5-1-2017

Asymmetry and the Arrow of Time

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by

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An Honors Capstone

submitted in partial fulfillment of the requirements

for the Honors Diploma

to

The Honors College

of

The University of Alabama in Huntsville

May 1, 2017

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Abstract

This paper is a literature study on the source of the unidirectional flow of time, hereafter called the ‘arrow of time.’ The conventional story for how one fixes the arrow of time involves entropy and the second law of thermodynamics. This paper argues that entropy fails as the source for the arrow of time in two ways: Loschmidt’s paradox reveals that entropy cannot make correct predictions in the case of reversible systems and entropy’s constraining assumptions make it a local rather than global effect. Instead of entropy, this paper presents four alternatives for fixing the arrow of time: quantum asymmetry, underdetermination, energetic causal sets, and the evolving block universe model. After summarizing each alternative (and defending the evolving block universe model from arguments that simultaneity invalidates the notion of ‘the present’), weaknesses in each alternative are explored. When the dust settles, the evolving block universe model is the strongest candidate of the alternatives considered.

Introduction

One concept that falls into the intersection of physics, philosophy, and everyday human experience is time. Time is a useful parameter in our physical descriptions of phenomena, a tantalizing metaphysical puzzle for generations, and the medium through which we experience our lives. Despite its ubiquity, time is a somewhat nebulous concept. In what sense does time refer not only to part of the fabric of reality but also the pacing and structure of daily life? Or in what way can time be both a definite variable and a vague notion? Perhaps these questions are too platitudinous to be of much merit. Instead, one could focus on one aspect of time: its directionality.

The everyday notion of time includes its division into past, present and future. Furthermore, it seems that one can only travel in time from the past into the future, unless one considers science fiction to be a faithful representation of reality. If one searches for an explanation of why time seems to be monotonically directed towards the future, one might stumble upon entropy and the second law of thermodynamics. The typical story for why time is directed in one way rather than another is that entropy fixes time's direction. Another term for time's direction is the 'arrow of time,' an arrow of direction rather than archery. In this paper, I will consider various arguments for how the arrow of time can be fixed. To jumpstart the discussion, I will first discuss the meaning of 'the arrow of time' in the next section.

What is the Arrow of Time?

The arrow of time has a phenomenological and a formal meaning. In everyday experience, the arrow of time is the idea that time has a direction or a flow. The arrow of time differentiates one's past from one's future. If I were to check my calendar on a Wednesday, events marked on Monday have already occurred, while events marked on Friday have not yet occurred. Furthermore, such intuitions about time's direction extend beyond anthropocentric activities like schedules. Fallen snow will eventually melt and nebulae collect dust that form new stars.

If one abstracts out a bit further from the phenomenological description, one could say that the arrow of time is related to an ordering of events in time. Time ordering can be explicated using the dual notions of parts of time and points of time. An interval of time with any duration can be called a part of time, while a point in time would be an instant of no duration that can separate two parts of time—such as noon separating morning from afternoon at the instant between 11:59:59 am and 12:00:01 pm (Torretti 2007, 735). For any two parts of time *a* and *b*, they can be subsets of each other, they can share some common interval, or they can be non-overlapping. Time ordering comes in this latter case where either *a* precedes *b* or *b* precedes *a*, where 'precession' arises when one part of time has ended before the other begins. Then, one can extend precession from parts to points by identifying any two distinct points in time *A* and *B* such that $A \in a, B \in b$, and *a* precedes *b* (or vice versa) (Torretti 2007, 735). In this context, the arrow of time would then be the direction that time is ordered, e.g. if *A* precedes *B* then the arrow of time 'points' from *A* towards *B*. One final note: time ordering is not identical with causality, though causality is a kind of ordering. For example, I can say that the Hundred Years' War precedes James Cameron's film *Titanic* without asserting a causal relationship between those two events. However, causality does have a kind of time ordering, namely that causes precede their effects (Drory 2008, 910). If one says that the cause occurs at some point of time *A*, its effect would then occur at some point of time *B* and *A* precedes *B*.

Finally, the arrow of time has a formal meaning for our physical laws. Formally, the arrow of time is related to whether a process is time-reversible or if the process is time-symmetric. Reversible and symmetric processes do not inform an arrow of time, while irreversible and asymmetric processes do inform an arrow of time. For example, a pendulum's swing can help define intervals of time (hence its use in grandfather clocks), but the swing can be described reversibly. If one swaps the time parameter for its negative ($t \rightarrow -t$), the equations of motion would still describe the periodic motion of the pendulum. (As a brief aside, the $t \rightarrow -t$ substitution is a common way of representing time symmetry, which will become relevant in a later section on the CPT theorem at the quantum scale.) Hence, the pendulum swing does not give a direction for the arrow of time (Ellis 2013, 255-6). In contrast, an hourglass can define both a given interval—depending on the volume of sand and the aperture between the chambers—and temporal directionality, since the sand flows from the top of the glass to the bottom. The gravitational potential sets up a gradient, and energy gradients convert spatial asymmetries into temporal asymmetries through irreversibility (Ellis 2013, 254).

An Untimely Tension

The discussion above gave a good description of how one can use the arrow of time to discuss time's directionality; however, the source of the arrow of time is not yet clear. A description does not give reasons for why the arrow of time is oriented from the past towards the future. Alternatively, mere descriptions cannot determine whether the arrow of time is necessarily future-directed. If one tries to determine the source of the arrow of time by comparing its expression at various scales, one finds a conflict arising in the relationship between macroscopic scales and microscopic scales. Most processes at the macroscopic scale are irreversible, from thermodynamic systems of gas to supernovae. For example, a plate of scrambled eggs would not spontaneously unscramble into a yolk and egg white. These macroscopic systems seem to increase in disorder as time passes, which appears to be the result of the second law of thermodynamics (Ellis 2013, 245). I will discuss entropy in detail in the next section.

