Making ”Past Hypothesis” More Robust

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Introduction

The emergence of statistical mechanics (SM) as a science in the late 19th century was marred by conceptual difficulties from the outset. The purpose of SM is to associate the dynamics of energetically isolated systems defined in terms of microstates with the type of behavior observed in thermodynamics (TD), i.e. the monotonic evolution of a small number of observables toward an equilibrium state.

Unlike other branches of physics, SM lacks a common set of assumptions required for cogency of its theoretical framework. Investigators of SM disagree on are:

- ways to represent physical systems;
- choice of initial conditions;
- the nature of the probability and statistical considerations;
- ways to translate TD properties into the language of SM,
- ways to measure and attribute entropy,
- the very nature of the reversibility and recoverability, and the list goes on.

Confusion often arises regarding the exact issues that are relevant. Is a Holy Grail of the investigation the disagreement between the monotonic behavior of TD systems and the time-reversibility of the dynamical laws of motion? Is entropy the relevant state function that makes the time asymmetry explicit? If so, exactly what definition of entropy should we use? Does thermodynamics reduce to statistical mechanics and, if so, what are the appropriate inter-theory translations? Are these questions equivalent?

Phrased in many different ways, the issue in question is the nature of time asymmetry. The relevant question is why microstates, which are governed by dynamical deterministic laws, move in the succession that they do, i.e., does one agree with Boltzmann's statistical postulate of the microstates monotonically acquiring higher entropy?

Typically, microstates are represented as points in configuration space that are volume-filling in their multitude based on a Lebesque measure. The standard way to illuminate the disagreement between the monotonic time-irreversible behavior of macro TD systems and time-reversal independent (TRI) fundamental laws of motion—classical or quantum—is to point out that it is logically impossible to *precisely* derive time-irreversible functions from TRI equations of motion and uphold all of t he assumptions inherent in describing ideal TD systems.

To be exact, the claim is that producing irreversible functions from TRI fundamentals is mathematically easy enough, but that the process inevitably involves truncating bits of information. Using a simple analogy as an example, if we add two numbers and divide the sum by two, the average number carries meaningful information about the initial components of our two-number system. In fact, it most often supervenes on the constituents. This average may be all we need for practical purposes and may be the only value useful to us. Yet, once the averaging is done, reversing the process and deriving the initial two numbers simply from their average value and the fact that the initial combination was composed of two numbers is impossible.

Approaches to Irreversibility

Statistical mechanics has a full panoply of techniques that do just that—truncate useless information for practical convenience: averaging (the ensemble approach by

Gibbs), coarse graining (Boltzman), and time graining (BBKNY) are among the many techniques employed. All of these approaches are infinitely useful to experimental physicists, accord with our observations, and solve a number of practical issues; however, in effect, they are all different forms of smudging. None of these techniques addresses the conceptual question of *exactly how* monotonic processes emerge from TRI fundamental laws of motion.

In contrast, numerous approaches were lauded to have established a genuine source of irreversibility. Some of the more prominent twentieth century schools of thought are worth mentioning here because they compete with the hypothesis that I analyze in some detail in the next chapter. These schools of thought are as follows.

- *Interventionists* claim that systems are never closed and environmental perturbations (e.g., fields) are the cause of randomization.
- *Limitationists* claim that reversing the time direction of microstates in any meaningful sense is impossible.
- *Quantum mechanists* claim that noncommutability of the observations of microstates is sufficient for introducing randomization; also, the classical phase space correspondence of microstates to their true QM equivalents is a poor match at best for reasons of in-translatability of QM degrees of freedom into classical equivalents.
- *Ontologists* claim that TRI laws are inadequate in describing microstates.

What is the Past Hypothesis?

Having exhausted the available conceptual and mathematical toolkit of physics during a 150-year quest to find a satisfactory answer, making the initial conditions of the relevant TD systems responsible for time-irreversible behavior has become canonical among physicists and philosophers of science. Presented with difficulty in pinpointing with precision T-zero for any TD system (Albert, p.89) [1], it is common to assume that the relevant initial conditions are those at the beginning of the universe itself, sometime at or shortly after the Big Bang.

Importantly, the claims about the early universe's low entropy state are usually made from purely statistical considerations. To quote Albert [1] (p.18), "the fact that the universe came into being in an enormously low-entropy macrocondition cannot possibly be the sort of fact that we know or ever will know, in the way we know of straightforward everyday particular empirical facts... Our grounds for believing it turn out to be more like our grounds for believing general theoretical laws. Our grounds are inductive; our grounds have to do with the fact that the proposition that the universe came into being in an enormously low-entropy macro condition turns out to be enormously helpful in making an enormous variety of particular empirical predictions."

Albert echoes Roger Penrose [2], who suggested just such a law—one that governs space-time singularities and mandates them to have low entropy. Penrose achieves this goal through the invocation of a geometrical limitation on space-time curvature that forces a smooth intrinsic structure and, therefore, extraordinarily low entropy.

