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The ultimate fate of life in universes which undergo inflation

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It is shown that life – in its most general sense as an entity which codes information that is preserved by natural selection – cannot continue forever in any of the standard inflationary models. In these cosmologies, the continuation of life is ultimately stopped by the Eternal Return Problem: the complexity of a living entity, or more generally the entire biosphere, is bounded above, and once this upper bound is reached, life either dies out, or begins to repeat its previous states. I argue that this need not happen in a closed universe, because if the Wheeler boundary condition is imposed on the universal wave function, quantum gravity will permit life to increase its complexity without limit below the Planck length as the universe goes into the final singularity.

1. Introduction

In a recent series of papers and books [1–4], Andrei Linde has expressed the opinion that "One of the main purposes of science is to investigate the future evolution of life in the universe". He has also attempted to show that in an eternal chaotic inflationary universe with sufficiently small cosmological constant, it would be possible for life to survive forever. In contrast, he paints a gloomy view of life in a conventional open/flat or closed universe without inflation: in the former, life is doomed as baryons and all other structures decay, whereas in the latter, life is wiped out in the Big Crunch. He is dubious of the proposal of Barrow and myself [5–7] that life might be able to process an infinite amount of information in the finite amount of proper time before the final singularity, and hence survive forever in subjective time, because such a scenario would require information processing at densities above the Planck density, and such cannot occur because quantum fluctuations would preclude the existence of classical spacetime.

I fear I must disagree with Linde. After devoting section 2 to using information theory physics to define precisely what it means for life to survive forever, I shall show in section 3 that by this definition of survival – which includes Linde's as a special case – life either dies out, or just repeats a finite set of states ad infinitum in Linde's eternal chaotic inflationary universe. Finally, in section 4, I shall show that with the proper boundary condition on the wave function of the universe, it is possible in a canonical quantum gravity cosmology for life to continue at densities arbitrarily above the Planck density. I point out that it is possible this result could be extended to string field quantum cosmologies.

2. What does it mean for life to survive forever?

Let us avoid defining "life" to be a special process based on the carbon atom, and instead let quantum field theory define "life" in its most general sense. The Bekenstein bound [8,9] says that the amount of information I coded within a sphere of radius R containing total energy E is

$$I \leqslant I^{\mathrm{B}}_{\max} \equiv \frac{2\pi ER}{\hbar c \ln 2}$$

$$= 2.57686 \times 10^{38} \left(\frac{M}{1\ \mathrm{g}}\right)\left(\frac{R}{1\ \mathrm{cm}}\right) \mathrm{bits} \qquad (1)$$

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and that the rate dI/dt at which this information is processed is bounded above [8] by

$$\frac{dI}{dt} \leqslant \dot{I}^{B}_{max} \equiv \frac{\pi E}{\hbar \ln 2} = 3.86262 \times 10^{48} \left(\frac{M}{1\ \text{g}}\right) \text{bits/s}, \qquad (2)$$

where d/dt is the time derivative with respect to proper time in the rest frame of the sphere. In particular, (1) and (2) imply that all human beings are finite state machines, since a typical human being with $M \leqslant 10^5$ g and $R \leqslant 10^2$ cm can code at most 3×10^{45} bits of information, and can undergo at most 4×10^{53} changes of state per second. By using larger values of M and R, it follows that all the activities of all living beings everywhere in the universe are forms of information processing.

Since "life" – whatever its form or whatever its detailed physical processes – is ultimately a form of information processing, I shall follow Barrow and Tipler [5,6] and say that the following three conditions are *necessary* conditions for "life" to continue to exist forever:

(i) Information processing – the running of programs – continues along at least one future-endless timelike curve γ all the way into the future c-boundary of the universe.

(ii) The amount of information processed in $I^-(\gamma)$ between now and the c-boundary is infinite.

