal faces, it also depends crucially on the success of the project of underwriting the existence of genuine probabilities in a Universe governed entirely by the deterministic Schroedinger equation.

So much for the first challenge, the challenge of reconciling C1 and C3. On that challenge, the proposal seems to score low. It's not clear that the spirit of reconciling C1 and C3 is being preserved, since the notion "the entropy of the universe" in C1 is being used differently, on this proposal, than it is in C3. The notion of entropy that allows C1 to be obeyed is the entropy of a single Universe, but the notion of entropy that allows C3 to be obeyed is the entropy of the multiverse. It's not even clear, moreover, that there is a coherent notion of "the entropy of the multiverse" that can be maintained while preserving C4, since on an Everett-style interpretation of QM, there will be coexisting states with different arrangements of Universes—and we have no well-defined notion of entropy that I am aware of that applies to such massively entangled states. It is not clear that C5 is being met, because there is no clear axis of time against which all the baby universes jointly live.

7.3. Response to Challenge 2

What about the second challenge, the challenge of eliminating the high likelihood of a PBB scenario without eliminating it by hand? Here I think the verdict is mixed. Let us look further at why Carroll thinks the challenge is met. Recall that the problem is that, on the standard proposal (the one without an NPH put in by hand), after the universe reaches thermal equilibrium, it will eventually start to fluctuate into all its possible lower entropy states. And the further problem is that it will fluctuate into a state with a BB that is just like my present brain (which thinks it sees *The History of the Decline and Fall of the Roman Empire* [12] on its desk), surrounded by a thermal bath, overwhelmingly more often than it will fluctuate into a state that actually evolves into a Roman Empire that rises and falls, and leads to the printing of that book. And so from the information presently available to me right now (which is presumably just my own mental state), it follows, from the package in the standard proposal, that it is much more likely that I am BB than that there was a Roman Empire.

Why would Carroll's multiverse avoid this problem (without having to put an NPH in by hand)? Well, one thing that is clear is that a continuously branching multiverse will change the math from how it was in the last paragraph. In a single Universe, a genuinely big-bangy past state occurs only once. But the existence of a brain that is just like mine with respect to all its memories and observations will happen over and over again (thanks to the de Sitter fluctuations that mimic Poincaré recurrence). And so it's fairly easy to see, in a single Universe model, that a brain just like mine is much more likely to be a BB than one that veridically has records of a Roman Empire and a big bang. In a branching multiverse, the math gets more complicated. In a branching multiverse, actual, genuine big-bangy past states occur over and over again. And so the reasoning that leads to the PBB skeptical paradox is less ironclad. This much seems correct.

7.4. Assessing the Response to Challenge 1

But it is not clear that a PBB skeptical paradox is not still the most plausible result. That is, it is far from clear that the most plausible thing to think is that, even in a branching multiverse, BB with big-bangy memories and records will not still vastly outnumber real big bangs—even though there are now a whole lot more big bangs than there were in the single Universe (only one!). That's because it seems plausible to suppose that as each new Universe springs into being, it creates exactly one new actually big-bangy state, but the potential for innumerably many BBs with big-bangy memories and records. And so even on the multiverse model, it still seems plausible to suppose that, from only the evidence that is at my disposal and from the postulates of the model, it is still overwhelmingly more likely that I am a BB than that I have veridical records of a big-bangy past.

Thus, as regards the second challenge that Carroll aims to meet, it is clear that his proposal makes the math far more complicated, but it is far from clear that the probabilistic conclusion he hopes to avoid can be avoided.

8. Conclusions

Where does this leave us? We began with two worries about the standard proposal that turned out to be based on two philosophical intuitions. The first worry was that the past hypothesis, as a brute empirical postulate, was illegitimate. This was based on the intuition that the probability measure that is uniform on the whole state space is *a priori natural*, and that any initial state of the Universe that is unlikely on *that measure* requires explanation. The second worry was that the standard proposal leads to a Poincare recurrence version of the Boltzmann Brain scenario (we called this the PBB). Some claim that this scenario is empirically refuted. But as we saw, the situation is a bit more subtle. In fact the properly understood PBB is, by definition, precisely immune from empirical refutation. The problem with it, rather, is that it leads to a profound kind of skepticism and epistemological instability. And so it turned out that the PBB scenario could be avoided by putting something like the NPH into our picture by hand. Such a move might be justifiable, just like the Past Hypothesis itself, on transcendental grounds. The second worry, therefore, could only be maintained by a philosophical intuition that this sort of move is, for some reason or another, illegitimate.

