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Is our Universe natural?

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It goes without saying that we are stuck with the Universe we have. Nevertheless, we would like to go beyond simply describing our observed Universe, and try to understand why it is that way rather than some other way. When considering both the state in which we find our current Universe, and the laws of physics it obeys, we discover features that seem remarkably unnatural to us. Physicists and cosmologists have been exploring increasingly ambitious ideas in an attempt to explain how surprising aspects of our Universe can arise from simple dynamical principles.

What makes a situation 'natural'? Ever since Newton, we have divided the description of physical systems into two parts: the configuration of the system, characterizing its particular state at some specific time, and the dynamical laws governing its evolution. For either part of this description, we have an intuitive notion that certain possibilities are more robust than others. When we come across a situation that seems unnatural or finely tuned, physicists seize upon it as a clue pointing towards some underlying mechanism that made it that way. Such clues can occasionally be misleading, but they often serve to guide our thinking about how we can extend our understanding into unknown domains.

For configurations, the concept of entropy quantifies how likely a situation is. If we find a collection of gas molecules in a high-entropy state distributed uniformly in a box, we are not surprised, whereas if we find the molecules huddled in a low-entropy configuration in one corner of the box, we imagine there must be some explanation. For dynamical laws, the concept of naturalness can be harder to quantify. As a rule of thumb, we expect dimensionless parameters in a theory to be of order unity, not too large or too small. Indeed, in the context of effective quantum field theories, the renormalization group gives us some justification for this notion of 'naturalness'[1].

In field theory, the dynamics of the low-energy degrees of freedom fall into universality classes that do not depend on the detailed structure of physics at arbitrarily high energies. If an interaction becomes stronger at large distances, we expect it to be relevant at low energies, whereas interactions that become weaker are irrelevant; anything else would be deemed unnatural. (The parallel between natural states being high entropy and natural theories arising from the renormalization group is an analogy rather than a rigorous equivalence, although there has been some tentative work towards establishing a more formal connection — in particular linking Boltzmann's H-theorem describing the evolution of entropy and the c-theorem describing renormalization-group flow[2,3]. See for example ref. 4.)

If any system should be natural, it's the Universe. Nevertheless, according to the criteria just described, the Universe that we observe seems remarkably unnatural. The entropy of the Universe is not nearly as large as it could be, although it is at least increasing; for some reason, the early Universe was in a state of incredibly low entropy. And our fundamental theories of physics involve huge hierarchies between the energy scales characteristic of gravitation (the reduced Planck scale, $E_{\rm Pl} = 1/\sqrt{(8\pi G)} \approx 10^{27}$ electron volts), particle physics (the Fermi scale of the weak interactions, $E_{\rm F} \approx 10^{11}$ eV, and the scale of quantum chromodynamics, $E_{\rm QCD} \approx 10^{8}$ eV, not to mention the ill-understood neutrino masses) and the recently discovered vacuum energy ($E_{\rm vac} \approx 10^{-3}$ eV). (Throughout this paper I will use units in which $\hbar = c = 1$, so that 1 eV $= 1.8 \times 10^{-33}$ g $= 5.1 \times 10^{4}$ cm^{-1} $= 1.5 \times 10^{15}$ s^{-1}.) Table 1 includes some of these characteristic scales. Of course, it may simply be that the Universe is what it is, and these are brute facts that we have to live with. More optimistically, however, these apparently delicately tuned features of our Universe may be clues that can guide us towards a deeper understanding of the laws of nature.

Given this situation, physicists have been exploring dramatic extensions of our known theories, in an attempt to provide a larger context in which our apparently unnatural Universe is seen to make perfect sense. Interestingly, attempts to account for both the low entropy of the early Universe and the disparate energy scales of fundamental physics lead us to a similar idea: that the local Universe we observe is part of a much larger ensemble. This casts new light on the problems of naturalness, while raising vexing issues of its own; considerable advances in both theory and experiment will be necessary before we can decide whether we are learning the appropriate lessons from the clues provided by nature.