Deeming low entropy for emerging singularities as a new law of nature makes room for an equally important tagalong discussion on the behavior of branch subsystems, the kinds of things we observe daily; however, the law-like status of any overarching posit should, as a bare minimum, be subjected to all of the rigors of testing that the status implies. One such test is establishing that such a state is produced with regularity. For example, observing other singularities, or mini Big Bangs (white holes) so to speak, as having low entropy in accordance with such a posit would certainly support the claim to a law-like fame. To my knowledge, no successful experiments established this state with regularity. Lack of any experimental data and the very fact that this postulate is based on a single event makes the attribution of law-like status less convincing. Therefore, the task of making possible, if not plausible, the condition of initial low entropy of the universe is handled from different angles, on which more shortly is discussed.

Before going further, we recap the discussion up to this point.

The overarching conclusion is that epistemically observed macrostates would not be what they are (given the uniform distribution over microconditions compatible with the macrocondition of an observable universe or any of the TD subsystems) at present if a further severe restriction of compatibility with what we know of the past is not imposed. This additional limitation on the available phase space volume is only possible if the entropy of a TD system prior to the observed event—and in the limit, the total entropy of the universe at some point in its early life—is assumed to be small or, in any event, smaller than the entropy of the universe at any subsequent moment in time.

In other words, past hypotheses (PH) states that:

- at some point in the early universe, its entropy (defined in terms of a TD or SM apparatus) was lower than at any subsequent point in its evolution, and,
- this fact, jointly with the second law of TD, is responsible for the irreversible behavior of TD macrosystems that we observe daily.

Various advocates of the PH contend that establishing the link between statistical mechanics and early universe cosmology is an exercise loaded with conceptual difficulties. Opposition to the theory is strong. The thinking is that although we may never know the entropy generation mechanism at the time of the early universe, hypothetically suggesting just what it may be does not hurt. Better yet is to account for it in accordance with the indisputable established laws of physics. Simply postulating the entropy metric as being low and elevating it to the status of another fundamental law on this view is akin to replacing the genuine issue that calls for explanation with a label—a belief of sorts. Among others, Beckwith and Earman hold that the issue requires further analysis.

Opposition to PH

Scientists who reject PH make a two-pronged attack: they object to the applicability of all known definitions of entropy for the universe as a whole on a technical merit and, second, they question the *plausibility* of the low entropy state at the time of early universe based on statistical considerations that point to a large entropy of the universe at present.

To be fair, opponents of PH do not question the convenience of the would-be low entropy state of the early universe for the purpose of building the foundations of SM, but they do question the sense in which any notion of entropy is meaningful at the time of inflation and shortly thereafter.

Some of the apparent conflicts are easily solved. I would like to take a closer look at the ones that appear to be show stopping.

John Earman, a professor of philosophy at the University of Pittsburg, articulated views that are most radically opposed to PH. According to him, a connection between the initial conditions of the universe and epistemically derived values of TD branch systems is forced, unwarranted, and—at worst—akin to a category mistake made through binding ill-matched posits: laws applicable to closed systems are applied to a possibly infinite universe; the behavior of large-scale systems is made mathematically incoherent with that of branch component systems; and the Boltzmannian notion of entropy, ill-defined in his view for the universe at or shortly after the Big Bang, is irrationally made to account for the experimentally observed macrostates of ordinary systems. In his view, the very notion of pivoting the foundations of statistical mechanics on specific initial conditions at the beginning of time is borderline bizarre because the "advantage [of such an approach] is not worth the metaphysical baggage used to secure it." (Earman, p.414) [4]

Notwithstanding the strength of Earman's objections, I take a more benign view. Instead of invalidating the arguments to make PH plausible, I focus on the logical, mathematical, and experimental assertions that need to be made manifest to increase the credibility of the PH's role in the foundations of SM. Rather than reject out of hand our inability to define a meaningful entropy measure in the context of general relativity, I suggest qualifications to the entropy definition that make such a measure applicable to a statistical mechanics project.

To begin with, we delineate the assumptions that underlie textbook SM accounting. A perfect TD system is often viewed as:

1. energetically isolated,
2. made of particles viewed as hard spheres that are
3. undergoing perfectly elastic collisions,
4. guided by Hamiltonian dynamics,
5. and that has the property of being divisible into subsystems such that the sum total energies of the subsystems equals the total energy of the system.

The claim is that these assumptions, however rough an approximation they may be to the early universe, do not violate the integrity of the ensuing argument. Adherents of Boltzmann that view the entropy metric as a *number* that measures the phase space volume of microstates (based on a standard Lebesque measure) compatible with a given macrostate, depend on the above assumptions for the very existence of the theory. In its classical setting, the SM definition of entropy implies the ability to model the state as a point in configuration space with 6N coordinates—three for each particle's position and three for its momentum. If no particles exist, there would be positions and no momenta and, therefore, no phase space trajectories in any meaningful sense.

The counterclaim is that this simplification patently deforms the argument as it is applied to the early universe and, as a bare minimum, should not be made offhandedly.

To make the discussion of entropy intelligible, something needs to be said about what present-day cosmology holds as knowledge and commonly accepted conjecture for the early universe.