In contrast with the macroscopic scale's irreversibility, the fundamental physical laws and quantum theory seem to be temporally symmetric. Take, for example, the Schrödinger equation. For some wave function $\psi(x,t)$, the Schrödinger equation gives the following:

$$i\hbar \frac{\partial}{\partial t}\psi(x,t) = \widehat{H}\psi^*(x,t)$$

where $\widehat{H}$ is the Hamiltonian operator. Since the Hamiltonian operator is Hermitian, if one time-reverses the wave function by exchanging $\psi(x,t)$ for $\psi^*(x,-t)$, the Schrödinger equation is unaffected. Its perseverance through time-reversal means that the Schrödinger equation is time symmetric (Bacciagaluppi 2007, 441).

The tension between macroscopic and microscopic scales becomes relevant when one tries to determine the source for the arrow of time. Since macroscopic laws arise by coarse-graining microscopic laws, one would expect temporal symmetry at the microscale to result in temporal symmetry at the macroscale. Yet one finds the macroscale dominated by irreversibility. In other words, “the macro behavior displays a time asymmetry that is not apparent in the fundamental equations out of which they emerge” (Ellis 2013, 246).

Entropy, a Review

Since entropy and the second law of thermodynamics are typically cited as the source for fixing the arrow of time, a brief review of those concepts would be beneficial to more fully explore the tension presented above. First, I will present the distinction between microstate and macrostate. A microstate is a specific configuration of the components in a system. For example, the particles in a gas could have a microstate defined by the collection of their definite position and momentum vectors. Other quantities that could help define a microstate could include the spin of the particles or their magnetic dipole moments. The key is that microstates correspond with complete descriptions of specific particles or members of a system. In contrast, the macrostate is a set of definite values for constraints on the system itself. For example, a macrostate could be defined with (E, V, N, α), where E is the energy, V is the volume, N is the number of members, and α represents any additional constraints (Mandl 2010, 35). For some macrostate M, there could be multiple microstates that would produce the same macrostate. For example, exchanging the spin states of two electrons in a system would not alter the system's macrostate, but that exchange would define two distinct microstates. One can also use phase space to describe the relationship between microstates and macrostates. In that case, the microstate is defined as a point in the phase space of a system, and the macrostate is the equivalence class that partitions the phase space (Drory 2008, 890-1).

One relevant relationship between macrostates and microstates is the statistical weight. Statistical weight is represented as $\Omega(E, V, N, \alpha)$ and is the number of microstates comprising a macrostate defined by some (V, N, α) and having energy in the small interval of $E \rightarrow E + dE$ (Mandl 2010, 36). For example, suppose one had multiple boxes and ping pong balls. If the ping pong balls represented microstates and the boxes represented macrostates, the statistical weight would be how many ping pong balls were in a given box. Now, partly to reduce the magnitude of the quantities being discussed and partly to turn the discussion towards an extensive variable (a variable that scales with the size of the sample), thermodynamics turns to entropy. Entropy is defined as

$$S(E,V,N,\alpha) = k\ln[\Omega(E,V,N,\alpha)]$$

where k is Boltzmann's constant. One then takes the second law of thermodynamics to be "during real (as distinct from idealized reversible) processes, the entropy of an isolated system always increases. In the state of equilibrium, the entropy attains its maximum value" (Mandl 2010, 41-4). That version of the second law is also known as Clausius' entropy principle.

This formulation of entropy depends upon a few postulates Boltzmann took during his proof. The relevant postulates are as follows (Drory 2008, 891):

> *Statistical Postulate (SP)*: In a closed system, the probability of finding the system in a microstate corresponding to a macrostate *M* is proportional to the volume of the phase-space region corresponding to this macrostate.
>
> *Equilibrium Postulate (EP)*: There is one macrostate, thereafter called the equilibrium state of the system, whose phase volume is overwhelmingly larger than that of any other macrostate.

Taking these two postulates together, one can say that the equilibrium state of a system is the one that has the highest probability. If the system is initially in a region of low phase-space volume, it can be expected to evolve towards larger volumes of phase-space. These regions of larger phase-space correspond with larger values of entropy, culminating with the system settling into the equilibrium state. Also, for (SP), the probability of finding the system in a macrostate can be thought of as the amount of time a system spends in that macrostate over a long observation time (Drory 2008, 891).

There is one more set of assumptions for Boltzmann's formulation of entropy relevant to this paper's discussion. These postulates form some limitations on the scope of thermodynamic entropy, while (SP) and (EP) set up the entropy principle itself. Although there are seven such postulates in the original paper, for my purposes I will explicitly mention the two that are relevant for this paper (Torretti 2006, 743):

(i) The gas consists of a large but finite number of molecules insulated and confined by rigid walls in a large but finite space *R*

(v) The initial distribution of kinetic energies among the molecules is uniform on *R*

Entropy's Limitations

In this section, I will present two objections against using entropy to fix the arrow of time. The first objection, Loschmidt's paradox, argues that entropy is symmetric under time-reversal, and so the arrow of time must be fixed elsewhere. The second objection argues that even if entropy could fix the arrow of time in thermodynamic systems, it cannot extend to other scales. In other words, entropy is a local rather than global effect.