The state of our Universe

The state in which we find our observable Universe seems simple enough: on very large scales the distribution of matter is more or less homogeneous and isotropic, and distant galaxies are expanding away from each other in accordance with Hubble's law. But the early Universe was in fact in an extremely delicately specified state, analogous to a ball perched at the top of a hill. To account for this unusual initial condition, we need to ask what would really constitute a 'likely' state, and whether what we observe could arise from such a condition. If certain ideas about inflation and quantum gravity are correct, a universe like ours could come about as a quantum fluctuation from a pre-existing state that is simply empty space with a non-zero vacuum energy.

The Universe we see originated in a hot, dense state about 14 billion years ago. The deviations from perfect smoothness that we observe today have grown through gravitational instability from initially small perturbations of roughly equal amplitude on all length scales. Interestingly, the 'ordinary matter' made of particles described by the standard model of particle physics is only about 4% of the total energy of the Universe; another 23% is some 'dark matter' particle that has not yet been discovered. Even more interestingly, 73% of the Universe is 'dark energy', some form of smoothly distributed and nearly constant energy density[5–7]. The most straightforward candidate for dark energy is vacuum energy, or the cosmological constant: an absolutely constant minimum energy of empty space itself, with a density $\rho_{\rm vac} \approx E_{\rm vac}{}^4 = (10^{-3}\ {\rm eV})^4$ (ref. 8).

If the Universe were in a likely configuration, we would expect it to be

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in a high-entropy state: that is, in thermal equilibrium. Unfortunately, we do not have a rigorous definition of entropy for systems coupled to gravity, but we can make simple estimates. The entropy of matter and radiation (neglecting gravity) in our observable Universe is roughly the number of massless particles, $S_M(U) \approx 10^{88}$. This was the dominant contribution at early times when the matter distribution was essentially smooth; today, however, inhomogeneities have formed through gravitational collapse, creating large black holes at the centres of galaxies, and these black holes dominate the current entropy[9]. The Bekenstein–Hawking entropy of a black hole is proportional to its horizon area, A: $S_{BH} = A/4G \approx 10^{77}(M_{BH}/M_\odot)^2$, where $M_\odot$ is the mass of the Sun. As there are probably more than ten billion galaxies in the observable Universe with million-solar-mass black holes at their centres, the current entropy in black holes is at least $S_{BH}(U) \approx 10^{99}$. If we were to combine all of the matter in the observable Universe into one giant black hole, the entropy would be significantly larger, $S_{max} \approx 10^{120}$. So our Universe is currently in a rather low-entropy configuration, and it started out much lower. The fact that entropy tends to increase is of course just the second law of thermodynamics, and makes sense once we assume that the initial entropy was low. The puzzle is why the early Universe should differ so markedly from the late Universe, despite the intrinsic time-reversibility of the microscopic laws of physics; this is known as the 'arrow of time' problem.

Faced with the question of why our Universe started out with such a low entropy, most cosmologists would appeal to inflation[10–13]. According to this idea, a very tiny patch of space dominated by temporary vacuum energy undergoes a period of rapidly accelerated expansion, smoothing out any inhomogeneities and ultimately reheating to the radiation-dominated early state of the conventional Big Bang model. For inflation to begin, the initial patch must itself be smooth[14]; but because it is so small, one imagines that it cannot be that hard to find an appropriate region somewhere in the chaotic conditions of the early Universe.

It is worth emphasizing that the only role of inflation is to explain the initial conditions of the observable Universe. And at this it does quite a good job: inflation predicts that the Universe should be spatially flat, and should have a scale-free spectrum of adiabatic density perturbations[15–18], both of which have been verified to respectable precision by observations of the cosmic microwave background[7]. But we are perfectly free to imagine that these features are simply part of the initial conditions—indeed, both spatial flatness and scale-free perturbations were investigated long before inflation. The only reason to invoke inflation is to provide a reason why such an initial condition would be natural.

However, as Penrose and others have argued, there is a skeleton in the inflationary closet, at least as far as entropy is concerned[9,19,20]. The fact that the initial proto-inflationary patch must be smooth and dominated by dark energy implies that it must have a very low entropy itself; reasonable estimates for this entropy S_I range from about 1 to 10^{20}. Thus, among randomly chosen initial conditions, the likelihood of finding an appropriate proto-inflationary region is actually much less than simply finding the conditions of the conventional Big Bang model (or, for that matter, of our Universe ten minutes ago). It would seem that the conditions required to start inflation are less natural than those of the conventional Big Bang.