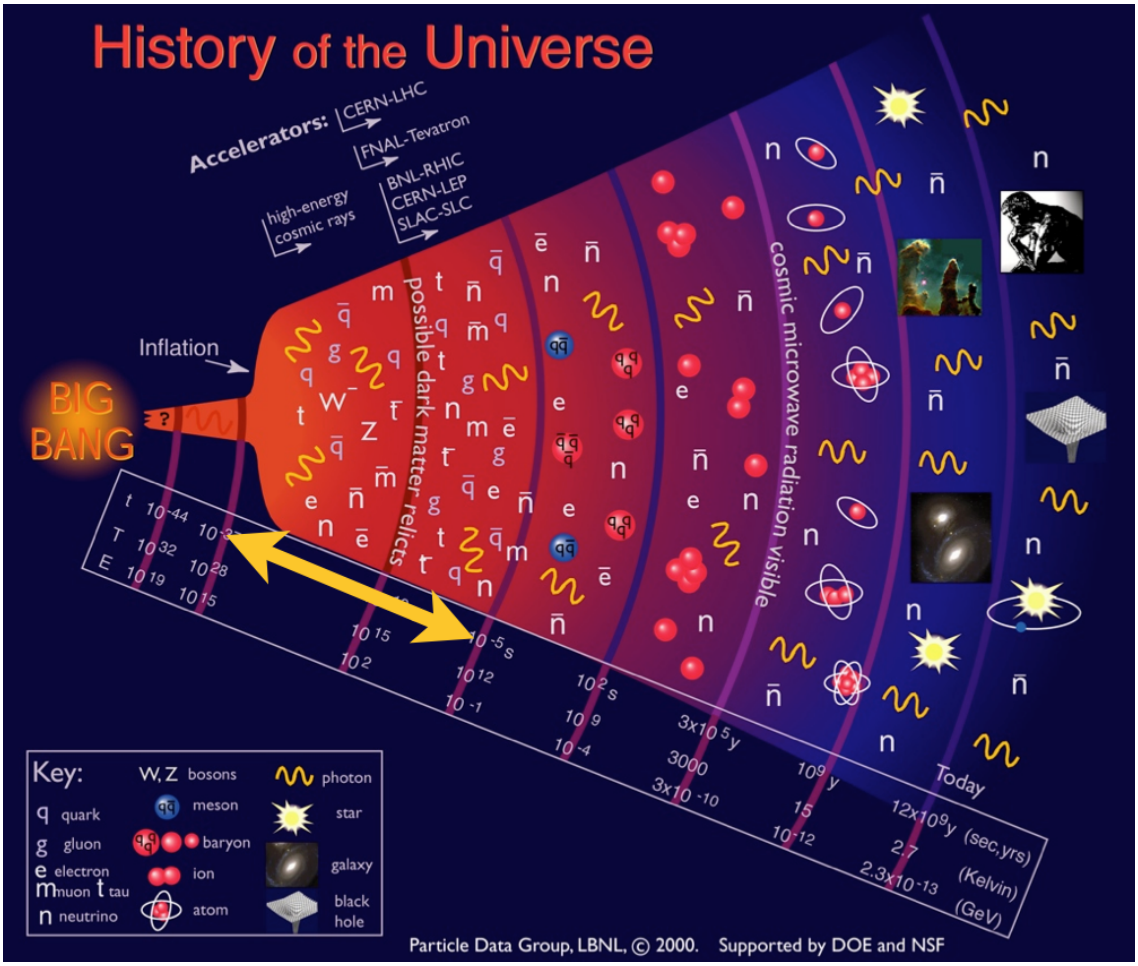

Figure 1: The history of the universe

Early Universe Cosmology Primer

Figure 1 is a visual depiction of universe's history. We are presented with a universe dating back to 10^{-43} seconds from T-zero. The conditions prior to 10^{-43}—the so-called Planck era—were so extreme that the physics we know is inadequate to describe them. This brief period of the unknown was followed by the so-called Grand Unification Theory (GUT) era that lasted between 10^{-43} and 10^{-38} seconds and superseded by the Electroweak Era (between 10^{-38} and 10^{-10} seconds) during which four fundamental forces of nature (gravity, strong, weak, and EM) manifested themselves separately.

Originally motivated by the need to explain the uniformity of photon distribution (Ryden [3] pp.191–208) and temperature observed experimentally through an analysis of cosmic microwave background (CMB) radiation coming at us from causally disconnected parts of the universe, a suggestion was made that, at some point at the end of the GUT Era or in the early Electroweak Era, the universe underwent a period of rapid exponential expansion and increased in size by a factor of at least 10^{43}. This gigantic and almost instantaneous increase in size is viewed as accounting for a universe that appears flat, homogeneous, and isotropic. Without this process, one expects to see a highly curved, heterogeneous space. This period of expansion, conveniently termed "inflation" by Alan Guth in 1980, lasted from 10^{-36} seconds after the Big Bang to sometime between 10^{-33} and 10^{-32} seconds.

However, our question is the issue of entropy under such extreme conditions.