Loschmidt's Paradox

For clarity, I will introduce the following expressions. Suppose one has a microstate of N particles represented by the phase-space vector $\boldsymbol{r} = (\boldsymbol{r_1}, \boldsymbol{p_1}, \boldsymbol{r_2}, \boldsymbol{p_2}, \ldots \boldsymbol{r_N}, \boldsymbol{p_N})$, where the $\boldsymbol{r_i}$ component is the *i*th particle's position and $\boldsymbol{p_i}$ component is the *i*th particle's momentum. Because the Hamiltonian equations of motion are time-symmetric, one can represent a time-reversal of $\boldsymbol{r}$ with some new phase-space vector $R\boldsymbol{r} = (\boldsymbol{r_1}, -\boldsymbol{p_1}, \boldsymbol{r_2}, -\boldsymbol{p_2}, \ldots \boldsymbol{r_N}, -\boldsymbol{p_N})$. Reversing the momentum components is equivalent with exchanging one's time parameter $t \to -t$ (Drory 2008, 892). Now, suppose that that $\boldsymbol{r}$ is part of macrostate *A* that is different from equilibrium; according to the entropy principle the system will evolve until it reaches equilibrium. The system begins at time $t = t_0$ with the microstate $\boldsymbol{r}(t_0) \in A$ and will evolve until it reaches equilibrium at time $t = \tau$ and microstate $\boldsymbol{r}(\tau) \in C$, where *C* is the equilibrium state.

Now, consider the system at some intermediate time $t_1 (t_0 < t_1 < \tau)$. At this intermediate time, the microstate $\boldsymbol{r}(t_1)$ will be an element in macrostate *B*. *B* should have a larger phase-space volume than A but should not have a phase-space volume as large as the equilibrium state C (Drory 2008, 892-3). These phase-space volumes correspond to the entropies of the system at those times; thus, one could say that $S(t_0) \leq S(t_1) \leq S(\tau)$. If one were to consider the microstate $\boldsymbol{r}(t_1)$, one expect it to evolve into the microstate $\boldsymbol{r}(\tau)$, since "random motions in phase space [take] one from less probable to more probable regions in phase space" (Ellis 2013, 246). But what of the phase-space vector $R\boldsymbol{r}(t_1)$, the time-reversed microstate? Since the Hamiltonian is time-reversible, the microstate described by $\boldsymbol{r}(t_1)$ and that of $R\boldsymbol{r}(t_1)$ are indistinguishable at t_1 (Torretti 2007, 748; Drory 2008, 893). In other words, the laws of mechanics governing the behavior of the microstate (the individual particles) are time-reversible, and thus the ensemble behavior of those particles (e.g. the macrostate) is identical for the original and time-reversed states.

From here, one can formulate Loschmidt's paradox in a couple ways. One is that this time-reversal leads to the conclusion that entropy must increase in both temporal directions away from t_1. In other words, not only should entropy increase towards $t = \tau$, but it should also increase towards $t = t_0$ (Ellis 2013, 246; Torretti 2007, 748). The paradox in this scenario comes from the entropy principle disagreeing with empirical observation; one observes that $S(t_0) \leq S(t_1)$ yet the entropy principle predicts that $S(t_0) \geq S(t_1)$. (I have included the "or equal to" inequalities to account for reversible processes, but those are exceedingly rare compared to irreversible processes.) Thus, the entropy principle predicts an increase in entropy towards the future as well as towards the past (see Fig. 1).

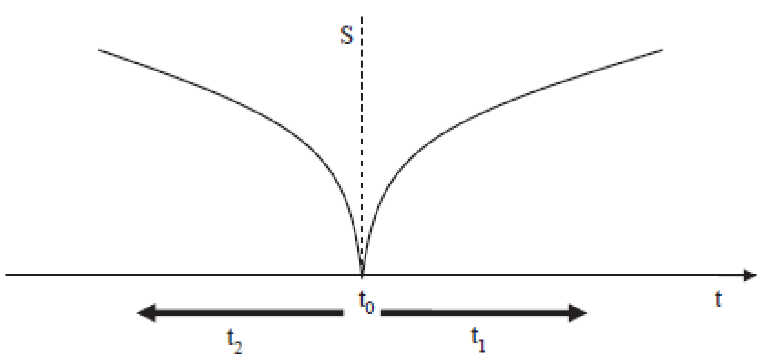

Figure 1. Loschmidt's Paradox. Source: Ellis 2013, 246.

The other formulation of Loschmidt's paradox involves the distinction between predictions and retrodictions. By 'prediction,' I refer to making assertions about the future state of a system. For example, I could make a prediction about the financial system when I invest in the stock market. In contrast, a 'retrodiction' is an assertion about the past state of a system. For example, archaeologists make retrodictions about long-gone civilizations. In one case (predictions), one is using present data to infer about the future; in the other case (retrodictions), one is using present data to infer about the past.

Returning to the intermediate microstate $\boldsymbol{r}(t_1)$, one can make predictions about how it will continue to evolve (e.g. $\boldsymbol{r}(\tau)$) and make retrodictions about what the system looked like in the past (e.g. $\boldsymbol{r}(t_0)$). Making predictions falls in line with traditional uses of the entropy principle; one asserts that entropy ought to increase as the microstate approaches $\boldsymbol{r}(\tau)$. However, one can make retrodictions for $\boldsymbol{r}(t_1)$ by considering the behavior of $R\boldsymbol{r}(t_1)$, the time-reversed microstate. In particular, $R\boldsymbol{r}(\tau)$ corresponds with $\boldsymbol{r}(t_0)$; in other words, the prediction for $R\boldsymbol{r}(t_1)$ acts as the retrodiction for $\boldsymbol{r}(t_1)$ through time-reversal (Drory 2008, 894). This relationship picks up Loschmidt's paradox, since $R\boldsymbol{r}(t_1)$ would also approach equilibrium via the random walk through phase-space. In this second formulation, Loschmidt's paradox shows that entropy makes good predictions but false retrodictions.