(iii) The amount of information stored in $I^-(\gamma) \cap S(t)$, where $S(t)$ denotes the constant mean curvature foliation of the universe, diverges to infinity as the leaves of the foliation approach the future c-boundary.

The terms "c-boundary" and the chronological past set $I^-(\gamma)$ are defined in Hawking and Ellis [10]. Roughly, the future c-boundary is the future end of time. Conditions (i)–(iii) are necessary and not sufficient conditions, because, although life is a form of information processing, the converse is not true. ("Life" is precisely defined [5,11] as an entity which codes information with the information being preserved by natural selection.)

Condition (i) simple says in precise terminology that life – information processing – goes on until the end of time. Condition (ii) says that this period is actually infinite in subjective time, as measured by the number of "thoughts" living beings have (each "thought" requires at least one bit of information to be processed). Without this condition of infinity, it would make no sense to say life goes on "forever". Condition (ii) also says that a bit processed counts as a potential "thought" only if it can be communicated to the observer γ. An integrated biosphere or personality is impossible without the exchange of information between parts of the biosphere or the brain coding the personality.

Condition (iii) is imposed to eliminate the Eternal Return Problem [12,13]. It is a theorem of computer science that a finite state machine, if run for infinite time, will fall into a subset of its state space for which it will repeat each state in that subset an infinite number of times. Condition (iii) makes life as a whole a potentially infinite state machine, for which such eternal returns are not inevitable. "Potentially infinite" ("infinite" in complexity theory terminology) just means that the causally accessible stored information at any given instant of universal time is not bounded above as time approaches its future limit. The constant mean curvature foliation – which exists [14] and is unique [15] in generic physically reasonable spacetimes (and which coincides with the rest frame [16] of the background radiation in FRW universes) – is the standard way of defining absolute time in classical general relativistic cosmology. I shall show in section 4 that condition (iii) can be generalized to apply in quantum cosmology, even if an underlying spacetime manifold does not exist, as can conditions (i) and (ii).

The ultimate pointlessness of the endeavors of intelligent life in an Eternal Return universe was eloquently, though unintendedly, expressed by Andrei D. Sakharov in his 1975 Nobel Peace Price Lecture: "In infinite space many civilizations are bound to exist, among them societies that may be wiser and more 'successful' than ours. I support the cosmological hypothesis which states that the development of the universe is repeated in its basic characteristics an infinite number of times. Further, other civilizations, including more 'successful' ones, should exist an infinite number of times on the 'preceding' and the 'following' pages of the Book of the Universe. Yet we should not minimize our sacred endeavors in this world, where, like faint glimmers in the dark, we have emerged for a moment from the nothingness of dark unconsciousness into material existence. We must make good the demands of reason and create a life worthy of ourselves and of the goals we only dimly perceive." (See ref. [17], p. 18. Quotation marks around "successful", "preceding", and "following" are Sakharov's.)

If Sakharov had accepted an eternally progressive universe, then he would never have felt it necessary to warn us not to "minimize" our endeavors. In a progressive universe, it is at least possible that our efforts make a permanent, and ultimately important, contribution on the cosmic scale. Sakharov's warning is due to his unspoken realization that in his Eternal Return cosmology, our civilization is inevitably doomed to sink back into "the nothingness of dark unconsciousness". Sakharov's own immense contribution to the cause of freedom in the world is ultimately meaningless in his own cosmology.

Linde himself appears to find the Eternal Return distasteful, for he states in ref. [1]:"... even though life will appear again and again in different domains, one may wonder whether life can exist without end in our own part of the universe, or whether *at least* [my emphasis] we can send some information to those who will live after us in other domains."