As previously mentioned, the theory of inflation is called on to explain the remarkable homogeneity of matter in space over large scales, as is evidenced by our CMB measurements. The energy and temperature of particles coming from beyond each other's causal horizon is the same to within one part in 10^5. To quote Barbara Ryden [3] (p.195), "If you invite $20,000$ people to a potluck dinner, and they all bring potato salad (having 10^5 dishes to choose from with equal probability), it starts to dawn on you that they must have been in contact with each other."

The mechanism for what caused and drove inflation is a hot debate topic but is commonly represented mathematically by a scalar field $\Phi(q,t)$ that was uniform (had the same value at every point in space) at the instance before the inflation began. Importantly, cosmologists do not make any attribution of meaning for why this field was such and such or what caused it in the first place—it is simply a mathematical representation of the mechanism that needs to account for the inflation the way we conjecture it to be. Espoused by the majority of mainstream cosmologists, this model holds that, immediately prior to inflation, the universe was dominated by radiation and the horizon size was:

$$d(\text{horizon}) \approx 6 \cdot 10^{-28} \text{ m}$$

The respective size of the universe visible to us at present was $6 \cdot 10^{-44}$ m prior to inflation. In other words, the constituents of the observed universe, whatever they may have been at the time prior to inflation, had plenty of opportunity to come into thermal contact with one another.

Immediately after the inflation, the causal horizon size shot to 0.8 parsec or $15,338,809,300,000$ miles. Also important is that *within this hugely expanded sphere* the portion of the universe *currently visible* to us given all of the stars, galaxies, and galaxy clusters that we observe was crammed into a sphere of six feet across.

We pause for a second because this metric is astonishing—what we see or can possibly ever see of the universe is smaller than the estimated size of the universe proper by a factor of 10^{16}! The difference is so staggering that it is, as is so many things in cosmology, impossible to comprehend with our classically conditioned mind. This drastic mismatch between, on the one hand, what we could possibly ever hold knowledge of or have experimental confirmation of and, on the other hand, what we could never know of the universe, forgives one for thinking that all of the talk of our ability to speak intelligently about the entropy of the entire universe is at best wild speculation. Indeed, what could be the relevant measure of entropy, if anything, immediately before and immediately after the inflation? Does this measure translate into any of the definitions of entropy we use in SM, TD, or information theory? Most importantly, what is the relevance of any such inference for the task of explaining macro-sized TD processes that we observe daily?

The first-order question is to establish whether "entropy" has an explicit meaning in the cosmological context at all.

Defining Entropy of the Universe

Conceptual problems start quickly and a great many of them received due attention in research papers. Even though there is often disagreement and confusion, time-honored ways exist to deal with small qualms. I quickly point out the relevant issues to assemble the mental toolkit for the main argument of this paper: the crucial arguments that are lacking, in my view, to make PH more credible.

Strictly speaking, the universe does not meet the criteria for a TD system. Because its gravitational energy cannot be partitioned into contained segments, the total energy of the universe—to the extent that it can be established—is not proportional to its volume; therefore, it is not an extensive quantity with additive properties, which is a requirement for a TD system. In the TD limit, entropy becomes a function of energy according to a well-known formula:

$$S(E, a\Delta E) = k_B \ln[\text{number of states with energy between } E \text{ and } E + a\Delta E] =$$
$$k_B \ln[\alpha \times (\text{number of states with energy between } E \text{ and } E + \Delta E)] =$$
$$S(E, \Delta E) + k_B \ln \alpha.$$

and should also be additive. Less clear is how this could be accomplished based on nonadditive properties of gravitational energy that prima facie need to be accounted for when total energy is calculated.

Second, the universe is expanding according to Hubble's law and, therefore, is not stationary—a requisite property of an equilibrium TD system. Third, by definition, for the universe to be in thermodynamic equilibrium with another system is not possible.

Therefore, discussion about the Clausius-type TD entropy described by

$$TdS = d(\rho V) + pdV (\rho \text{ and } p \text{ are the equilibrium energy density and pressure})$$

of the universe is sensible only if we apply the qualifications of a *local thermal equilibrium in the comoving volume* to account for the expansion.

If we agree on these qualifications, then this result echoes the standard TD description of entropy for *quasistatic* processes, i.e., processes of the kind for which the volume of the system is viewed to change slowly enough for molecular collisions to keep the system at instantaneous equilibrium.

If, in fact, the universe were in thermal equilibrium, the entropy per quasistatically comoving volume should have been conserved. And so the Standard Model assumes that the universe was expanding slowly enough following the initial exponential expansion for the first 300,000 years of its existence. It must follow then that if the entropy estimate for the observable universe of approximately 10^{90} is anywhere close to being true, this number is in radical disagreement with what we surmise to be the low entropy of the universe prior to inflation. This conjecture about the low entropy initial state, as we previously pointed out, is not a foregone conclusion and needs proofs that are more rigorous than the ever-present hand-waving arguments.