However, Drory's presentation of Loschmidt's paradox goes one step further than the entropic formulation: it distinguishes between systems of finite closure and infinite closure. Suppose one had a thermos of ice in lukewarm water. When the system has both ice and water, it is at a relatively low entropy state. In contrast, once the ice has melted and system is at equilibrium, it is at a relatively high entropy state. Loschmidt's paradox arises when one makes retrodictions five minutes into the system's past. The retrodiction states that it is more likely that the ice formed spontaneously from an equilibrium five minutes ago than the system having larger ice cubes and warmer water at that time (Drory 2008, 894). If the system had only been closed finitely long, the more sensible result would be that large ice was introduced to the system, the system became thermally isolated, and then the ice melted during those five minutes until it was observed.

The sensible result will change, however, if one considers a system that has always been closed (or at least closed for some very long time relative to the five minutes between our present and the retrodiction). In that case, "the system has been closed for infinitely longer than its thermalization time, so any ice cubes present at the 'initial time' must have melted long ago" (Drory 2008, 895). In that case, if one observes ice in the thermos, that ice must have resulted from a highly unlikely fluctuation in the system. Since such a low-entropy fluctuation away from equilibrium is highly unlikely, the size of the ice formed by that fluctuation matters significantly. It makes much more sense for that fluctuation to occur immediately prior to the observation rather than the fluctuation occurring five minutes ago, when the ice formed by the fluctuation must be even larger (Drory 2008, 895-6). In this case, entropy can make true retrodictions, but only in scenarios of infinite closure. Finitely closed systems still produce false retrodictions.

Mind the Assumptions

Even if one could resolve Loschmidt's paradox and entropy's ability to fix the arrow of time, one would still run into trouble trying to extend entropy beyond strictly thermodynamic systems. The starting assumptions Boltzmann made about entropy restrict the discussion to thermodynamic examples only. For example, by assuming (from *(i)* above) that the gas is contained in a large but finite space *R*, one should not apply the entropic principle to very large or very small scales. Microscopic scales would have an insufficient ensemble behavior, while very large scales pick up gravitational dependence (Torretti 2007, 742). Even if one were to only consider early cosmological phenomena such as the Big Bang or inflationary cosmology, one would then run into the issue of containment. If the whole universe is counted as the system, in what way might the system be contained or thermodynamically isolated? Alternatively, how do you connect a heat bath to the universe? The other restrictive assumption relevant for this paper is *(v)* above: that the initial distribution of kinetic energies among the molecules is uniform on *R*. Such uniform distribution may apply to thermodynamic systems, but it does not scale beyond those systems. Astronomical scales such as a star with interstellar medium or a galactic cluster cannot comply with condition *(v)*, once again due to gravitational effects (Torretti 2007, 742).

By taking these restrictive assumptions seriously, one finds that thermodynamic entropy can only fix the arrow of time locally. By definition, local phenomena do not guarantee global agreement. In particular, "local determination has to arbitrarily choose one of the two directions of time…as this decision is made locally, there is no reason whatever why it should be consistent globally. If it emerges locally, opposite arrows may be expected to occur in different places" (Ellis 2013, 247). To achieve a satisfactory explanation for fixing the arrow of time, one must strive for a global solution.

If Not Entropy, then What?

Since thermodynamic entropy cannot fix the arrow of time globally, the field has opened for other contenders. Fortunately, there are other candidates in the literature for fixing the arrow of time. In this section, I will discuss four such alternatives. Specifically, this section will cover quantum asymmetry, underdetermination, energetic causal sets, and the evolving block universe model.

Quantum Asymmetry

One possible avenue for fixing the arrow of time could be cases of asymmetry at the quantum level. Although the Schrödinger equation itself seems time-symmetric, one can find a few instances of asymmetric behavior. The argument goes that if one can find asymmetry at the quantum level, then such events would fix the direction of the arrow of time at the quantum scale. Then, that fixed direction would determine behavior of systems at larger scales, like the thermodynamic system. This macro-micro relationship mirrors the tension sketched above about coarse-graining from microscopic laws to macroscopic behavior, except the tension is resolved by finding asymmetry at both levels. This argument depends on causal links between levels of scale. For example, one could draw causal links between particle physics and nuclear physics in the sense that the nucleons are assemblages of quarks or that atomic physics dictates behavior at the molecular scale, which transfers to discussions of thermodynamics (Ellis 2013, 243). As for sources of quantum asymmetry, I will present two cases: the arrow of collapse and the decay of neutral kaons.