3. Why life cannot survive forever in Linde's eternally inflating universe

Linde shows [1–4] that if the cosmological constant is less than a very small positive value, density perturbations by the inflaton field will result in our domain behaving in the far future as an S^3 Friedmann–Robertson–Walker (FRW) universe with current average density μ_0 greater than the critical density and with current scale factor size

$$l^* \sim \exp(2\pi M_{\rm Pl}/m) \sim \exp(2\pi \times 10^6)\ \text{cm},$$

where $M_{\rm Pl}$ is the Planck mass, the effective potential of the inflaton field is $V(\phi)=\frac{1}{2}m^2\phi^2$, and the value of m is chosen to make the amplitude of the density perturbations be about 10^{-4} as observed. (If the cosmological constant is larger than the Linde value, our domain will behave in the far future like de Sitter space with its exponential inflation, and our calculations agree [2,6] that information processing – life – would eventually become impossible in that environment.)

However, Linde shows [1–4] that within the distance l^*, there will be many new inflating domains, each of which will become a new universe like ours, but connected to ours by a large wormhole. He proposes that life can continue forever if it repeatedly transfers itself from a dying domain to a newly formed one ad infinitum. He argues that indeed sending a signal from a parent domain to a daughter may be physically possible (if the cosmological constant is not too large), and thus conditions (i) and (ii) might hold. Linde himself mentions the possibility [31] that by the time the signal arrives, the daughter universe may have become older than the parent was when the signal was sent, and thus the conditions for life may actually be worse at the receiver than at the sender.

A more fundamental problem is that the Bekenstein bound places an ultimate limit on the amount of information that can be transmitted from parent domain to daughter, and thus condition (iii) cannot hold; our descendants must die out or become locked in an Eternal Return.

To prove this, let me follow Linde and approximate the domain with average density greater than the critical density by the metric of an S^3 FRW universe. Recall that the metric of an S^3 FRW universe is

$$ds^2 = -dt^2 + a^2(t)[d\chi^2 + \sin^2\chi(d\theta^2 + \sin^2\theta\, d\phi^2)]$$

$$= a^2(t)[-d\tau^2 + d\chi^2 + \sin^2\chi(d\theta^2 + \sin^2\theta\, d\phi^2)],$$

where t and τ are respectively the proper and conformal time of world lines normal to the surfaces of homogeneity and isotropy, and $0 \leqslant \chi \leqslant \pi$ is the radial coordinate. The time evolution of the scale factor $a(t)$ is governed by the Friedmann equation

$$G_{\hat t \hat t} = 8\pi G T_{\hat t \hat t} = 3[(a'/a)^2 + a^{-2}] = 8\pi G\mu,$$

where the prime denotes the proper time derivative, and μ is the mass density. If the equation of state is $p=(\gamma-1)\mu$, with $\gamma > \frac{2}{3}$, then the conservation equation $(\nabla \cdot T)_{\hat t} = 0$ implies $\mu \propto a^{-3\gamma}$, in which case the Friedmann equation becomes

$$(a'/a)^2 = Ma^{-3\gamma} - a^{-2},$$

where M is a constant.

This equation can be integrated by setting $y \equiv a^{(3\gamma-2)/2}$, and transforming to conformal time. (I am grateful to Professor J.D. Barrow for pointing out this transformation to me.) In which case the Friedmann equation becomes

$$\left(\frac{dy}{d\tau}\right)^2 + [\tfrac{1}{2}(3\gamma-2)]^2 y^2 = M[\tfrac{1}{2}(3\gamma-2)]^2 .$$

This is just the energy equation for a simple harmonic oscillator, so y satisfies

$$\ddot{y} + [\tfrac{1}{2}(3\gamma-2)]^2 y = 0 ,$$

where the dot denotes the conformal time derivative. Hence,

$$a(\tau) = a_{\max}[\sin(\tfrac{1}{2}(3\gamma-2)\tau)]^{2/(3\gamma-2)} ,$$

and

$$t(\tau) = a_{\max}\int_0^{\tau} \sin^{2/(3\gamma-2)}(\tfrac{1}{2}(3\gamma-2)x)\,dx , \tag{3}$$

where $a_{\max}$ is the value of the scale factor at maximum expansion. The total lifetime τ_{life} of the universe in conformal time is the conformal time between two zeros of y or a, or in other words,

