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The Thermodynamical Arrow of Time: Reinterpreting the Boltzmann–Schuetz Argument

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The recent surge of interest in the origin of the temporal asymmetry of thermodynamical systems (including the accessible part of the universe itself) has put forward two possible explanatory approaches to this age-old problem. Hereby we show that there is a third possible alternative, based on the generalization of the classical ("Boltzmann–Schuetz") anthropic fluctuation picture of the origin of the perceived entropy gradient. This alternative (which we dub the Acausal-Anthropic approach) is based on accepting Boltzmann's statistical measure at its face value, and accomodating it within the quantum cosmological concept of the multiverse. We argue that conventional objections raised against the Boltzmann–Schuetz view are less forceful and serious than it is usually assumed. A fortiori, they are incapable of rendering the generalized theory untenable. On the contrary, this analysis highlights some of the other advantages of the multiverse approach to the thermodynamical arrow of time.

KEY WORDS: entropy; arrow of time; anthropic principle; philosophy of cosmology.

If the doors of perception were cleansed,
everything would appear to man as it is, infinite.

William Blake, *The Marriage of Heaven and Hell* (1793)

1. INTRODUCTION: THE NATURE OF THERMODYNAMICAL EXPLANANDUM

The problem of the time-asymmetry of thermodynamics—already more than a century old in its *modern* form!—is the following. In our experience,

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systems increase in entropy in the forward direction of time. The underlying dynamical laws, which are taken to govern thermodynamic systems, however, are symmetric in time: statistical mechanics predicts that entropy is overwhelmingly likely to increase in both temporal directions. So where does the asymmetry of thermodynamics and of our experience generally come from? It was, of course, the great Ludwig Boltzmann who—prompted by Loschmidt, Culverwell, and Burbury (joined later by Zermelo)—asked that deep question, contingent on his statistical explanation of thermodynamical phenomena; in his words, "is the apparent irreversibility of all known natural processes consistent with the idea that all natural events are possible without restriction?"[1]

During the last decade we have been witnessing a renaissance of interest in the problem of thermodynamical asymmetry of the world around us among physicists and philosophers alike (e.g., Refs. 2–7). In two recent remarkably clear and interesting papers, Australian philosopher of science Huw Price attempted to show that there are two competing projects for the explanation of the perceived thermodynamical asymmetry, which he labels Causal-General and Acausal-Particular approaches.[8, 9] Furthermore, his intention was to show the superiority of the Acausal-Particular approach, which is in accordance with other pieces of his atemporal worldview, which he also presented in his recent brilliant monograph on the subject of temporal asymmetries (Ref. 3). The answer Price advocates relies on a low-entropy initial boundary condition: if the initial state of the universe is one of extremely low entropy, then Boltzmannian statistical considerations yield an overwhelmingly likely entropy increase towards the future throughout the history of the universe. Price contrasts this account—a version of what he calls the *Acausal-Particular* approach—with those theories that derive thermodynamic asymmetry from some underlying asymmetric causal or dynamical mechanism operating at all times (like the quantum-mechanical state reduction in quantum theories with dynamical reduction), what he calls *Causal-General* views (cf. Ref. 5). Causal-General views necessarily contradict Boltzmann's attitude toward the time-reversal asymmetry: "This one-sidedness lies uniquely and solely in the initial conditions." To Price's mind, these two kinds of account are the only serious contenders to explain the time-asymmetry of thermodynamics.

In this paper, we would like to show that this account (implicitly accepted by other recent writers on the topic) is biased and lacking some important ingredients. While the desire for clarification of the common explanatory task is highly commendable, it is important that the taxonomy is kept both maximally comprehensive *and* just. The suggested taxonomy fails in one important respect: it fails to notice an alternative to both the

Causal-General and Acausal-Particular views. Therefore, we would like here to point out that from Price's Acausal-Particular approach bifurcates another option which deserves a separate mention in reviewing the ways toward the explanation of thermodynamical asymmetry. This third approach differs markedly from the other two in its conception of what needs to be done to solve the puzzle. In proposing this, we follow the lead of Price himself who, introducing his two proposals, points out that (Ref. 9, Sec. 1.1)

> So far as I know, the distinction between these two approaches has not been drawn explicitly by other writers. Without it, it is not easy to appreciate the possibility that many familiar attempts to explain the time-asymmetry of thermodynamics might be not *mistaken* so much as *misconceived*—addressed to the wrong problem, in looking for time-asymmetry in the wrong place.

We shall see that, unfortunately, "those who use the sword will be killed by the sword," and that there are several instances in which Price's own favorite proposal is misconceived for *exactly* the same reason: searching for a solution to the puzzle in the wrong place.

The second goal of the present note is to demonstrate that the classical arguments (accepted unquestioningly by Zeh, Price, Albert, and other contemporary authors) against the classical Boltzmann–Schuetz anthropic fluctuation picture are much less forceful than it was hitherto assumed. This serves an important role in bringing the atypical initial cosmological conditions within the domain of physical explanation.

2. ACAUSAL-ANTHROPIC APPROACH

Our first motivation is a full and faithful acceptance of Price's account of the nature of the explanatory task ahead (Ref. 8, Sec. 2.2):

> First of all, let's assume that basic explanatory questions are of the form: "Given that C, why E rather than F?" The thought here is that we never explain things in isolation. We always take something as already given, and seek to explain the target phenomena in the light of that. C represents this background, and E the target phenomenon. (C might comprise accepted laws, as well as "boundary conditions" being treated as "given" and unproblematic for the purposes at hand.)