To devise a path toward such theoretical or experimental proofs, we need to look at the mechanism in the very early universe that was responsible for this massive increase in entropy between the beginning of the Electroweak era and the time when the expansion became linear and quasi-static. The next step is to analyze how the emergence of structure driven by nuclear and gravitational forces (that prima facie looks like an entropy-reducing process) could accord with the second law of TD. This could shed light on the argument of whether entropically favorable processes in the universe are continuing and whether they could be responsible for the behavior of the subsystems that we observe.

Before we proceed, we quickly summarize of the previous discussion.

- The definition of the entropy of the universe invoking the Boltzmann/Gibbs apparatus is not straightforward. It can be made intelligible (1) for the observable universe and (2) under the assumption that a mechanism exists that accounts for the influence of gravity.

- At present, the entropy of the universe is a very large number that is severely mismatched with the low entropy of the universe in its supposed initial smooth state.

- The reasons for the attribution of low entropy to the initial smooth state need to be made explicit.

A *statistical mechanical* approach to universe entropy is no less contentious.

Universe curvature is described by the Robertson–Walker metric, which can have values of –1 (open-ended universe), 0 (flat universe), and +1 (closed universe). The current mainstream view is that, in its present state, the universe is flat and open-ended at large scales and is curved locally. Even if it was not open-ended and was closed at large scales, most of the universe is unobservable as we previously established, and is causally disconnected from us, leading to a well-researched horizon problem.

In this context, the introduction of the Gibbsian micro-canonical ensemble is less than straightforward. In standard fashion, the ensemble is applied to closed systems to normalize both the measure on the volume of phase space taken up by microstates compatible with a given macrostate and the total volume of the phase space. Short of well-defined normalization functions, the mechanics of a relationship between entropy and probability distribution begs closer examination because it goes beyond the scope of well-known formulae.

As a minimum, the infinite extension of the universe appears to chip away at our ability to use the standard SM definition of entropy of the Boltzmannian mint, preventing us from using the classical configuration space (either phase space of mu-space) for a closed system. Indeed, how are we to invoke a measure of "volume of phase space compatible with the present macrocondition relative to all available phase space" if "all available phase space" is infinity?

The standard way out of this conceptual hiccup is to forego talk about the entropy of the universe as a whole and to replace it with an entropy density distribution over the observable part of the universe. To this end, cosmologists often talk about "entropy per baryon" in the observable universe.

The second issue—the effects of gravity—seems to breed much confusion in philosophical literature. One claim is that gravity makes the universe patently nonergodic in that the trajectories of the microstates of the universe are not free to pass through all available points in phase space (Hawking and Page, 1988 referred to by Earman [4], p 417). Instead, the trajectories of the microstates are restricted by the non-negligible gravitational degrees of freedom.

In this sense, gravity severely limits the available phase space for a given macrocondition. For example, a cloud of gas in a smooth uniform state that is considered in thermal equilibrium to imply the highest entropy state available to it would in fact be in a state of low entropy in the presence of gravity. This prima facie contradiction is viewed as invalidating – from a different angle – the probability interpretation of phase space relations. It also manifestly makes space averages unequal to time averages—a definition of ergodicity. In Earman's view, it is unclear how one applies appropriate coarse graining to such a system to make it compatible with the Gibbsian ensemble apparatus.

Another school of thought exists on the issue of gravity. A highly illuminating paper on the subject was published in 2009 by David Wallace, an Oxford scholar [5].

Echoing Albert [1], Wallace proposed to treat gravity as just another force between the particles. He disputed the claim that gravity changes the volume of any given macrostate. Instead, in his view, gravity affects the *value of macroscopic parameters* (such as energy) that characterizes each macrostate. Short of a limiting case of black holes in which gravitational radiation is present, he proposed treating gravity as simply a force between matter particles in a Newtonian sense and claimed that the talk of *gravitational degrees of freedom* as such is nonsensical. Wallace presented compelling arguments in favor of viewing gravity as a catalyst rather than a cause of thermodynamic processes. In his view, phase space in the Boltzmannian sense is just what we always said it was: six degrees of freedom for each particle—three for the position and three for the momentum.

Yet another approach is advocated by practitioners of Quantum Field Theory [6]. They suggested a mechanism for evaluating the contribution of gravity to entropy through the counting of gravitons, a hypothetical spin-2 massless particle. "The standard which should be used is that of talking of information, in the Shannon sense" [6] (p.2). Of course, the missing argument is the detection of a graviton. When and if this discovery is made, gravitons could be directly introduced into the specification of the microcondition of the universe. Incidentally, the estimate for the entropy of the observable universe QFT is on the order of 10^{88}, off by only two orders of magnitude from the traditionally motivated number of 10^{90}.

An alternative is to renounce the approach altogether and to make an argument along the lines of the following:

1. The contribution of gravitation over distances larger than galactic clusters is negligible and most matter in the universe is gravitationally unconnected.

2. As a result, the universe is homogenous over large distances and, most importantly -

3. The entropy contained in massive objects is infinitesimal compared with that carried by mass-less particles that make up CMB.

One expects an immediate objection to the first two points, stating that prior to the inflation, this was not the case. Thus, we are left struggling with the question of why the universe was uniform at for the first 300,000 years of its existence against overwhelming odds.