Table 1 | Orders of magnitude of the characteristic scales of our Universe, in units where $\hbar = c = 1$

Scale	Energy	Length
Planck (gravitation)	$E_{Pl} = (8\pi G)^{-1/2} \approx 10^{27}$ eV	$L_{Pl} \approx 10^{-32}$ cm
Fermi (weak interactions)	$E_F = (G_F)^{-1/2} \approx 10^{11}$ eV	$L_F \approx 10^{-16}$ cm
QCD (strong interactions)	$E_{QCD} = \Lambda_{QCD} \approx 10^8$ eV	$L_{QCD} \approx 10^{-13}$ cm
Vacuum (cosmological constant)	$E_{vac} = \rho_{vac}^{1/4} \approx 10^{-3}$ eV	$L_{vac} \approx 10^{-2}$ cm
Hubble (cosmology)	$E_H = H_0 \approx 10^{-33}$ eV	$L_H \approx 10^{28}$ cm

The reduced Planck energy is derived from Newton's constant G; the Fermi scale of the weak interactions is derived from Fermi's constant G_F. The QCD scale Λ_{QCD} is the energy at which the strong coupling constant becomes large. The vacuum-energy scale arises from the energy density in the cosmological constant. The Hubble scale characteristic of cosmology is related to the total density ρ by the Friedmann equation, $H \approx \sqrt{\rho}/E_{Pl}$. Note the large dynamic range spanned by these parameters.

One possible escape from this conundrum has been suggested under the name of 'spontaneous inflation'[21], a particular implementation of the idea of 'eternal inflation'[22–25] (for related ideas see refs 26–28). In general relativity, high-entropy states correspond to empty space; given any configuration of matter, we can always increase the entropy by expanding the Universe and diluting the matter degrees of freedom[21]. But if empty space has a non-zero vacuum energy, it can be unstable to the creation of baby universes[29–36]. In an empty universe with a positive cosmological constant (de Sitter space), quantum fluctuations will occasionally drive scalar fields to very large values of their potentials, setting up precisely the conditions necessary to begin inflation. The resulting bubble can branch off into a disconnected space-time, leading to an inflating region that would resemble our observable Universe.

The resulting ultra-large-scale structure of space-time is portrayed in Fig. 1. Time runs vertically in the empty background universe. Baby universes originate in quantum fluctuations, and break off from the background to form disconnected regions of space-time. In this way, each new universe naturally has very low entropy conditions at one boundary. The second law of thermodynamics is not violated, as the small region of the background from which the new universe arose has an even smaller entropy. The baby universes are portrayed as evolving sideways, because the locally defined arrow of time will not necessarily be smoothly connected to that of the background.

Needless to say, proposals of this type are extremely speculative, and may well be completely wrong. One mysterious aspect is the process of baby-universe creation, which certainly lies beyond the realm of established physics. In the context of string theory, there seem to be circumstances in which it can happen[37–41] but also ones in which it cannot[42]; whether it will occur in realistic situations is still unclear. Another issue is the nature of gravitational degrees of freedom in the context of the holographic principle, according to which degrees of freedom are distributed non-locally over volumes of space-time (see for example ref. 43). Given the relevance of inflation to observable phenomena, however, it is important to establish that inflation actually solves the problems it purports to address. In spontaneous inflation, there is a simple explanation for the low entropy of the initial state: it is not really 'initial', but rather arises by way of quantum fluctuations from a pre-existing de Sitter state with very large entropy and a very low entropy density. Whether this particular idea is on the right track or not, it is crucial to understand whether inflation plays a role in explaining how our observed configuration could be truly natural.

The laws of physics

The dynamical laws of nature at the microscopic level (including general relativity and the standard model of particle physics) are tightly constrained in the form that they may take, largely by symmetry principles such as gauge invariance and Lorentz invariance. The specific values of the numerical parameters of these theories are in principle arbitrary, although on naturalness grounds we would expect mass and energy scales to be roughly comparable to each other. As mentioned in the introduction, that is not what we observe: the Planck scale, Fermi scale, quantum chromodynamics (QCD) scale and vacuum-energy scale are separated by huge hierarchies. An intriguing possibility is that such hierarchies are not inevitable outcomes of deeper dynamics, but simply characterize the local conditions of our observable Universe, which is part of a much larger ensemble. In this case, what we think of as the 'laws of physics' are no more fundamental than the number of planets in our particular Solar System; they reflect environmental conditions rather than ineluctable truths.