We should, naturally, seek to make C maximally comprehensive. Obviously, our existence as observers is part of the necessary background. Should it not be included in C? ("It is very much in the spirit of scientific inquiry to welcome any theory which widens the range of applicability of science.”—Ref. 10, p. 74) In most practical physical applications it is irrelevant, at least in the first approximation (and therefore is usually omitted, although reasons for the omission are seldom explicated). Our existence as observers hardly impacts on the explanatory project for, say, matter-enhanced neutrino oscillations or the fractional Hall effect. However, *in the cosmological context*, leaving observers out of the picture does not lead to happy consequences, as was first shown by Dicke and Carter in 1960s and 1970s. The debate between Dirac and Dicke on the nature of explanatory projects for the “large number coincidences” is especially instructive in this respect, since several parallels with the projects for explaining thermodynamical asymmetry can be drawn. The reader may recall that the famous “Dirac’s hypothesis” (or the “large-number hypothesis”) to explain the ubiquitous dimensionless number 10^{40} came from a bold suggestion that all these numerical coincidences are in fact exact equations related to the age of the universe.(11) In other words, the relevant number is large because the universe is old.

From this profound and simple (but wrong!) idea, Dirac and later investigators (e.g., Ref. 12) have deduced a wealth of extremely interesting and challenging empirical predictions, the most famous being the decrease in the Newtonian gravitational constant G during cosmological evolution. Using the completely opposite approach, Dicke(13) has suggested that large number coincidences are *observed* only because any conceivably different values to such dimensionless quantities would be incompatible with our existence as intelligent observers (and consequently the relationships are only approximate). Consequently, the two explanatory projects, Dirac’s and Dicke’s, found themselves in the open arena of physical investigations.

Not only has subsequent empirical evidence disproved Dirac’s ideas; notably, the decreasing G has been spectacularly falsified by experiments with the *Viking* space probes, as well as in the binary pulsar experiments;(14, 15) more important is the fact that the subsequent developments show Dirac’s general approach to be rather sterile in comparison to Dicke’s. What we are really interested in here is a comparison of explanatory approaches. We can schematically compare the view of the large-numbers explanandum in this case:

Dirac: “objective” coincidences (no properties of observers included in C);

Dicke: “observed” coincidences (properties of observers included in C).

The outcome of that particular duel should warn us against dogmatism when cosmological theories are the subject of inquiry.[2]

With this in mind, we propose a novel approach to the explanation of thermodynamical asymmetry, one which could be labeled (for the reasons explained below) the *Acausal-Anthropic approach*. It represents a Dicke-like approach applied to the specific problem of thermodynamical asymmetry and the nature (entropy-wise) of the cosmological initial conditions. To understand what this proposal encompasses, perhaps the best way is to use Price's "parsing" the natural phenomena for the different approaches (Ref. 8, Sec. 2.3; Ref. 9, Secs. 3.1–3.2). Applied to the Acausal-Anthropic approach, it may look like this:

> Symmetric boundary conditions—entropy high in the past;
> symmetric default condition—entropy likely to be high (always);
> + asymmetric observational selection effect;
> –
> observed asymmetry.

This should be compared with similar parsing scheme for the Causal-General view:

> Asymmetric boundary condition—entropy low in the past;
> + asymmetric law-like tendency—entropy constrained to increase;
> –
> observed asymmetry.

Similarly, for the Acausal-Particular view[8] the analogous scheme obtains:

> Asymmetric boundary condition—entropy low in the past;
> + symmetric default condition—entropy likely to be high, *ceteris paribus*;
> –
> observed asymmetry.

[2] In spite of the fact that Dirac himself emphasized the "optimistic" nature of his explanation in comparison: "On Dicke's assumption habitable planets could exist only for a limited period of time. With my assumption they could exist indefinitely in the future and life need never end."[16] This goes some steps toward addressing vulgar objections still heard in some quarters that anthropic explanations are anthropocentric or even "cozy" (e.g., Ref. 17).

The basic idea of the Acausal-Anthropic approach is that, having already received from (quantum) cosmology a useful notion of the multiverse, we could as well employ it in order to account for the *prima facie* extremely improbable choice of (local) initial conditions. In other words, we imagine that everything that exists, for which we shall use the term multiverse,[3] represents a "Grand Stage" for the unfolding of—among other things—the thermodynamical histories of chunks of matter. Entropy *in the multiverse* is high almost everywhere and at all times ("almost" here meaning "everywhere minus a possible subset of small or zero measure"). In other words, the multiverse is, formally speaking, in the state of "heat death," as envisaged by classical thermodynamics.[18, 19] Our cosmological domain ("the universe") represents a natural fluctuation—presumably of small or zero measure; but the anthropic selection effect answers the question "why do we find ourselves on an upward slope of such a fluctuation?" Hence what needs explaining is not that there are such fluctuations (this is entailed by Boltzmann's statistical measure); nor the fact that the local initial conditions are of extremely low probability (this results from a distribution over all domains); but the fact that we happen to live in such an atypical region of the "grand total" which is almost always in equilibrium. And that is to be explained by showing why the observed entropy gradient is necessary for our existence as intelligent observers.[4]

From the point of view of the present Acausal-Anthropic approach, Boltzmann (and his assisstant Dr. Shuetz to whom he gave credit for the original idea; see Ref. 20) was on the right track in proposing what came to be known as the "anthropic fluctuation" picture.[21] The idea was to explain the local thermodynamical disequilibrium by appealing to the size

[3] Not to be confused with the multiverse of quantum mechanics ("Everett's multiverse" = the totality of wavefunction branches). Here we refer to the multiverse of quantum cosmology ("Linde's multiverse" = set of different cosmological domains, possibly causally and/or topologically disconnected from ours). This distinction does *not* preclude the relationship between the two, however. But that relationship belongs to the quantum-cosmological domain and is certainly beyond the scope of the present manuscript.