The attitude that we took in this paper to those two philosophical intuitions was one of suspended judgment. We saw that we could avoid Carroll's worries by modifying those intuitions, and so we took the attitude that we would follow Carroll, and see where it took us—reasoning that if those intuitions could lead us to a clearer picture of the origin of the universe, than so much the better for the intuitions. On the other hand, if those intuitions lead us, for technical or scientific reasons, to an impasse, than we should keep in mind that there are alternatives—and perhaps so much the worse for the intuitions.

Unfortunately, they did seem to lead us to an impasse. First, we found that the intuition that we ought to insist on the a priori *naturalness* of insisting that the Universe began in its highest entropy state led, at best, to a conclusion that the demand itself was incoherent—to the conclusion that the world as a whole *has* no highest entropy state. We also found that to make that assumption consistent with our other commitments, we had to invoke a time-asymmetric interpretation of quantum mechanics, and, perhaps worse, to measure the increase in entropy against an external time parameter. And finally, we found that even in the final model, it was not clear that we could avoid the need to add a Near Past Hypothesis by hand. The costs, therefore, of the Carroll/Chen model seem high, and the benefits few.

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5. Giving a formal definition of a time-reversal operator that works for any kind of dynamical system is notoriously difficult, but it is usually relatively uncontroversial whether we have one when we see it.
6. In our discussion, the entire dynamical system is the universe as a whole, but we want the apparatus to underwrite the macroscopic predictions we might make about any isolated, or relatively isolated, thermodynamic sub-system.

7. Whether or not it is plausible to suppose that the actual dynamics of our universe is, and has been for all time, "friendly" enough is a matter of some controversy. The idea has been criticized in [27,28]. Alternative pictures are presented in [29,30]. I ignore those issues here and assume, for the purpose of evaluating the prospects of statistical-mechanical cosmology, that they will be resolved in favor of the standard picture.
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20. Carroll, S. *From Eternity to Here: The Quest for the Ultimate Theory of Time*; Dutton: New York, NY, USA, 2010; p. 312.
21. I should note that while, most of the time, Carroll makes it sound like he thinks the PBB scenario is empirically refuted, there is one passage late in the book that sounds a slightly different tone. "Most observers will find themselves alone in the universe, having arisen as random arrangements of molecules out of the surrounding high-entropy gas of particles… You could potentially fluctuate into something that looks just like the history of our Big Bang cosmology; but the number of observers within such a fluctuation is much smaller than the number of observers who are otherwise alone" [31]. This statement is correct. But that is not the PBB scenario. It is true that

fluctuations into creatures like me, who observe themselves to be alone, are much more likely than fluctuations into creatures like me who think they see a big-bangy universe around them (or who actually do see such a universe.) And the former possibility is indeed empirically refuted. But this was not the problem that was on the table—PBB scenarios are ones in which we calculate probabilities based on what we observe and based on our cosmological model. The real PBB problem was, given what I take myself to be observing: what is the most likely state of affairs if Poincare recurrence (or an equivalent de Sitter state with fluctuations) is a reality. And here the answer was that it is much more likely that I have fluctuated into a being who merely thinks he observes a big-bangy universe than that the universe has actually fluctuated into a big-bangy state. And the problem with that dilemma is not that either one of those scenarios is empirically falsified (how could it be?) but that the former scenario is epistemologically unstable, and leads to a skeptical paradox. Carroll seems to be confusing the first prediction (that I should be a creature that doesn't observe a big-bangy universe around me—which is not entailed by anything anyone has ever proposed) with the second one: that I should be a creature who thinks he sees a big-bangy universe but really doesn't.

22. It is worth noting that making a move like this might have implications for the metaphysical status of some elements of the standard picture package. I explore these issues in [32].
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