$$\tau_{\text{life}} = \frac{2\pi}{3\gamma-2} , \tag{4}$$

independent of $a_{\max}$. The total proper lifetime of the universe is obtained by setting the upper limit of the integral (3) equal to τ_{life}. This gives

$$t_{\text{life}} = a_{\max}\frac{2\sqrt{\pi}\,\Gamma(3\gamma/2(3\gamma-2))}{(3\gamma-2)\Gamma((3\gamma-1)/(3\gamma-2))} , \tag{5}$$

where Γ is the gamma function. For matter-dominated universes ($\gamma=1$), $t_{\text{life}} = \pi a_{\max} = 4M/3M_{\text{Pl}}^2$, where $M \equiv 2\pi^2 a_0^3 \mu_0$ is the total "mass" of the universe, since $a_{\max} = 8\pi\mu_0 a_0^3/3M_{\text{Pl}}^2$. For radiation-dominated universes ($\gamma=\frac{4}{3}$), $t_{\text{life}} = 2a_{\max}$. These are the usual results. I have obtained τ_{life} and t_{life} for all γ because a realistic universe would be better approximated by a model in which γ varied between 1 in the low temperature regime and $\frac{4}{3}$ in the hot.

When combined with the Bekenstein bound, these results imply that the amount of information that can ever be coded in any domain is less than a universal upper bound, hence the Eternal Return is inevitable in an eternal chaotic inflation cosmology. For, from (1) we have

$$I_{\text{now}} \leqslant 3\times10^{38}[\mu_0(l^*)^3]l^* \sim 10^9\exp(8\pi\times10^6)$$
$$\sim \exp(8\pi\times10^6) ,$$

so

$$I_{\text{now}} \leqslant \exp(8\pi\times10^6)\ \text{bits} \tag{6}$$

is the upper bound on the information that can be coded in our domain at the present time. Following Linde [1], I have set $\mu_0 = 10^{-29}$ and $M = 2\pi^2\mu_0(l^*)^3$.

Since for matter-dominated universes, we have

$$M(t)R(t) = [2\pi^2\mu(t)a^3(t)]a(t)$$
$$= (2\pi^2\mu_0 a_0^3)a(t) \sim \mu_0(l^*)^3 a(t) ,$$

the upper bound on the information which can be coded in our domain increases linearly with the scale factor $a(t)$. Thus the absolute upper bound is given by the setting $a(t) = a_{\max}$. Using $a_{\max} = 4M/3M_{\text{Pl}}^2$ we get

$$(MR)_{\max} \sim \frac{8\pi\mu_0^2}{3M_{\text{Pl}}^2}(l^*)^6 .$$

So the maximum amount of information that can ever be coded in *any* domain is

$$I_{\text{domain}}^{\max} \leqslant \exp(12\pi\times10^6)\ \text{bits} . \tag{7}$$

Thus sending signals describing us and our domain to daughter domains ad infinitum as Linde proposes would ultimately be futile; once the complexity of life reaches the limit set by eq. (7), life would have to repeat its previous actions ad infinitum. (Actually, the upper bound to the information that could be *sent* from the parent to a daughter domain would be *less* than (7), because the parent and daughter would be connected by wormholes, which would look like black holes to both parent and daughter, and the Bekenstein bound would have to be applied to the surfaces of these black holes, which are smaller than either parent or daughter, being contained in each.)

The fundamental limit (7) arises because inflationary cosmology has fundamental length and mass scales, l^* and M respectively, obtained from the mass m in the effective potential $V(\phi)$. However, Linde [1] points out that the scale of universal closure may not occur at l^* but at nl^*, where n is an integer, since the mechanism causing closure is the relative density fluctuations $\delta\mu/\mu_0$ becoming greater than 1. Hence the closure size is defined by the first integer n giving this relative density fluctuation wavelength scale.