The third point on the list is significant. It makes manifest the question of what we are ultimately attempting to achieve. Should we indeed be concerned with attempting to understand the specifics of the cosmic entropy density and somehow build the bridge between whatever inferences we derive from it and our daily experiences? Alternatively, should we attempt to make an argument along the lines of what entropically favorable processes brought our stellar neighborhood to the state in which we observe it to be, and then attempt to explain how TD processes in our immediate stellar vicinity could be responsible for the behavior of TD macrosystems that we observe?

To answer this question, we look at the early universe again.

Transition to 10^{90} Entropy, Baryogenesis

In the following section we will be addressing the entropy-favorable processes during the period after approximately one minute from the Big Bang. We will conclude that these processes were conducive to the formation of structures, aka low entropy matter and high entropy radiation, at the same time preserving the adiabatic nature of the expansion and the second law of TD. However, something needs to be said about how the entropy theoretically available to the universe could have leapt from its initial pre-inflation low value when the universe had but a handful of quarks and gluons to a state of relatively high entropy immediately afterwards.

To be fair, it is unclear what kind of entropy is applicable to this accelerated expansion stage, the inflation being a highly non-equilibrium process. Some authors suggest that, other than thermal and statistical entropies, a quantum entanglement entropy should be looked at, as it relates particles located within the causal horizon and those outside [5].

The standard Big Bang cosmology offers baryogenesis as the dynamical mechanism that, at some point in the early Electroweak era, generated a large net baryon number that were further used in nucleosynthesis. The inference that baryons were produced out of quantum perturbations that followed the initial exponential inflation is purely theoretical. It would be enormously illuminating to have an experimentally observable and detectable CMB spectrum that is sensitive to the formation of baryons and further re-heating resulting from fusion.

It is a conjecture worth investigating whether baryogenesis and issues associated with the initial exponential inflation produced a massive jump in entropy and therefore are responsible for the asymmetries of time. We only point out this issue on the basis of its fundamental significance to the question of the direction of time. We will side-step further analysis of baryogenesis focusing instead on how the processes that took place *after* the universe had 10^{90} particles could cohere with our daily observations.

Early Universe Equilibrium

Numerous approaches exist on how exactly to account for universe entropy but there seems to be an agreement on one thing: the Standard Model of the universe does make a direct claim that the universe after the initial exponential inflation was a smooth primordial soup of elementary particles, i.e., some kind of very hot uniform gas. This primordial cloud was self-gravitating; yet, for 300,000 or so years, it remained a very hot uniform gas. Earman and others referred to a heuristic argument by Penrose that, when accounting for gravitational DFs, the probability that the universe is in an initially smooth state is one part in 10^{10-123}. Regardless of how this number is arrived at and its the level of precision, the claim is that the smooth initial state of the universe is overwhelmingly improbable, translating into a very low entropy measure.

As an aside, one school of thought states that probability is the wrong term to use for the beginning of a universe altogether. This view claims that the Big Bang is a one-of-a-kind event that, of course, by definition prevents it from being related to the frequency of similar observations. The definition and interpretation of probability is an immensely rich philosophical debate that is beyond the scope of this paper; thus, for the sake of our discussion, I suggest that we use the term *unlikely* and *improbable* synonymously. We are concerned with the question of what relative entropy attribution to make to this initial state. Whether the entropy metric is low or high is purely a conjecture on the basis of certain assumptions about the initial state. As David Wallace stated in his 2009 paper (Wallace. [5]), 'on a pain of a crisis in physics, the entropy of the early Universe had better be lower than its present entropy.'

The PH, more of a foundational posit for philosophers rather than that required by physics, pivots its validity on this very fact: that the entropy at some point in the early universe was small and, importantly, that metric has increased ever since. The following summary is based on textbook physics that echos Wallaces views mentioned in the previous section. The most significant worry seems to be the attribution of low entropy to the state that we hold to be in near thermal equilibrium. We go back to the definition of equilibrium. TD equilibrium is a state that experiences no net flows of matter or of energy, no phase changes, and no unbalanced potentials, within the system. Typically, equilibrium also means that a system is in the state of highest entropy available to it, which is easy to say for the ideal gas for which particle interactions are assumed to be negligible forever and gravity is neglected.

In the case of the expanding universe, until the temperature dropped to the point at which fusion reactions were possible, to remain in equilibrium, the expansion had to be slow enough to account for the equilibration effect of particle collisions. Until the fusion became available, the expansion was most likely quasi-static and adiabatic. In the "primordial soup" of the early universe the attractive potentials of the strong force and gravity were balanced by the immense kinetic energies of the elementary particles moving about. These enormous kinetic energies of the particles prevented them from fusing with one another - a process that would give rise to processes that are favorable to further increases in entropy and the universe for the time being was only in local thermodynamic equilibrium.