The Arrow of Collapse

One alternative to the Schrödinger equation for descriptions of quantum phenomena is the arrow of collapse formulation. The arrow of collapse formalizes the evolution of one quantum state $|\psi\rangle$ to some state $P_\alpha|\psi\rangle$, given that P_α is "the eigenprojections of the measured observable" (Bacciagaluppi 2007, 442). That evolution of quantum states would then have a probability given by $Tr(|\psi\rangle\langle\psi|P_\alpha)$. Notably, the arrow of collapse formulation does not appear to be symmetric under time reversal. In general, if one were to represent the evolution of a quantum state $|\psi(t_0)\rangle$, one would find the original collapse to be represented by

$$|\psi(t_0)\rangle \longrightarrow U_{t_{n+1}t_n} P_{\alpha_n} U_{t_n t_{n-1}} . \ . \ . U_{t_1 t_0} |\psi(t_0)\rangle$$

with probability given by

$$Tr\big(P_{\alpha_n} U_{t_n t_{n-1}} \ldots P_{\alpha_1} U_{t_1 t_0} |\psi(t_0)\rangle\langle\psi(t_0| U^*_{t_1 t_0} P_{\alpha_1} \ldots U^*_{t_n t_{n-1}} P_{\alpha_n}\big),$$

where $U_{t_{i+1}t_i}$is a Schrödinger evolution period and $P_{\alpha_i}$is a collapse and the index *i* increments through *n* number of evolutions. In contrast, if one time-reverses this process by starting with the final state and 'evolving' in reverse, one gets instead the following:

$$|\psi(t_{n+1})\rangle \longrightarrow U^*_{t_1 t_0} P_{\alpha_1} U^*_{t_2 t_1} . \ . \ . P_{\alpha_n} U^*_{t_n t_{n-1}} |\psi(t_{n+1})\rangle$$

with probability given by

$$Tr\big(P_{\alpha_1} U^*_{t_2 t_1} \ldots P_{\alpha_n} U^*_{t_{n+1} t_n} |\psi(t_{n+1})\rangle\langle\psi(t_{n+1}| U_{t_{n+1} t_n} P_{\alpha_n} \ldots U_{t_2 t_1} P_{\alpha_1}\big),$$

which differs from the result of $|\psi(t_0)\rangle$ (Bacciagaluppi 2007, 442).

As an example, consider the evolution of the quantum state of a spin-½ particle. The particle's initial state will be $|\psi(t_0)\rangle = \alpha|+_x\rangle + \beta|-_x\rangle$, and the particle will be measured twice. The first measurement occurs at t_1 and will be of the particle's spin in the x-direction; the second measurement occurs at t_2 and will be of the particle's spin in the z-direction. If one goes through the evolution of the quantum states described generally above, the end probability of the event 'spin-x up, followed by spin-x up' is $\frac{|\alpha|^2}{2}$. In contrast, the time-reversal of this evolution generates a final probability for the event 'spin-z up, preceded by spin-x up' as merely $\frac{1}{2}$ (Bacciagaluppi 2007, 442-3). In other words, the probability for one event differs from a time-reversed description of that event, which is a prime example of time-symmetry breaking at the quantum level.

CPT and Neutral Kaon Decay

Another possible source for time asymmetry at the quantum level is the decay of neutral kaons. However, a brief discussion of the CPT theorem must precede the neutral kaon example. At the quantum level, there are a few testable symmetries: charge symmetry (C), parity symmetry (P), and time symmetry (T). If an interaction is symmetric, then the corresponding quantity is conserved if one reverses the system. For example, charge symmetry means that if one exchanges the charge of a particle for its opposite (e.g. replacing an electron with a positron), then the interaction should be identical. Parity symmetry involves reflecting the spatial axes into a mirror image, such as reflecting across the y=x line for a 2-dimensional plot. Finally, time symmetry would entail time-reversing, or switching all values of *t* for -*t*. Another way to determine time symmetry is to reverse the direction of the momentum vectors in a system, as above for Loschmidt's paradox.

According to the CPT theorem, for any relativistic quantum mechanical system "the result of successfully carrying out the charge conjugation operation C, the parity operation P, and the time-reversal operation T is to leave the essential description of the behavior of the system unchanged" (Eisberg and Resnick 1985, 658). Furthermore, if one of the symmetries is violated, then there must be a violation in at least one of the other symmetries as well. So, if a system is not C-symmetric, then must be violate P-symmetry and/or T-symmetry as well. This quality of the CPT theorem, that asymmetry in one part indicates further asymmetry in another, is the relevant notion for the discussion of neutral kaons.

The neutral kaon provides an opportunity to check for symmetries in the weak interactions (in contrast, strong and electromagnetic interactions can be tested with multiple particles). There are two different ways of expressing the neutral kaon, depending on the value of the strangeness operator. The K^0 has a strangeness operator value of +1 and the $\overline{K^0}$ has a strangeness operator value of –1 (Eisberg and Resnick 1985, 658). This oddity makes assessing eigenfunctions of CP symmetry initially difficult, especially since as a particle-antiparticle match they have degenerate energies. However, one can perturb the neutral kaon to generate two states which linearly combine to form the degenerate neutral kaons. The perturbation arises from a sequence of two weak interactions, specifically $K^0 \rightleftarrows 2\pi \rightleftarrows \overline{K^0}$, a process that transitions through pions. These perturbed states are denoted with K_1^0 and K_2^0. One can express those perturbed states using CP eigenfunctions in the following way (Eisberg and Resnick 1985, 659):

$$K_1^0 = \frac{1}{\sqrt{2}}[K^0 + CP(K^0)] = \frac{1}{\sqrt{2}}(K^0 + \overline{K^0})$$

$$K_2^0 = \frac{1}{\sqrt{2}}[K^0 - CP(K^0)] = \frac{1}{\sqrt{2}}(K^0 - \overline{K^0})$$