Thus one might hope to avoid the limit (7) by going from a domain for which $n=1$ to one for which $n=2$, and then to one with $n=3$, and so ad infinitum. Unfortunately, such a survival strategy will not be successful either.

This follows from the fact that the conformal lifetime τ_{life} is independent of a_{max}, and from the fact that all light rays obey the equation $\tau=\chi$. Hence the number of circumnavigations of the universe in its lifetime by a light ray which starts a finite time after the initial singularity is less than $\tau_{life}/2\pi=1/(3\gamma-2)$, which for matter-dominated universes is 1 and for radiation-dominated universes is $\frac{1}{2}$, and these numbers are independent of a_{max}. Therefore, it will not be possible for any light signal to circumnavigate any domain, however large, before it terminates in a final singularity (or until curvatures get large; either case putting us back to life surviving arbitrarily close to the final singularity).

This means that it will be impossible to search for a domain with its n larger than the current domain, send the message back across the universe of a success, and transmit the information to the larger domain, before one's current domain approaches its final singularity. This argument thus applies to any inflationary cosmology, even one which contains no fundamental scale besides the Planck length L_{Pl} – for instance extended inflationary cosmology. The crucial fact is that the conformal lifetime, eq. (4), of the universe contains no length scale, since it depends only on the spacetime conformal structure.

Conversely, one might think [18] to survive by sending the information to a mini-universe created in the laboratory. In this case, the mini-universe is hidden behind a black hole event horizon of area $A=4\pi R^2$, with $R=2GM/c^2$, so the Bekenstein bound (1) becomes

$$I\leqslant \frac{A}{4L_{Pl}^2 \ln 2}\,. \tag{8}$$

Since for the horizons of typical laboratory universes [18], $A\sim 4\pi L_{Pl}^2$, no significant information can be transmitted to the mini-universe, unless the "black hole" is enlarged by putting most of the mass of our universe inside, but this possibility is eliminated by the causality bound obtained above. (We would have to go out, collect the matter, and bring it back, but there can be less than one circumnavigation of our universe before it ends.)

However, the derivation [9] of the Bekenstein bound (1) assumes that the vacuum state is unique, which implies there is no information coded in the vacuum. Linde [18] suggests that superstring theory may violate this assumption, and that we might be able to code information about ourselves in the vacuum state of the laboratory universe. But Linde also points out that such different vacua can arise only if the initial density of the mini-universe is near the Planck density M_{Pl}^4. I claim this implies a significant number of such mini-universes beyond M_{Pl}^4, since the probability of creation is maximized at M_{Pl}^4.

In summary, life in an eternal chaotic inflationary universe would ultimately be poor, solitary, nasty, brutish, and – by comparison with the infinite age of the universe – short.

4. Life below the Planck length

So if it is to survive, life must be prepared to survive arbitrarily close to the final singularity. The definition of "life" given in section 1 was based on classical spacetime concepts, and Linde is certainly correct to be dubious about the validity of these notions close to the final singularity, when the radius of the universe is less than L_{Pl}.

But should we regard L_{Pl} as the limit for the validity of the idea of spacetime? In the 1930's both Bethe and Heitler [19] [#1], following the general opinion, argued that "the quantum theory is definitely wrong for electrons of ... high energy (presumably for $E>137m_ec^2$)." Their reason: the de Broglie wavelength of an electron of such energy was shorter than the classical radius ($E=hc/\lambda>hc/r_0=2\pi(\hbar c/e^2)=2\pi(137)m_ec^2$). Furthermore, from the 1930's to the end of his life (ref. [20], p. 542), Heisenberg believed that quantum mechanics broke down at a critical length; in the 1930's he argued that this length was h/mc, where m was the mass of the Yukawa meson (ref. [20], pp. 360, 407). In the 1920's Bohr himself believed [20] quantum mechanics broke down when applied to regions smaller than 10^{-13} cm. If history is any guide, it is quite possible that classi-

#1 Quote on p. 13 of ref. [19].

cal spacetime concepts may be valid at distances smaller than L_{Pl}.