As inflation progressed and temperatures dropped to those that made fusion reactions possible (approximately 10^{11} K), the time scales changed. The inflation at that point was required to progress much slower to preserve equilibrium because the equilibration mechanism needed to account not just for interatomic collisions but also for the possibility of fusion. Expansion at the same rate would have thrown the system out of equilibrium and - importantly - increased the maximum possible entropy available to it. As fusion reactions became dominant, the entropy increased even though the cloud became less uniform and less smooth. Even though this process intuitively appears to be entropy-*reducing*, that is, even though the matter appears to be evolving from a smooth state into a state that has structure, *under the right kind of thermodynamic and gravitational environment both fusion and gravitational clustering are entropically favorable processes.*

Wallace questioned the oft-cited claim that the increase in entropy during the clumping should be attributed to gravitation. The entropic effects from gravitational energy (simply an attractive potential energy of the system) should be viewed only in conjunction with the kinetic energy of the system. Moreover, the typical contraction of gravitating systems that lead to the formation of nonuniform structures is, in any event, only to a certain degree, dependent on the kinetic energies. Therefore, any view that implies that all gravitationally endowed processes should simply be expected to undergo a gravitational collapse to achieve their highest entropy states without any regard for other energies available to the system is wrong. Instead, gravity should be viewed a catalyst that aids the crossing of energy barriers that exist through thermodynamic entropy-increasing processes.

The exact mechanics of anisotropies resulting from inflation involving gravity and quantum fluctuations is not relevant for our purpose. What is important is that in both cases the clumping (structure formation) was followed by the immense release of photon radiation that, as we mentioned before, accounts for the large portion of new entropy. So what we have in the end is low entropy matter that accounts for the small part of the entropy budget and radiation that takes up most of it. Therefore, to sumarize, we hold that the combination of factors that started with

1. inflation, leading to
2. universal cooling, leading to
3. the decrease in the kinetic energies of the particles, leading in turn to
4. fusion reactions available at the right temperaturesis the culprit for the entropic increase.

Importantly, the overall entropy of such a system then splits into a relatively low entropy of the matter and a very high entropy that is released into space in the form of radiation.

Branch Systems

So far we made a very high-level account of the universe evolving towards states of higher entropy from its initially low state. We also said that the formation of structure, large scale (galactic clusters) and small scale (stars) is in no violation with the entropically favorable processes in the purely Boltzmannian sense. So how do we parlay this over-arching mechanism into our everyday experience? In other words, how do we make an argument that all of what we said about the universe is relevant to a drop of milk dissolving in coffee and all of the ice cubes placed in cups of lukewarm water around the world melting? Well, prima facie, this should not be a problem: take an active star (Sun) that is undergoing nuclear reactions at its core releasing immense amount of radiation into space in the form of photons. This radiation supplies energy into energetically open systems of nearby planets (Earth) throwing TD processes on their surfaces out of balance and supporting the formation of complex structures (life) in the process. If any part of the planetary system that could approximate a TD system (milk and coffee) is energetically isolated, things move to high entropy states (for the most part, but not necessarily, disorderly states) quickly in accordance with the Second Law of TD.

Eric Winsberg, a University of Florida scholar, presents us with the following conceptual wrangle that stems from the Boltzmannian phase relations of micro-states [23] :

> At time S, no matter what the macro-state of the universe, the micro-state of the universe is confined to the small fibrillated region that is compatible with the past hypothesis. Now restrict attention to the sub-space of the uni- verses state space that represents only the particles that will be trapped inside the cooler. The macro-state of the cooler will be confined to the region that is compatible with the past hypothesis. Since it is overwhelming likely that the universe is in a region that will lead in the future to steadily higher entropy, it must be overwhelmingly likely that the micro-state of the cooler is in some subregion of the fibril-lation that will lead in the future to the coolers steadily higher entropy. Conversely, it is overwhelmingly un- likely that the micro-state of the cooler-contents is in the extremely small subregion that will lead to its having decreasing entropy from time P to time T. Thus, I know that the entropy at time P must be lower than at time T, which is in turn lower than at time T+ But here is the rub: these are the same two sets! Restricting the set to those micro-conditions that are compatible with the past hypothesis does nothing because the cooler-contents pre-

vious interaction with the rest of the universe effectively randomizes the micro-configuration of the cooler- content.

Winsberg's argument makes the danger of simplifying the assumptions very clear. Specifically, what is lacking, and this is where he is making an important point, is the mathematical argument that makes explicit how the phase space taken up by micro-states of branch systems is restricted by the PH. Indeed, the PH claims that the observable branch systems' micro-state ensembles should be restricted by (1) their compatibility with the observed macro-conditions, as well by (2) the available evolution trajectories compatible with the hypothesis of the low early universe entropy. How indeed can we compare the phase space volume of systems that have vastly different number of dimensions? By way of a simple example, a hypothetical branch-system's phase space can have exactly 6 dimensions if we are considering a system composed of one elementary particle. The phase space of the universe, by the same token, is approximately 10^{88}N. Further, the phase space of the universe itself could have undergone radical changes in dimensionality during its evolution. We make compelling arguments in the previous section how the formation of structure could be an entropically favorable process but the question of compatibility of phase spaces of branch systems with that of the universe is mathematically non-trivial. Lending this argument to the rigors of mathematical physics formulae would be an momentous breakthrough in support of the PH.