[4] Note that we employ the term "acausal" here in the same sense as Price does: the absence of law-like reason explaining a particular feature of the physical world. This usage has nothing to do with Lorentz invariance, superluminal motions and the like! It has been recognized for quite some time in the philosophy of physics that there are two rather different meanings attached to the notion of "causality." Causality as a geometrical relation between events on the spacetime manifold is different from causality as an order relation between stages of a developing physical process. In accordance with Horwitz, Arshansky, and Elitzur,[67] we may call the former *spacetime causality* and the latter *process causality*. The Anthropic-Acausal approach described here is acausal in the sense of process causality, not in the sense of spacetime causality.

of the universe and the conditions necessary for our existence. Remember the famous words of the Viennese master:[20]

> If we assume the universe great enough, we can make the probability of one relatively small part being in any given state (however far from the state of thermal equilibrium), as great as we please. We can also make the probability great that, though the whole universe is in thermal equilibrium, our world is in its present state. It may be said that the world is so far from thermal equilibrium that we cannot imagine the improbability of such a state. But can we imagine, on the other side, how small a part of the whole universe this world is? Assuming the universe great enough, the probability that such a small part of it as our world should be in its present state, is no longer small.

In other words, in the Boltzmann–Schuetz view the world in general is in the state of maximal entropy ("heat death"). We exist within a fluctuation of low entropy (*without* reason, i.e., acausally!), which makes our existence possible. Thus, any acausal version of the explanatory project on even vaguely "Boltzmannian" grounds has to include the anthropic selection effect. Boltzmann and Schuetz thus, in our present view, were on the right track and could not have done better under the circumstances. What they did lack was the input of modern cosmology, exemplified by the multiverse concept.[5] If we summon such help, we may truly inherit the Boltzmannian project of setting up the explanatory proposal for the observed entropy asymmetry.

How many domains are required in order to account for the observed thermodynamical asymmetry? While the exact answer is difficult to conceive, we may follow the lead of Penrose and use the Bekenstein–Hawking formula[22, 23] to estimate the *lower limit* on the size of ensemble of domains in which we expect to find one similar to ours on purely probabilistic grounds. Obviously, the celebrated Boltzmann formula $S = \ln W$ (in "natural" $k = 1$ units we shall use in the entire discussion) suggests that the required number is $N_{\rm min} \sim \exp S_{\rm max}$, where $S_{\rm max}$ is the entropy of the state of maximal probability of the matter in our domain (what would be traditionally called the entropy of the "heat death" state). However, our domain is limited by our particle horizon at present, and will be almost certainly limited[24, 25] by an *event horizon*, due to the contribution Ω_Λ of the vacuum energy density ("cosmological constant"). Numerically, the difference between the two in the realistic case is not very large in cosmological terms (~ 1 Gpc), so we will not make a big error in attributing the state of low entropy to those currently invisible (but visible to our descendants!) parts of our domain between the particle and the event horizon. Thus, we need to account for the entropy of matter of cosmological density Ω_m (predominantly in CDM

[5] Boltzmann understood the difficulties of his position quite well; there are several examples of his regarding his own cosmological thoughts as remote speculations.

or similar particles, with ~ 15–20% of baryons). On the assumption that our domain is globally flat, with no net electric charge and no net angular momentum, we obtain:

$$N_{\min} \sim \frac{\exp S_{\max}}{\exp S_0} = \frac{1}{\exp S_0} \exp\left(\frac{c^3}{G\hbar}\frac{A}{4}\right) = \frac{1}{\exp S_0} \exp\left(\frac{4\pi G}{\hbar c} m^2\right)$$
$$= \frac{1}{\exp S_0} \exp\left(\frac{\pi}{G\hbar c} H_0^4 \Omega_m^2 R_h^6\right), \quad (1)$$

where H_0 is the present-day Hubble constant, and R_h the size of the horizon. Using the case of an event horizon which is fixed by the magnitude of the cosmological constant only (e.g., Ref. 26),

$$R_h = \frac{c}{H_0 \sqrt{\Omega_\Lambda}}, \quad (2)$$

we obtain the following remarkable expression (for the flat $\Omega_m + \Omega_\Lambda = 1$ universe):

$$N_{\min} \sim \exp\left(\frac{\pi\, c^5}{G\hbar} \frac{\Omega_m^2}{\Omega_\Lambda^3} \frac{1}{H_0^2} - S_0\right) = \exp\left[\frac{\pi\, c^5}{G\hbar} \frac{\Omega_m^2}{(1-\Omega_m)^3} \frac{1}{H_0^2} - S_0\right]. \quad (3)$$

We notice the appearance of all major constants of nature (including the "silent" Boltzmann constant, which is omitted since we are working in "natural" units!) in this formula, with the exception of the elementary charge, which is reasonable since we are dealing with the standard electrically neutral universe. In addition, the total entropy of our cosmological domain, S_0, appears and it represents, in a sense, the outcome of all and every process which has actually taken place since the beginning of time!

How big is the realistic entropy S_0? The conventional answer is simple: the entropy is by far dominated by the photons of the cosmic microwave background, whose specific entropy ("entropy-per-baryon") is a well-known dimensionless number (e.g., Ref. 21):

$$s_{CMB} = \left(\frac{n_\gamma}{n_B}\right)_0 \approx 10^8, \quad (4)$$

where n_γ and n_B are number densities of photons and baryons respectively. Taking the standard estimate that the total number of baryons within horizon is $\sim 10^{80-81}$, we may be certain that S_0 is not larger than 10^{90} (in natural units as well).