We do (claim to) understand one of these hierarchies, that involving the QCD scale. For the strong interactions, the characteristic scale is governed by the logarithmic running of the QCD coupling constant, so a hierarchy is not that surprising. The difference between the Planck and Fermi scales ($E_{Pl}/E_F \approx 10^{16}$) is a celebrated puzzle in high-energy physics, known simply as 'the hierarchy problem'; ideas such as supersymmetry may provide partial answers. The discrepancy between the Planck scale

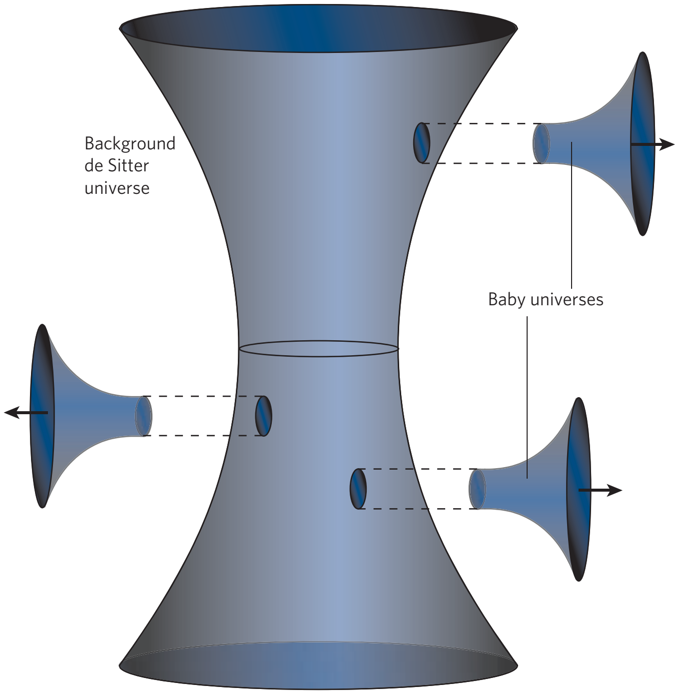

Figure 1 | A possible space-time diagram for the Universe on ultra-large scales. A natural state for a Universe with a positive vacuum energy is empty de Sitter space; this is the background universe in the figure, with time running vertically. In the presence of an appropriate scalar field, quantum fluctuations in such a background can lead to the nucleation of baby universes. Each baby universe is created in a proto-inflationary state, which then expands and reheats into a universe like that we observe. These universes are portrayed as evolving 'sideways', to emphasize that the local direction of time may not be related to that of the background space-time.

and the vacuum-energy scale ($E_{\rm Pl}/E_{\rm vac} \approx 10^{30}$) is another puzzle, 'the cosmological constant problem'; most researchers agree that there are no compelling solutions currently on the market.

In contemplating the nature of these hierarchies, a complicating factor arises: we could not exist without them. If all of the energy scales of fundamental physics were roughly equal, it would be impossible to form structures in which quantum gravity did not play a significant role, and the large cosmological constant would make it difficult to imagine any complex structures at all (as the rapidly accelerating expansion of the Universe would work to tear things apart). One can imagine two very different attitudes in the face of this situation. (1) We just got lucky. The constants of nature just happen to take on values consistent with the existence of complex organisms. (2) Environmental selection. The parameters we observe are not truly fundamental, but merely reflect our local conditions; hospitable regions of the Universe will always show large hierarchies.

In the first case, there are two separate possibilities: either we are really lucky, in the sense that the observed hierarchies are truly unnatural and have no deeper explanation, or there exist unknown dynamical mechanisms that make these hierarchies perfectly natural. The latter possibility is obviously more attractive, although it is hard to tell whether such dynamical explanation will eventually be forthcoming. Environmental selection, sometimes discussed in terms of the 'anthropic principle', has received renewed attention since the discovery of the dark energy. The basic idea is undeniably true: if our observable Universe is only a tiny patch of a much larger 'multiverse' with a wide variety of local environments, there is a selection effect due to the fact that life can only arise in those regions that are hospitable to the existence of life. Of course, to give this tautology any explanatory relevance, it is necessary to imagine that such a multiverse exists.