If one performs the CP operations in the above equations, one would get an eigenvalue of +1 for the K_1^0 perturbation and -1 for the K_2^0 perturbation. To pick up these eigenvalues and to preserve CP, the K_1^0 and K_2^0 perturbed states decay differently. In particular,

$$K_1^0 \rightarrow \pi^+ + \pi^- \quad \text{but} \quad K_2^0 \nrightarrow \pi^+ + \pi^-$$

$$K_2^0 \rightarrow \pi^0 + \pi^0 + \pi^0 \quad \text{but} \quad K_1^0 \nrightarrow \pi^0 + \pi^0 + \pi^0$$

(Eisberg and Resnick 1985, 659). Now, since the two perturbed states have dissimilar decay patterns, one can discern what combination of K_1^0 and K_2^0 decays occur in any processing of the neutral kaon from the K^0 to the $\overline{K^0}$. Furthermore, the two perturbed states have differing lifetimes, since the K_2^0 state decays into three particles instead of two. Combining these two features together, one can determine that even when all the K_1^0 perturbed states have decayed away, a fractional amount of K_2^0 perturbed states remain. Therefore, by expanding the neutral kaon into its two perturbed states, one can measure T-symmetry violation through CP-symmetry violation (Eisberg and Resnick 1985, 659).

Underdetermination

Another alternative to thermodynamic entropy for fixing the arrow of time is underdetermination. By underdetermination, I mean that available data is insufficient to support one outcome over another. For example, if I were trying to choose a restaurant for a celebratory dinner, I might wish to choose the venue based on quality. Suppose I look for Michelin 3-star restaurants in New York City. Since there is more than one restaurant with three Michelin stars, that data alone cannot lead me to choosing a particular venue: I would need additional information like the kind of food being offered or the price of admission in order to make my choice.

For the arrow of time, underdetermination comes up when one compares predictions into the future and retrodictions into the past. From the discussion above, Boltzmann's statistical postulate (SP) cannot be applied to systems that are only finitely closed (Drory 2008, 897). The erroneous extension of (SP) beyond cases of always-closed systems came about precisely because it seemed to correctly predict future outcomes. Loschmidt's paradox points out that SP makes erroneous retrodictions into the past for finitely-closed systems. Thus, the phenomenon that needs description is that traditional thermodynamic entropy makes successful predictions into the future for both always-closed systems and finitely-closed systems, but it can only make successful retrodictions into the past for the always-closed system. Based on this observation, one can develop a principle that expresses said phenomenon:

> *Principle of Underdetermined Past (PUP)*: The behavior of an ensemble of macroscopic systems that are thermodynamically closed and isolated for a finite time T *after* some initial moment t_0 will be the same during this time T as that of an identical (at t_0) ensemble of systems thermodynamically closed and isolated for *all* times after t_0. No similar claim holds about the past of the system (Drory 2008, 904).

(PUP) deals with ensembles rather than individual members of the system to avoid accidentally choosing an anti-thermodynamic member.

One important caveat to (PUP) is that it is not a fundamental law or a formal theory. Rather, it is a description of the behavior that needs further explanation (Drory 2008, 905). Its purpose is to augment Boltzmann's assumptions to avoid Loschmidt's paradox. The statistical postulate (SP) and equilibrium postulate (EP) of Boltzmann's system are time-reversible and concerned with systems that are always-closed, so a third principle is needed to avoid the paradox. (PUP) highlights the distinction between always-closed systems and finitely-closed systems and provides a direction for further investigation of thermodynamic time-asymmetry.

Energetic Causal Sets

The next alternative method for fixing the arrow of time, the energetic causal sets model, is a more radical approach: it proposes that time asymmetry is fundamental and any apparent symmetries are merely emergent. It opposes the view that time is emergent from fundamental physics and that any asymmetries are contingent or accidental. This model argues that "in contrast to the time reversal symmetry which is standard practice, time is fundamentally asymmetric and irreversible. The future is different from the past: the process by which the present becomes the past and gives rise to the future cannot be inverted to allow the perfect reconstruction of the past" (Cortês and Smolin 2014, 1). In other words, energetic causal sets take the asymmetry of time to be a primitive or foundational aspect of physical law.

How might this radically different model of fundamental physics operate? In this model, the fundamental interactions are causal chains between unique and distinguishable events, and those events have intrinsic energy-momentum variables. Each event has a history in its causal past, and these chains of relations identify the present events uniquely: there can be no two events that are identical to each other. The fundamental laws of the model avoid massive input/output sizes by embedding the causal histories into an emergent spacetime. The chain of past causal interactions transform into a definite location in the spacetime, and the coordinates in spacetime then uniquely identify each event (Cortês and Smolin 2014, 2). One might worry that the uniqueness condition disagrees with observations of repeated events or processes. For example, uniqueness seems to be at odds with the ability to run multiple trials of the same experiment. However, repeated events can be expressed through coarse-graining the causal pasts through truncating the histories at some boundary condition; such truncation preserves our observations of repeated experiments by allowing for approximate similarity between events (Cortês and Smolin 2014, 2). Elsewhere in their paper, Cortês and Smolin present a numerical model that takes these chains of energetic causal sets and demonstrate how spacetime can emerge from their assumptions (Cortês and Smolin 2014, 4-5).

This model has a few principles that frame the discussion; the principle most relevant to this paper is "Principle B," which states that time has a fundamental direction and is irreversible in the sense that the past cannot be reconstructed from the present state (Cortês and Smolin 2014, 1). In contrast with quantum asymmetry or the principle of underdetermined past, the energetic causal sets model presupposes the arrow of time as fixed. Rather than attempt to explain time's asymmetry within the framework of existing theory, this method inverts the discussion: asymmetry is taking as a primitive and the other theories are emergent behavior.