The common numerical values of the cosmological parameters Ω_m (≈ 0.3) and H_0 (≈ 60 km s^{-1} Mpc^{-1}) inserted in (3) give us a stupendous double exponential

$$N_{\min} \sim \exp(1.9 \times 10^{121}). \quad (!!!) \tag{5}$$

At least that many domains in the multiverse are needed to account for the observed asymmetry in this manner.[27] (This is easily generalized to the case of charged or rotating universe characterized by some other set of parameters, but their exact values make almost no difference when numbers of such magnitude are involved.) This is the price one must pay for embedding the atypical initial conditions into a wider manifold (see below, Sec. 4). Of course, the total number of domains may be infinite, in which case the conclusions of Ellis and Brundrit[28] will apply, and any worry about the "specialty" of our initial conditions is immediately discarded. On the truly global scale—i.e., in the multiverse—there is no thermodynamical asymmetry, no arrow of time.

Note that the end result of both this and the two proposals Price describes (given by the parsing schemes above) is the same: it is an *observed asymmetry*. However, the attribute seems superfluous in both Acausal-Particular and (especially) Causal-General approaches. It has no function at all in either approach. Only in the anthropic approach advocated here it does receive a proper place in the *core* of the perceived explanandum. Is "observed" in this context the same as "objective" or it is not? By equivocating on this, Price attaches a strongly realist (indeed, essentialist) character to the two approaches he favors. Boltzmann and Schuetz, on the contrary, adopt more cautious stance and employ the attribute "observed" in its true and literal meaning (i.e., observed by intelligent observers possessing specific capacities, epistemic and otherwise).

In other words, a symbolic way of *roughly* representing the relationship of the present approach to the Boltzmann–Schuetz hypothesis is the following scheme:

Acausal-Anthropic approach
= (Boltzmann measure + anthropic selection effect) + the multiverse
= Boltzmann–Schuetz picture + the multiverse.

(It is necessary to qualify this as "roughly," since the cosmological data of the XX century has been fully taken into account in the present approach, data which Boltzmann was, naturally, completely ignorant about.) The multiverse or world ensemble has by now become quite a familiar term to cosmologists, as well as to at least some philosophers. Thus, Bostrom cogently writes:[(29)]

> ...The meaningfulness of the [world] ensemble hypothesis is not much in question. Only those subscribing to a very strict verificationist theory of meaning would deny that it is possible that the world might contain a large set of causally fairly disconnected spacetime regions with varying physical parameters. And even the most hardcore verificationist would be willing to consider at least those ensemble theories according to which other universes are in principle physically accessible from our own universe. (Such ensemble theories have been proposed, although they represent only a special case of the general idea.)

The anthropic selection effect is nothing particularly new either. It was the great French physicist, mathematician and philosopher Henry Poincaré who first noted that the functioning of an intelligent mind would have been impossible in an entropy-decreasing universe.[(30)] Later it was elaborated by Norbert Wiener in his celebrated *Cybernetics* (Ref. 31, p. 35):

> Indeed, it is a very interesting intellectual experiment to make the fantasy of an intelligent being whose time should run the other way to our own. To such a being, all communication with us would be impossible. Any signal he might send would reach us with a logical stream of consequents from his point of view, antecedents from ours. These antecedents would already be in our experience, and would have served to us as the natural explanation of his signal, without presupposing an intelligent being to have sent it. If he drew us a square, we should see the remains of his figure as its precursors, and it would seem to be the curious crystallization—always perfectly explainable—of these remains. Its meaning would seem to be as fortuitous as the faces we read into mountains and cliffs. The drawing of the square would appear to us as a catastrophe—sudden indeed, but explainable by natural laws—by which that square would cease to exist. Our counterpart would have exactly similar ideas concerning us. *Within any world with which we can communicate, the direction of time is uniform.*

What the father of modern computer science had in mind, is that the existence of an entropy gradient of particular size in a sufficiently large region of space is a necessary precondition for the cognitive operations of intelligent life as we know it. In order to immediately preempt any misgivings about the alleged anthropocentrism which undeservedly follow practically any anthropic argument, it should be explicitly stated that this property does not have any particular association with *homo sapiens* (except the trivial and temporary one that we are the only certain example of intelligent observers known so far; that circumstance is likely to change soon, as a result of either SETI or AI efforts).

Of course, the premiss that intelligent observers select particular entropic behavior (and thus entail a temporal asymmetry) should not be taken for granted—and here we come to the crux of the explanatory task ahead. Instead of searching for strange, hitherto never seen time-asymmetric microprocesses (as in the Causal-General approach), or attempt to find a new law applying to global singularities (as in the Acausal-Particular approach), here we would like to investigate and ascertain *why* intelligent observers are dependent on the entropy gradient to function. This, obviously, brings explanatory tasks into the realm of information theory, but also to the disciplines like complexity theory, cognitive sciences, and neurosciences. But this does not mean these are not physical questions! An awareness that the link between information theory and various physical theories is the *centre piece of any attempt at understanding nature* has been rapidly growing over several decades. Since the brilliant book by Brillouen,[32] physicists are gradually getting accustomed to the idea, (e.g., Refs. 33–35), and this struck cord with philosophers too (for a particularly nice example, see Ref. 36). On the other hand, the working philosophy of computationalism has become established as the basis of the bulk of cognitive sciences.[37] In all quarters one may nowadays hear scholarly debates on "physical reductionism," "monism," "physicalism," and many other labels which pertain to essentially the same thing: that cognition (and the various phenomena associated with it, including the apparent temporal asymmetry) is, in principle, explicable in physical terms. That we are still far from such an explanation, is certainly unnecessary to elaborate upon. Thus, the project suggested here is neither non-physical nor easy![6]