Conclusions

Our observations of irreversibility are manifestations of state functions for monotonic TD systems. Entropy defined using the standard analytical SM apparatus is as good a candidate for the representation of monotonic behavior as any, but also is more helpful than competing functions in a number of relevant ways. Irreversibility can be viewed as a manifestation of time asymmetry that, from the viewpoint of calculating entropy, could be traced to the beginning of the universe. The Past Hypothesis holds that the initial state of the universe had low entropy and that the entropy for the observable part of the universe as a cumulative metric has increased since. As the originally hot and smooth universe cooled with expansion, the clumping up of this primordial gas through nuclear fusion and gravitational potential became entropically favorable. This clumping in perfect accordance with the second law of TD resulted in the formation of structures, such as stars and planets and, eventually, black holes concurrent with the release of radiation. Stars and planets, such as the solar system and the Earth, account for a very small part of the universe's entropy, the largest part being taken up by CMB and black holes. In particular, an active star could be in a state of local TD equilibrium and, therefore, in a state of highest entropy available to it at the time. This entropy is still significantly lower than the entropy level available to the star if its entire mass was converted into uniformly distributed radiation that is equivalent to the state of global equilibrium. An active star undergoing entropically favorable processes of TD fusion radiates energy to nearby planets. This energy upsets the TD equilibrium of various systems on these planets that allows, on the one hand, for the formation of more complex structures (such as life) and, on the other hand, for the observational experience of the irreversible evolution of macro-sized subsystems—temporarily knocked out of equilibrium—toward states of higher entropy in accordance with the second law of TD.

In my view, this account could be further endorsed if:

1. An agreement was reached on the established procedure for calculating the entropy of the universe.
2. Experiments identified an observable that is sensitive to baryon production and re-heating of the early universe; and
3. A mathematical argument was devised for exactly how the PH limits the phase space available to macro-conditions of branch systems.

References

[1] *Albert, D.* Time and Chance, Harvard (2000).

[2] *Penrose, R.* “Singularities and Time Asymmetry.” Cambridge: Cambridge University Press (1979).

[3] *Ryden B.* Introduction to Cosmology, Addison Wesley (2003).

[4] *Earman J.* ‘The “Past Hypothesis”: Not even false’, Studies in History and Philosophy of Modern Physics, Elsevier (2006).

[5] *Wallace D.* ‘Gravity, entropy, and cosmology: in search of clarity’ (2009), arXiv:0907.0659v1 [cond-mat.stat-mech] 3 Jul 2009

[6] *Beckwith A.* “Entropy growth in the early universe and confirmation of initial big bang conditions”

[7] *Frigg, R.* Compendium of Quantum Physics, Springer (2009).

[8] *Frigg, R.* Time, Chance and Reduction, Cambridge (2010).

[9] *Thalos, M.* ‘An Essay on Competitions between Micro and Macro in Mechanics’, Philosophy and Phenomenological Research, 1999, Vol. 59, No. 1.

[10] *Butterfield J., Earman J* Philosophy of Physics, Elsevier (2007).

[11] *Frigg, R.* ‘Entropy – A Guide for the Perplexed’ (2010).

[12] *Sklar, L.* Physics and Chance, Cambridge (1993).

[13] *Pathria, R., Beale, P.* Statistical Mechanics, Elsevier (2011).

[14] *Frigg R.* ‘Chance in Boltzmannian Statistical Mechanics’ (2008).

[15] *Callender C.* ‘Reducing Thermodynamics to Statistical Mechanics: The Case of Entropy’, The Journal of Philosophy, 1999, Vol. 96, No 7, pp. 348-373.

[16] *Batterman R.* ‘Irreversibility and Statistical Mechanics: A New Approach?’, Philosophy of Science, 1990, Vol 57, No 3, pp. 395-419.

[17] *Uffink, J.* ‘Irreversibility and the second law of thermodynamics’ (2001).

[18] *Lieb E., Yngvason J.* ‘Physics and Mathematics of the Second Law of Thermodynamics’ (1999) http://lanl.arxiv.org/abs/cond-mat/9708200v2.

[19] *Chen, P.* ‘Inflation as a Solution to the Early Universe Entropy Problem’ (2013), arXiv:1212.1087v3 [astro-ph.CO] 1 May 2013.

[20] *Carrol S., Chen J.* ‘Spontaneous Inflation and the Origin of the Arrow of Time’ (2004), arXiv:hep-th/0410270v1 27 Oct 2004.

[21] *Callender C.* ‘The Past Hypothesis Meets Gravity’, Department of Philosophy, UCSD, La Jolla, CA 92093, USA (2012).

[22] *Uffink, J.* ”Compendium of the Foundations of Classical Statistical Physics” in Philosophy of Physics (Handbook of the Philosophy of Science), eds. J. Butterfield and J. Earman, North Holland, Amsterdam (2007), pp. 923-1047

[23] *Winsberg E.* ‘Can Conditioning on the “Past Hypothesis” Militate Against the Reversibility Objections?’ (2004).