But if not, then I shall outline how to generalize conditions (i)–(iii) to apply to quantum cosmology, provided only that a complex valued wave function of the universe can be defined, and the second law of thermodynamics holds at arbitrarily high energies.

Let us first consider a quantum cosmology based on superspace, in which the basic entity is a wave functional $\Psi(\tilde{h}, \Phi, S)$ on compact three-manifolds S with three-metrics h and non-gravitational fields Φ. (I have placed a tilde over the three-metric h to express the fact that superspace is Riem(S)/Diff(S): the space of all riemannian metrics mod diffeomorphisms.) Fix S and write $\Psi(\tilde{h}, \Phi) = \mathscr{R}(\tilde{h}, \Phi) \times \exp[\varphi(\tilde{h}, \Phi)]$. The wave functional thus defines *histories* – phase trajectories – in superspace, each history being a path whose tangent is the functional derivative $\delta\varphi/\delta\tilde{h}_{ij}$. In non-relativistic quantum mechanics (QM), $\psi = R\exp(i\varphi)$ generally can be chosen [21,22] so that these phase trajectories (those with $\nabla\varphi$ as tangents) are the classical paths for the hamiltonian. For example, the phase trajectories of the plane wave $\psi = \exp(i\boldsymbol{k}\cdot\boldsymbol{r})$, constitute all the classical trajectories with momentum $\boldsymbol{k}$ of the free particle hamiltonian, and $\psi(x, t=0) = \delta(x-a)$ used as the initial wave function of the one-dimensional harmonic oscillator will generate a wave function whose phase trajectories in time are all classical trajectories with zero amplitude at $x=a$. But in both QM and quantum gravity, one gets classical trajectories only if one imposes field equations, Schrödinger's and DeWitt–Wheeler for $\psi(\boldsymbol{r}, t)$ or $\Psi(\tilde{h}, \Phi, S)$, respectively. In the absence of such equations (and appropriate boundary conditions), the trajectories serve only as a foliation of the base space – the superspace of all three-metrics and all three-manifolds for $\Psi(\tilde{h}, \Phi, S)$, with the three-metrics and manifolds identified under diffeomorphisms – in terms of histories. Each history can be regarded as a spacetime.

I propose to obtain the universal wave function not by separately assuming equations and imposing boundary conditions, but by requiring conditions (i)–(iii) to hold on each of the histories in superspace for which $\mathscr{R}$ is non-zero. Thus the histories which "really" exist – those for which $\mathscr{R} \neq 0$ – are generated entirely by the requirement that "life" arises in all "real" histories and continues to exist in each such history until its end. This requirement can be regarded as a precise mathematical formulation of Wheeler's idea [23] that the universe is a self-excited circuit: the universe is brought into existence by the activities of "life" in its general sense. I thus propose to call it the *Wheeler boundary condition* for the universal wave function.

The non-gravitational fields Φ are constrained not by field equations but by condition (iii). I propose defining the amount of information in a given three-geometry $(\tilde{h}, S)$ as $I^{B}_{max} - S_{Pl}$ where I^{B}_{max} is given in eq. (1) and S_{Pl} is the entropy of the gravitational and non-gravitational fields, both quantities being computed on the subset of each $(\tilde{h}, S)$ in $I^{-}(\gamma)$ in each history/phase trajectory. Bekenstein [8,9] has developed an algorithm for computing I^{B}_{max}, and it is well known how to compute the non-gravitational part of S_{Pl}, but although there are a number of conjectures, it is still not known how to compute the entropy of the gravitational field. At present, I propose to avoid this difficulty by restricting the calculation to quantum cosmological models with high symmetry – low frequency modes for which the gravitational entropy is presumably zero, containing high frequency gravitational radiation the entropy of which can be calculated in the standard way. What condition (iii) thus says is that $I^{B}_{max} - S_{Pl}$ diverges *in only one direction*, a direction in which S_{Pl} also increases, in each history as it unfolds (the "one direction" restriction is the quantum version of "future"). Imposing the increase of S_{Pl} means that we are imposing the second law of thermodynamics. (If $\Psi = \Psi(g, \Phi, M)$ rather than $\Psi = \Psi(\tilde{h}, \Phi, S)$, where (M, g) is a spacetime, then one requires $\mathscr{R} = 0$ on any (M, g) for which conditions (i)–(iii) do not hold.)