We notice that this still represents the one-asymmetry approach, a sort of a cousin to the Acausal-Particular approach. However, the asymmetry is located at a different place from the one in the Acausal-Particular approach favored by Price. *Very roughly* speaking, we need information theory and cognitive science rather than quantum gravity or even the "Theory of Everything"—which presumably, although Price remains silent on the issue, determines the nature of the initial low-entropy conditions necessary for operation of the Acausal-Particular mechanism. The fact that we seem to know more about the former than about the latter (especially since quantum cosmology, through its multiverse theories, demonstrates

[6] As an aside, let us note that the issue of the psychological arrow of time has been lightly and casually dismissed by most writers of the temporal (a)symmetry as a (matter-of-course) consequence of the thermodynamical arrow (e.g., Ref. 38). This uncritical behavior has been criticized in the influential paper of John Earman,[39] and we might add only that, given the contemporary state of the issue, the critique has been too mild! There is no single piece of hard evidence produced so far that the psychological arrow can be reduced in such way to the thermodynamical one; one of the priority tasks within the proposed Acausal-Anthropic approach would be to clarify this difficult issue from the point of view of the information theory and cognitive sciences.

that the true "Theory of Everything" may not exist at all; cf. Refs. 40–42) is another advantage of the Acausal-Anthropic approach.

A possible objection against this explanatory project may be formulated as follows. How did the multiverse come into being? If it came into being by, say, a particular form of spontaneous symmetry breaking, would not that count as manifestly unidirectional process in time? In other words, it may look as if the concept of the multiverse itself *presumes* an arrow of time.[7] This certainly contradicts what we have said about Boltzmann's statistical measure and the totality of cosmological domains being in perpetual thermodynamic equilibrium. Two recourses are available for defense of the Acausal-Anthropic approach, both belonging to the core of quantum cosmology (and the accompanying ontology) and each being worthy a lengthy discourse in its own right. First, we may argue that the multiverse, being the grand stage for everything that happens, holds a privileged position and is not further explicable. So, any theory pertaining to explain the multiverse itself would be superfluous, since the multiverse is a "brute fact." This would be the most straightforward generalization of the original Boltzmann–Schuetz idea (cf. Chapter 2 of Ref. 43). A more interesting defensive strategy would be to argue that the critique actually restricts a range of possible multiverses to those which are, in Linde's terms, "eternal, self-reproducing fractals." Its eternal nature obviates the need for explaining its origination, and its self-reproducing feature enables what philosophers call "explanatory self-subsumption." If the principle necessarily has the feature it speaks of, then it necessarily will apply to itself (cf. Ref. 44). Individual domains—"universes"—are created and destroyed (for instance, through return to the Planck space-time foam upon recollapse), but the multiverse itself stays completely time-reversible. Of course, further elaboration of these ideas is certainly necessary, but the objection does not seem to be fatal at the moment.

So, what are the additional benefits of this project, beyond a novel look at the explanandum of thermodynamical asymmetry? We have already seen some of them: dropping the *ceteris paribus* clause, for instance. We are now free to state that entropy is always high in by far the predominant part of everything that exists. Thus we avoid "a surprising consequence of the one-asymmetry view:"[(9)] the fact that Boltzmann's statistics—being based upon temporally symmetric probabilities—implies high entropy in the past as well as in the future. And we avoid it in a natural and simple manner, which Boltzmann has endorsed himself!

[7] Special thanks are due to one of the anonymous referees for bringing the author's attention to this interesting point.

However, the greatest advantage comes from the possibility of connecting to cosmology, and especially contemporary currents in quantum cosmology. This is achieved without much further effort which the Acausal-Particular approach necessitates. From Bruno, who argued for innumerable worlds by using a specific form of the principle of plenitude, to Hume and his "innumerable worlds botched and bungled," to Linde, Vilenkin and other modern cosmologists, as well as some respected contemporary philosophers,[(43, 45)] people by and large did not take this issue lightly and casually. There are several different approaches which all lead to the conclusion that what we perceive as our cosmological domain is just a minuscule fraction of everything that exists (cf. Refs. 40 and 46).

A brief historical aside seems due at the end of this section. The Acausal-Anthropic view in the modern (post-Boltzmann) sense was first formulated by Clutton-Brock.[(47)] As the story often goes, this highly unorthodox contribution was published in an astronomical journal of rather modest circulation and went almost unnoticed. Clutton-Brock explicitly considered the distribution of the initial entropy-per-baryon over the set of existing *worlds*, and concluded that only a relatively narrow range of this quantity permits the formation of the complex structures we perceive and, presumably, the formation of life itself.[8] The importance of his results has, however, been slightly obscured by some unnecessary assumptions, as well as by confusion over the two types of the multiverse that have been proposed (see footnote 2). Similar analysis for the parameter Q, describing the amplitude of cosmic microwave background fluctuations, has been given only recently by Tegmark and Rees,[(49)] who discuss the anthropic selection effects plausibly underlying the magnitude of the anisotropies of the early universe, as detected recently with *COBE*. This point is directly related to the problem of low initial entropy, since these authors correctly identify the amplitude of these fluctuations in microwave background radiation with the amplitude of gravitational potential fluctuations in the early universe when they enter the horizon. The observed fact that this number is of the order of $Q \sim 10^{-5}$ cannot be derived from known physical theories, and—as Tegmark and Rees emphasize at the very beginning of their paper—one may either wait for some future fundamental theory from which Q could be computed or take the option (supported independently by various inflationary scenarios) that it is effectively a random number drawn from some wide distribution whose observed values will be constrained by the anthropic selection. What they persuasively

[8] It should be noted that Clutton-Brock was not dogmatic on this; in Ref. 48 he proposes a version of the Gold model close to the one Price favors.

demonstrate in the rest of their paper is that such constraints are effective in keeping the expected *observed* value in the approximate interval $10^{-6} \leqslant Q \leqslant 10^{-4}$.