Evolving Block Universe

The final alternative I will discuss makes a similar move to the energetic causal sets in the last section: it also opposes the standard conception of time. However, rather than saying that time is a primitive that precedes physical laws, the evolving block universe model asserts that the arrow of time is fixed by the ontological structure of spacetime. Here, 'ontology' refers to the study of existence or being. For example, one might say that a blue cup sitting on a table exists, while the hallucination of a similar cup does not exist: the hallucination is illusory. In this context, the standard line on existence and spacetime is that all of spacetime exists; our perception of a past/present/future distinction is illusory or emergent.

There are three ontological commitments one can make about existence and spacetime: presentism, the block universe model, or the evolving block universe model. Presentism advocates for the existence of only the present moment; the past used to exist but no longer does and the future does not yet exist. The block universe model, as mentioned briefly above, takes the position that the past, present, and future all exist in a 4-dimensional structure. This is the standard account for spacetime. The final ontological commitment is the evolving block universe model. For the evolving block universe model, the past and the present both exist, but the future does not yet exist. Specifically, the present "[separates] the past (which exists) from the future, which does not yet exist and so does not have the same ontological status. The past is the set of events that have happened and so are determined and definite; the future is a set of possibilities that have not yet happened" (Ellis 2013, 258).

Ellis' larger project involves inter-level interactions, such as structure in larger scales emerging from the coarse-graining of smaller scale variables (Ellis 2013, 243). The discussion above about the relationship between macrostate and microstate fits into this narrative. However, Ellis asserts (counter to the quantum asymmetry alternative) that the lowest-level processes fix the direction of their arrow of time not by themselves, but through top-down effects that began at the cosmological scale (Ellis 2013, 244-5). For an example of top-down effects, consider the boundary conditions for paramagnetism. Depending on the strength of the external magnetic field and the temperature of the system, the magnetic dipole moments of the sample will align to the external field differently. In the case of low magnetic field and high temperature, the thermal agitation of the sample will correspond with a weak alignment with the external field and the magnetic susceptibility is proportional to temperature ($\chi_m \propto \frac{1}{T}$). In contrast, for a strong magnetic field and low temperature, the magnetic dipole moments are completely aligned with the external field and the magnetic susceptibility loses its temperature proportionality (Mandl 2010, 71-2). Boundary conditions at a higher level influences the behavior of members at a lower level.

Returning to the evolving block universe model, Ellis asserts that a top-down effect has fixed the arrow of time for the quantum scale, and then the bottom-up effect has extended that directionality for the arrow of time to reach other scales via coarse-graining. The top-down effect in question is the start of the universe. Ellis posits that "the global master arrow of time [resulted] from the universe's early expansion from an initial singularity in an Evolving Block Universe…pointing away from the initial singularity towards the growing boundary of spacetime" (Ellis 2013, 248). In this model, since spacetime itself has a direction (from its expansion away from the singularity), then time's asymmetry is baked into the model ontologically. From there, one can use the proper world lines of any two events to compare their relative location to each other. In fact, "if the proper time τ_P along a fundamental world line from the initial singularity to the event P is greater than the proper time τ_Q from the initial singularity to the event Q, then the direction of time is from Q to P" (Ellis 2013, 249).

One potential issue with the evolving block universe model, however, is that the model requires the present to be a definite notion. In Ellis' system above, the present acts as the transition between the past and the future. However, the present is a somewhat troubled concept: it seems to conflict with relativity's issue of simultaneity. The next section will defend the present from the simultaneity issue.

Philosophy of Time and the Present

The tension between the concept of the present and the problem of simultaneity boils down to reference frames. Suppose some event E_1 in spacetime that one wishes to say occurs 'now.' Based on one's chosen reference frame, the class of events that occur simultaneously with E_1 can vary. Events that are spatiotemporally distant from each other are simultaneous if one can construct a plane of simultaneity that connects the events to each other (Brading 2015, 15). However, there is no method for choosing a preferred plane of simultaneity within relativity itself; any selection of reference frame (that defines the plane of simultaneity) is an addition beyond relativity. Thus, if one takes the present to be all such events that occur 'now,' then the present concept is thwarted by simultaneity. Likewise, if one wishes to defend the present against simultaneity, one must find an alternative conception of the present.

One alternative definition of the present is a law-constitutive approach. In this approach, the present is taken to be "a spatiotemporal region of whatever size is needed to sustain the dynamical system in question" (Brading 2015, 17). By 'law-constitutive,' I refer to the notion that what constitutes a body or an object is that which satisfies some definite laws. For example, a Newtonian body would be one which satisfies all of Newton's laws of motion (Brading 2015, 16). Instead of the ontology being determined prior to the formalism of law, the scope of the laws sets up what is real. Now, the issue of determining the present emerges once again. If one takes a law-constitutive approach, then the present gets grounded in what exists (spacetime) without commitments to it being a singular 'now.' In fact, since the present is a spatiotemporal region in this arrangement, it can be extended in time just as it is extended in space (Brading 2015, 17). Although Brading uses this new formulation to posit an alternate version of presentism, one can take a similar approach for the present as needed in the evolving block universe model. Particularly, the presentist must distinguish the ‘present’ from the ‘history’ of a body, where the history of a body is the record of its entire spatiotemporal evolution. In contrast, the evolving block universe model needs no such distinction, since it freely accepts the existence of past events.