If the phase trajectories can be approximated at arbitrarily small sizes by a classical closed universe history, then it can be shown [5,6] that the Bekenstein bound will not prevent the divergence of information stored near the final singularity, because although $R \to 0$ as the singularity is approached, the mass–energy available from the gravitational shear to store the information diverges as R^{-3}, so the total amount of information stored can diverge as R^{-2}; also,

$$\int^{\text{c-bound}} \left(\dot{I}^{B}_{max} - \frac{dS_{Pl}}{dt} \right) dt$$

diverges [5,6]. Thus, an infinite amount of information can be processed and stored in a finite proper time before the final singularity. Finally, using the shear, life can force horizons to disappear [5,6], making an infinity of circumnavigations possible. Although such a history exists for only a finite proper time, life exists for infinite subjective time.

The increase of $I^{\mathrm{B}}_{\mathrm{max}} - S_{\mathrm{Pl}}$ is clearly a separate condition from the second law and is not implied by it. But Frautschi [24], Layzer [25,26] and Landsberg [27] have all pointed out that the actual universe to date has obeyed this rule. I propose that it is generally true and that it can be used to define the universal wave function; an equation for $\Psi(\tilde{h}, \Phi, \mathrm{S})$ like the DeWitt–Wheeler equation is redundant. Biologists like Brooks and Wiley [28,29] (see also ref. [30]) have shown that a restricted version of $I^{\mathrm{B}}_{\mathrm{max}} - S_{\mathrm{Pl}}$ can be used to define what is meant by "information" in biological systems, and that its increase measures evolutionary progress. The activity of life itself causes the increase of $I^{\mathrm{B}}_{\mathrm{max}}$. Following Wheeler, I suggest this will also occur near the final state.

Thus Linde's worry about quantum fluctuations wiping out life is obviated with the Wheeler boundary condition, because in this case, the universe continues to exist *because* life itself does; quantum fluctuations large enough to destroy life cannot occur because they are prevented by the boundary condition from forming.

The preceding analysis was based on canonical quantum gravity, in which it is assumed that the three-metric h and three-manifold S are defined for arbitrarily small sizes. But in superstring theory both h and S are macroscopic objects, arising from the superposition of string excitations. However, the Wheeler boundary condition can in principle also be imposed on string fields if a "foliation" of the string state space can be made in which on each leaf of the foliation an entropy can be defined, with the direction of increase of entropy defining a "time" direction. Notice that this "time" need not be related to the metric of spacetime at high string excitations; the metric presumably does not exist at these energies. If entropy can be defined, so can an analogue of the Bekenstein bound $I^{\mathrm{B}}_{\mathrm{max}}$, which is just the logarithm of the number of possible states in a region of phase space; one must first be able to define the total number of states in order to define the entropy. The past light cones used in conditions (i)–(iii) would not exist in this case when the radius of the universe became less than L_{Pl}, but Barrow and I [5] have suggested that this light-cone constraint may actually be redundant: the divergence of information defined as $I^{\mathrm{B}}_{\mathrm{max}} - S_{\mathrm{Pl}}$ simply cannot occur as the final state is approached unless the information is effectively integrated by signals of some sort.

Thus, I conclude that it is in principle consistent with known physics for life to continue forever in a closed universe arbitrarily close to the final singularity, but such survival is not possible in an eternal chaotic inflation cosmology.

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