3. IS BOLTZMANN–SCHUETZ INTRINSICALLY UNTENABLE?

What problems may the Acausal-Anthropic view face? There are two objections to the *Boltzmann–Schuetz version* of this view, both of which have surfaced from time to time in the literature. We shall denote each by using the names of the two famous 20th century physicists who elucidated them. Before we investigate their status, two issues should be kept in mind.

(I) Strictly speaking, the Acausal-Anthropic view we propose does not need to answer these objections, since the multiverse is not necessarily the same topologically connected entity to which these objection refer. However, we shall show the weakness of these arguments even against the classical Boltzmann–Schuetz picture, in order to re-display the one-sidedness of Price's account, who almost casually dismisses this proposition.[9] An important motivation for doing this is that we are still very much in the dark about the detailed physical nature of the multiverse (and in particular, the issue of its causal structure). But, obviously, if we weaken the arguments against the "one-domain" anthropic picture (i.e., the classical Boltzmann–Schuetz view), the multiverse view may just benefit.

(II) *Any reasonable defense* of the Boltzmann–Schuetz picture must be qualified, since the progress of modern cosmology has made obsolete practically all ideas about the universe on the largest scales which were current at the end of the 19th century.[10] Thus, this theory is certainly indefensible when set against the objection that the empirically established age of (our) universe is much shorter than the timescale required for large entropy fluctuations. Many other—mainly astrophysical—objections, related to inhomogeneities in the distribution of matter, the universal photon heat bath, entropy production in stars and black holes, quantum properties of matter, the existence of horizons, etc., could also be stated if

[9] Telling is his locution that anthropic selection suggested by Boltzmann makes "this option less unappealing than it initially seems." (Ref. 9, Sec. 3.4—underlined by M. M. Ć.)

[10] This point is probably the content of Price's remark (Ref. 8, Sec. 1) that "this strategy [Boltzmann–Schuetz], never entirely satisfactory, seems to have been decisively overturned by recent work in cosmology."

the Boltzmann–Schuetz picture is to be taken literally nowadays. After all, that is the main reason why we have adjoined the multiverse concept to this picture in presenting the Acausal-Anthropic view above. In contrast, in the rest of this section we shall question the *intrinsic* tenability of the Boltzmann–Schuetz picture, without entering too much into the empirical considerations stemming from perceived astrophysics. The point is to show that the classical objections are significantly overrated, and that by embedding this picture into contemporary multiverse theories we can gain much more than we can lose. In other words, the death of the anthropic-fluctuation picture has been somewhat prematurely proclaimed.

That said, let us consider the argument Price and other critics put forward against the Boltzmann–Shuetz view. We have:

1. Feynman's argument (FA): why is the size of low-entropy fluctuation so much larger than is necessary for the emergence of intelligent observers on Earth?(50)
2. von Weizsäcker's argument (vWA): How could we believe the information of a low entropy past, when a smaller (and *eo ipso* likelier) fluctuation is sufficient to produce such (false or misleading) evidence?(51)

Let us consider FA first. There is an obvious way out (first hinted at by Schelling in the early 19th century!): simply deny the antecedent—namely the assertion that less (low entropy) space is required for the emergence of intelligent observers than we perceive. This assertion is by no means obvious, since we still know too little about the physical and chemical preconditions for the origin of life, not to mention intelligence. Suppose, for instance, that the conventional Oparin–Haldane ("warm little pond") hypothesis for the origin of life (e.g., Ref. 52) is unsupported or wrong (as many researchers have claimed; e.g., Refs. 53–55). The most serious scientific alternative to the received view is the panspermia hypothesis: the view that life was formed at some other place in the universe and has been brought to Earth via either terrestrial encounters with interstellar dust, clouds or comets or even the intentional action of an advanced galactic civilization.(56–58) It is immediately clear that the *size* requirements of these two views (Oparin–Haldane vs. panspermia) are significantly different. If the *a priori* probability of a spontaneous assembly of complex molecules necessary for the creation of life is of the order of 10^{-3000} (or even less, as has been suggested in the references critical of the received view), then we are entitled to insist on a much larger spatiotemporal volume than the conventional "warm little pond" on a single planet. Such a larger volume is necessary even if we know, for instance, of only one single isolated human observer in his cubicle somewhere on Earth.

An FA proponent could retort that panspermia is a highly speculative idea. Of course, it certainly is to a degree because science lacks the universal yardstick of "speculativeness". The received view is also quite speculative.[11] But another point is central here. Not wishing to enter into a biological discussion about which of these options is more likely to account for the totality of empirical data, it seems clear that we should not *presume* any one of them to be correct when evaluating proposals for the origin of the entropy gradient—and that is exactly what FA does. It puts the explanatory cart in front of the horse.

Weakness of FA is graphically manifested if we try to cast it into a somewhat more rigorous form. Let us consider a causal chain of n events e_1, e_2,..., e_n leading to the emergence of intelligent life capable of reading Feynman and Price:

$$e_1 \Rightarrow e_2 \Rightarrow \cdots \Rightarrow e_n = \text{existence of intelligent observers on Earth}, \qquad (6)$$

(for the sake of the argument, we shall assume that n is a finite natural number, and that there is a well-defined first member of the sequence). Examples of links in this chain are the formation of oxygen in the primitive Earth's atmosphere, or the synthesis of ^{12}C in stars through the triple-α reaction.[(55, 59)] Now, we can, in principle, assign a volume $V(e_i)$ to all links in the chain as

$$V(e_i) \equiv \text{ minimal spatial volume necessary for } e_i \text{ to occur,}$$

which is intuitively clear (one cannot expect galaxy formation to occur within 3.6 m^3, etc.). FA can therefore be translated as a statement

$$(\forall i)\, V(e_i) \ll (R_H)^3, \qquad (7)$$

where $(R_H)^3$ is any prototype of the representative part of the observable universe, which may be visualized as a cube with sides equal to the Hubble radius (or less, depending on our assessment of the high-redshift astrophysical data). Is (7) the truth so self-evident that anybody (with Boltzmann and Schuetz) who doubts it may be casually dismissed as "ridiculous"? Not likely. What is $\max[V(e_i)]$? Not so obvious either. As Barrow and Tipler[(21)] correctly note, if the process of cosmological structure formation