Existence of the multiverse requires two conditions: the possibility of multiple vacuum states with differing values of the constants of nature, and the realization of those states in distinct macroscopic regions. Recent ideas in string theory suggest that there may be a 'landscape' of metastable vacua arising from different ways of compacting extra dimensions in the presence of branes and gauge fields. Numbers such as 10^{500} vacua have been contemplated, promising more than enough diversity of possible local conditions[44–49]. Meanwhile, the possibility of eternal inflation discussed in the previous section provides a mechanism for realizing such states: quantum fluctuations can lead to episodes of inflation that reheat into universe-sized domains in any of the permitted vacuum states[50]. Thus, the ingredients of the multiverse picture seem to be in place, even if they remain speculative.

If all the multiverse does is allow for the existence of a region that resembles our own, it adds nothing to our understanding; it is equally sensible to say that our Universe is simply like that. Instead, the possible epistemological role of the multiverse is to explain why our observed parameters are natural. In principle, the multiverse picture allows us to predict the probability distribution for these parameters. In particular, the probability $P(X)$ that an observer measures their Universe to have feature X (such as "the ratio of the vacuum-energy scale to the Planck scale is of the order of 10^{-30}") will be roughly of the form

$$P(X) = \frac{\Sigma_n \sigma_n(X) V_n \rho_n}{\Sigma_n V_n \rho_n} \qquad (1)$$

In this expression, the index n labels all possible vacuum states; $\sigma_n(X)$ equals 1 if vacuum n has property X and 0 if it does not; V_n is the space-time volume in vacuum n; and ρ_n is the space-time density of observers in vacuum n.

Obviously, there is considerable imprecision in the definition of equation (1); for example, we have been vague about what constitutes an 'observer', not to mention 'space-time volume' and 'density'. Interesting attempts have been made to formulate more precise versions of an equivalent expression[51–56]. This expression suffices for our current purpose, however, which is to point out that actually calculating the probability is at best beyond our current abilities, and at worst completely hopeless. Just to mention the most obvious difficulty: in the context of eternal inflation, there is every reason to believe that the volumes V_n of some (if not all) vacua are infinite, and the expression is simply undefined.

The fact that equation (1) is undefined has not stopped people from trying to calculate it. The most famous example is Weinberg's prediction of the magnitude of the cosmological constant[57–60]. This calculation imagines a flat prior distribution for the vacuum energy, keeping all other parameters fixed, and relies on the fact that the Universe recollapses in the presence of a large negative vacuum energy and expands too quickly for galaxies to form in the presence of a large positive vacuum energy. Under these assumptions, the predicted value of $\rho_{\rm vac}$ is not too different from what has been observed; moreover, the prediction was made before the measurement. Attempts have also been made to apply similar reasoning to models of particle physics[61–65].

Unfortunately, there is little reason to be satisfied with this calculation of the expected vacuum energy. In terms of equation (1), it is equivalent to imagining that the factor $\sigma_n(X)$ counting appropriate vacua is distributed uniformly in $\rho_{\rm vac}$, the volume term V_n is simply a constant, and the density of observers ρ_n is proportional to the number of galaxies. The first of these is a (reasonable) guess, the second is likely to be fantastically wrong in the context of eternal inflation, and the last only makes sense if all of the other parameters are held fixed, which is not how we expect the multiverse to work. For example, allowing the amplitude of primordial density fluctuations to vary along with the vacuum energy can greatly change the result[66–69], not to mention variations of other parameters[56,70].

At present, then, there is no reliable environmental explanation for the observed value of the cosmological constant. To be fair, it does seem as though the allowed region in parameter space is very small, even if many parameters are allowed to vary, so it may be possible to make predictions about specific functions of the various parameters[68]. Meanwhile, other attempts to use anthropic reasoning seem to lead to predictions that are in wild disagreement with observations[71]. But objections to the credibility of the apparently successful predictions of the multiverse idea have equal force when applied to the apparently unsuccessful predictions; whether or not the idea is falsifiable, it would be an exaggeration to say that it has already been falsified.