Another alternative definition of the present is to define it as a surface of spacetime. Ellis provides a definition of the present in his discussion of the nature of spacetime in the evolving block universe model. He states that “surfaces of constant time $S(\tau)$ will be determined by the integral of proper time τ along the timelike eigenvectors of the total matter stress tensor T_{ab} from the start of the universe to the present time” (Ellis 2013, 259). In this context, ‘S’ does not refer to entropy, it is a surface of spacetime. Notice that the upper bound for that integration will be the present time. If $S(\tau)$ defines any surface of constant time, then there exists a particular surface at the present time. Ellis denotes this surface with $S(\tau_0)$, and he goes on to define spacetime as existing for any time $0 < \tau < \tau_0$ but not for any time $\tau > \tau_0$ (Ellis 2013, 259). This definition shares with the law-constitutive approach above a distinction between the present and the ‘now.’ In Ellis’ case, he states that “these surfaces of transition need not be instantaneous for the preferred world lines, and are not even necessarily spacelike” (Ellis 2013, 259). All in all, these two definitions provide the necessary maneuver to protect the concept of present from simultaneity arguments: both allow the present to be extended past a single moment.

A Case for the Evolving Block Universe Model

The four alternatives for fixing the arrow of time presented above have significant differences with respect to each other. In this section, I will discuss some issues that these alternatives face. I will also present a case for how the evolving block universe model emerges relatively unscathed (though by no mean unmarred).

The quantum asymmetry position argues that there are cases of temporal asymmetry at the microscale that can then be coarse-grained to macroscopic scale. This continuous thread of asymmetry fixes the arrow of time in all contexts. Quantum asymmetry is weak to the following argument: cases of quantum asymmetry are corner cases rather than fundamental ones. In the case of neutral kaons, the temporal asymmetry is relatively minor; the measured symmetry violation has a magnitude of approximately 10^{-3} (Eisberg and Resnick 1985, 654). Since the magnitude is small and the asymmetry seems to pop up only in weak interactions of this particle, one can argue that quantum asymmetries are insufficiently weighted to have significant effect on the macroscale (Ellis 2013, 246).

The Principle of Underdetermined Past (PUP) also has a weakness. On the surface, (PUP) has some purchase in the discussion. It augments Boltzmann's statistical and equilibrium postulates to patch Loschmidt's paradox. However, I already mentioned above the caveat that (PUP) is not a formal law, rather it is a description of what a true solution to the paradox must accomplish (Drory 2008, 905). Furthermore, (PUP) does not escape the second limitation for entropy fixing the arrow of time: it is still a local fixing rather than a global one. Even if one found a formal law that accomplishes what (PUP) sketches out, that would still result in asserting that entropy is all one needs to fix the arrow of time. These two weaknesses cast serious doubt on (PUP) being the definitive source for fixing the arrow of time.

The energetic causal sets and the evolving block universe model both involve assuming temporal asymmetry to varying degrees. The energetic causal sets argument explicitly takes temporal asymmetry for granted as a primitive in its system. Although the evolving block universe model does not take temporal asymmetry as a primitive, it does argue that temporal asymmetry results from an ontological commitment about the nature of spacetime. In that sense, both positions ascribe temporal asymmetry a more fundamental location in their systems than either quantum asymmetry or underdetermination. Thus, both energetic causal sets and the evolving block universe model are vulnerable to a similar criticism. In the effort to locate the source of temporal asymmetry, both positions instead take as a given that asymmetry occurs globally.

However, between the two positons, the evolving block universe model has stronger ground. First, the energetic causal sets have additional baggage: they require a radical overhaul of physical theory. As I presented above, the energetic causal sets take as fundamental a chain of causally linked events. The rest of physical theory then becomes emergent behavior of that causal chain (Cortês and Smolin 2014, 4-5). The energetic causal sets have a further radical turn: as a completely deterministic model, it must explain the probabilistic nature of quantum mechanics. Cortês and Smolin assert that the truncation of the past histories of events leads to “nearly identical copies” that have hidden variables that preserve uniqueness (Cortês and Smolin 2014, 14). In contrast, the evolving block universe model preserves much of the preexisting physical theory. In fact, Ellis’ larger project about inter-level interactions depends on coarse-graining and boundary conditions in the preexisting physical theory. The energetic causal sets rewrite the canon, while the evolving block universe model adds an ontological preface to the canon. The evolving block universe model does much less violence to our theories.

Concluding Remarks

As I have demonstrated above, the common-sense notion that entropy and the second law of thermodynamics is all one needs to fix the arrow of time has key flaws. First, Loschmidt's paradox calls into question whether the second law could fix the arrow of time at all. However, even if one assumes that entropy does fix the arrow for thermodynamic systems, the locality issue prevents that arrow from affecting systems of other scales. Hence, one must search for a source for the arrow of time that would fix its direction globally.

Rather than entropy, one could find solace in alternative models for fixing the arrow of time. These alternatives included quantum asymmetry, underdetermination, energetic causal sets, and the evolving block universe model. Although each alternative had some merit, they also ran into difficulties. In summary, quantum asymmetry is not substantial enough to explain macroscopic asymmetry, underdetermination fails to avoid the locality issue, and energetic causal sets require a radical reorganization of the physical canon in addition to assuming as a primitive what it is trying to prove. Even though the evolving block universe model also takes temporal asymmetry to be more foundational, it is the strongest of the four alternatives I have presented. Therefore, the evolving block universe model is the most promising candidate for the source of the arrow of time out of the alternatives discussed in this paper. Whether some further alternative can avoid the evolving block universe model's shortcomings is a question for further research.

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