[11] And the Gold-type recollapsing universe suggested by Price in the context of his favorite Acausal-Particular approach is far more so.

is a necessary part of the causal chain (6), we have every reason to believe the contrary proposition, namely (e.g., Ref. 60)

$$(\exists j)\, V(e_j) \approx (R_H)^3. \tag{8}$$

Of course, this is part of the modern, evolutionist view; in the time of Boltzmann and Schuetz, everything was considerably easier, since the Hubble expansion and consequent developments were more than thirty years in the future. Nowadays, one may justifiably ask whether R_H in (7) and (8) should be temporally indexed, so that it pertains to the relevant cosmological scale *at epoch of* e_i. This makes FA even less persuasive: if some perturbation, phase transition, or any other part of the quantum cosmological lore is truly necessary for our emergence as intelligent beings, then we have every right to conclude that the entire observable universe is an "all or nothing" matter.[40]

Another way to visualize this option is to imagine that there is a minimum spatial volume (or "cell") which is necessary in order for intelligence to arise at a single point within such volume. Each point in spacetime is either within a cell or it is not. If you are within a cell, then you perceive stars, galaxies, etc.—the entire familiar low-entropy universe. If you are not, then you perceive something of high entropy, presumably lots of black holes—but you cannot be there. How big is the volume of the smallest cell? Feynman estimates it to be much smaller than the observed universe (essentially the Hubble sphere); still there is no argument except crude intuition to that effect.

Price himself testifies that vWA is not an overwhelmingly persuasive objection: when treating globally symmetric cosmologies (à la Gold) he explicitly dismisses vWA—and in a footnote at that, obviously not deeming it necessary to invoke an elaborate explanation. The same issue happens in his discourse on the epistemology of the relationship between randomness and high entropy (footnotes 6 and 7 in Ref. 9): "Again, I am ignoring von Weizsäcker's sceptical difficulties about inference to the past." Remarks such as this provoke a simple question which one is fully entitled to ask of Price: can von Weizsäcker's view be ignored or not, in the final analysis? Because, if it is not ignored when disputing the anthropic approach to the explanatory project (and thus, indirectly, disputing what we have called the Acausal-Anthropic approach), and simultaneously it is conveniently ignored in the elaboration of the Acausal-Particular approach, then it seems clear that we are operating a double standard.

However, in order to be fair toward vWA, we should not construe this double standard as a counter-argument. A true counter-argument is to analyze things further: what exactly in vWA is *problematic* for the Boltzmann–Schuetz picture? Of course, vWA ridicules our epistemic capacities—but that is *non sequitur*. Remember that Boltzmann and Schuetz arrived at their view exactly starting from a high-entropy *default condition*, which does not call for an explanation (as Price is entirely correct in proclaiming). They have not relied in deriving their hypothesis on any one specific piece of empirical data, in particular any empirical data telling of *past conditions* of the universe. Thus, their hypothesis cannot be refuted by accepting that such-and-such empirical data which tells us about a low-entropy past is either "simulated" or invalid. vWA may conflict with propositions embodying the weak anthropic principle (that the values of physical and cosmological parameters are constrained through the requirement of existence of the carbon-based life, sufficiently stable conditions, etc.), but that is only because anthropic theoreticians have not bothered to cope with the case of simulated evidence. Another issue is that "simulation" cannot be as simple as it is tacitly assumed in von Weizsäcker's or Price's account; the fact that we observe coherent information flow from the past to the present (as, for instance, in the Collins' postulate of uniform thermal histories; Ref. 61) seems just a coincidence on this account. This is consequence of the fact that information-theoretical background of this possibility has not been investigated in detail so far. The status of vWA, thus, is that it shows a bizarre and unexpected side of the Boltzmann–Schuetz view, but does not reveal true contradiction or incoherency.

Also, one is prompted to ask: how exactly do we prove that "simulation" is cheaper (in entropy terms) than "reality" in all (or just most of) cases? Again, the opponent of Boltzmann–Schuetz (von Weizsäcker this time) offers just a hunch and "common sense" intuitions. The question is admittedly difficult and depends again on the information-theoretical uncertainties mentioned above. There is at least one serious study claiming the contrary, the one of Tegmark;[35] more precisely, it claims that in cases of an extremely high degree of symmetry (with help of Everett's quantum theory and the environmental decoherence), the algorithmic information content of the entire observable universe may be very small, essentially the same one as in the earliest moments of its existence. In Tegmark's view (especially appealing to cognitive scientists and information theory researchers), the whole is much simpler than its parts, and almost everything we perceive is a sort of illusion. In particular, the apparent complexity of everything around us—not just evidence of the past—is illusory (or "simulated")! We may find Tegmark wrong on several issues, but the lesson of his work is that our current methods (in the theory of complexity and related disciplines) are far from being entirely reliable and disputable in the matter of the entropy cost of perceived pieces of reality.

Let us note that the two arguments discussed in this section are not even strictly co-tenable. FA cannot be coherently formulated if we assume that vWA is correct (since what then is the size which matters? how can we define it, since our knowledge on the properties of life itself—not to mention the standards of measurement—is based upon simulated evidence?). Conversely, on FA it would be idle speculation to ask "what is the real nature of the universe outside of our small confines?," as vWA would prompt us to. (One may play off one against the other, claiming that, for instance, an intelligence-bearing cell of necessary low entropy is the size of our Galaxy, and all extragalactic information is simulated. There have been similar suggestions in the older cosmological literature and in a different context, notably so-called McCrea's uncertainties; see Ref. 62)

4. EMBEDDING THE ATYPICAL INITIAL CONDITIONS

It has been well-known for quite some time that there are three basic approaches to answering the question "Why the initial conditions of the universe were such-and-such?" The first rejects the validity of the question. It may be motivated either by positivistic refusal to discuss issues forever closed to any form of direct verification or theological reasons (all standard theistic accounts of the creation belong to this option). This rather nihilistic option should only be entertained as a truly last resort, a counsel of despair. Of the other two, one—causal—entails the idea that there is a law-like reason (presumably to be derived from the future "Theory of Everything") for the atypical or surprising structure of the early universe. In other words, an enormous amount of information, necessary for the description of the atypical initial conditions, can be encoded in some new law(s) of nature and consequent law-like correlations of various matter and vacuum fields. The other—anthropic—option avoids giving a specific description by embedding those conditions into a sufficiently symmetric background. Again, stated in terms of information, the same long description of what we perceive as atypical initial conditions arises—as so often in physics!—from the process of *symmetry breaking*. The overall description is simple enough, and may be reduced (in the extreme case) to a rule similar to "All possible combinations of initial conditions exist." That such a high degree of symmetry can indeed completely reproduce the situation in our particular domain becomes then an immediate consequence (cf. Refs. 35 and 63).[12]

In a sense, the appeal of the anthropic selection effect is, figuratively speaking, to kill two birds with one stone: to set up a project for the explanation of common thermodynamical asymmetry and to obtain the cheapest possible (in both physical and epistemological terms) explanation of the initial conditions, in particular vis-à-vis cosmological fine tunings. Appeal to the multiverse enables us to "cleanse the door of perception" and overcome the narrow coffines of our specially restricted viewpoint.

Price's suggestion (Ref. 8, Sec. 3.3) that the anthropic selection effect(s) may be necessary only for an explanation of the initial conditions of our domain—and even then it is obviously less interesting option for him, since it can be conveniently "ignored"—certainly does not do justice to the scope and ingenuity of anthropic reasoning. His preferred option, the existence of a law-like reason for low entropy is, in effect, a strange retreat from the *acausal* behavior of thermodynamical systems correctly emphasized at the present time. Granted that there may be interesting reasons for exploring the law-like possibility, we are still entitled to ask: why should one, after rejecting the law-like behavior of matter in the present epoch, ask for a new law-like behavior in epochs long gone—say at Planck time—to explain the very same thing? Especially if a plausible (and rather more "Boltzmannian") anthropic alternative is at hand?

[12] A brief literary analogy may be helpful here. In the beautiful story of "The Library of Babel," Jorge Luis Borges has described a world consisting of a huge library in which piles of seemingly completely random books are stored.[(64)] The nature and content of each book look extremely puzzling to the inhabitants of that world, most of whom have never encountered a book with a single meaningful line. Gradually, they reveal the truth: although each book *per se* requires lots of information to be described—"long description"—the entire content of the Library is extraordinary simple: it is completely described by the following proposition: *All variations of letters and punctuation marks exist in the Library*. Thus, although lost works of Plato or Tacitus are *certainly* located somewhere in the Library (and are presumably *unique*), the wealth of information they contain from a human perspective is completely lost among myriads of less and less similar copies of the supposed original, and myriads of completely worthless "chaotic" volumes. Similarly with the multiverse. A book containing perfect Socratic dialogues stands in the same relation towards the Library as a domain containing intelligent observers relates to everything that exists. Note that the number of books in the Library is, as an anonymous genius discovers in the story, still finite, although incredibly huge, and thus the number of meaningful books is *not* of measure zero in the entire set. Similar is the situation with the domains of the multiverse, as discussed above. In the infinite case, the number of those allowing for emergence of intelligent observers is probably of measure zero.

5. CONCLUSIONS

We conclude that a generalized Boltzmann–Schuetz or Acausal-Anthropic approach may be able to account for the perceived thermodynamical asymmetry at least in the same degree as the other approaches explicated in the recent literature. Neither of the two conventional arguments is really decisive and sufficient to reject the Boltzmann–Schuetz anthropic fluctuation picture. *A fortiori*, these are either irrelevant or insufficient to reject the Acausal-Anthropic view proposed here. (Which makes this approach largely insensitive as to the speculative issue of the exact physical nature of the domains within the multiverse.)

An enormous additional benefit comes, of course, from being able to account for other anthropic coincidences (or "fine-tunings") within the same conceptual framework received from the rapidly developing ideas of quantum cosmology. Further advantages include a connection with the latest thinking in quantum cosmology (incorporating the idea of the multiverse), dropping of the *ceteris paribus* clause in specification of the default thermodynamical condition, better accounting for thermodynamical counterfactuals and obviation of the necessity to double-deal with cosmological data. At the same time, many of the virtues of the Acausal-Particular approach are retained in the Acausal-Anthropic picture.

Future behavior of the universe is rapidly becoming a recognized and legitimate target for "everyday" scientific work, and less and less an arena for wild speculation and "grand principles."[65] The nascent discipline of physical eschatology (e.g., Ref. 66) has already reached many interesting results, and it is highly misleading to present contemporary astrophysicists as ignorant about the subject as their colleagues in the time of Boltzmann or Haldane or Gold. According to unequivocal conclusion drawn from these empirical developments, the asymptotic final state of our cosmological domain (or "universe") will be one of extremely diluted matter and extremely high entropy (at least as long as one keeps possible intentional actions of advanced intelligent communities out of the picture).

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