More importantly, limitations in our current ability to calculate expectation values in the multiverse are not evidence that there is no truth to the idea itself. If we eventually decide that environmental selection plays no important role in explaining the observed parameters of nature, it will be because we come to believe that the parameters we measure locally are also characteristic of regions beyond our horizon, not because the very concept of the multiverse is aesthetically unacceptable or somehow a betrayal of the Enlightenment project of understanding nature through reason and evidence.

Future prospects

Naturalness is an ambiguous guide in the quest to understand our Universe better. The observation that a situation seems unnatural within a certain theoretical context does not carry anything like the force of an actual contradiction between theory and experiment. And despite our best efforts, naturalness is something that is hard to quantify objectively.

The search for naturalness plays an important role as a hint of physical processes that are not yet understood. In particle physics, attempts to find a natural solution to the hierarchy problem have driven investigations into supersymmetry and other models; in cosmology, attempts to explain the uniformity and flatness of our contemporary Universe helped to drive the development of inflationary cosmology. We can hope that attempts to understand the cosmological constant and the low entropy of the early Universe will lead to compelling new ideas about the fundamental architecture of nature.

The ideas discussed here involve the invocation of multiple inaccessible domains within an ultra-large-scale multiverse. For good reason, the reliance on the properties of unobservable regions and the difficulty in falsifying such ideas make scientists reluctant to grant them an explanatory role[72]. Of course, the idea that the properties of our observable domain can be uniquely extended beyond the cosmological horizon is an equally untestable assumption. The multiverse is not a theory; it is a consequence of certain theories (of quantum gravity and cosmology), and the hope is that these theories eventually prove to be testable in other ways. Every theory makes untestable predictions, but theories should be judged on the basis of the testable ones.

The ultimate goal is undoubtedly ambitious: to construct a theory that has definite consequences for the structure of the multiverse, such that this structure provides an explanation for how the observed features of our local domain can arise naturally, and that the same theory makes predictions that can be directly tested through laboratory experiments and astrophysical observations. To claim success in this programme, we will need to extend our theoretical understanding of cosmology and quantum gravity considerably, both to make testable predictions and to verify that some sort of multiverse picture really is a necessary consequence of these ideas. Only further investigation will allow us to tell whether such a programme represents laudable aspiration or misguided hubris. ■

1. 't Hooft, G. in *Recent Developments in Gauge Theories* vol. 59 (eds 't Hooft, G. *et al.*) NATO Advanced Study Institute, Series B: Physics (1980).
2. Zamolodchikov, A. B. 'Irreversibility' of the flux of the renormalization group in a 2-D field theory. *JETP Lett.* **43,** 730–732 (1986).
3. Cardy, J. L. Is there a c theorem in four-dimensions? *Phys. Lett. B* **215,** 749–752 (1988).
4. Gaite, J. & O'Connor, D. Field theory entropy and the renormalization group. *Phys. Rev. D* **54,** 5163–5173 (1996).
5. Riess, A. G. *et al*. Observational evidence from supernovae for an accelerating universe and a cosmological constant. *Astron. J.* **116,** 1009–1038 (1998).
6. Perlmutter, S. *et al.* Measurements of Omega and Lambda from 42 high-redshift supernovae. *Astrophys. J.* **517,** 565–586 (1999).
7. Spergel, D. N. *et al*. First year Wilkinson Microwave Anisotropy Probe (WMAP) observations: determination of cosmological parameters. *Astrophys. J.* **148** (suppl.), 175–194 (2003).
8. Carroll, S. M. The cosmological constant. *Living Rev. Rel.* **4,** 1 (2001).
9. Penrose, R. in *The Emperor's New Mind* Ch. 7 (Oxford Univ. Press, Oxford, 1989).
10. Guth, A. H. The inflationary universe: a possible solution to the horizon and flatness problems. *Phys. Rev. D* **23,** 347–356 (1981).
11. Linde, A. D. A new inflationary universe scenario: a possible solution of the horizon, flatness, homogeneity, isotropy and primordial monopole problems. *Phys. Lett. B* **108,** 389–393 (1982).
12. Albrecht, A. & Steinhardt, P. J. Cosmology for grand unified theories with radiatively induced symmetry breaking. *Phys. Rev. Lett.* **48,** 1220–1223 (1982).
13. Linde, A. D. Chaotic inflation. *Phys. Lett. B* **129,** 177–181 (1983).
14. Vachaspati, T. & Trodden, M. Causality and cosmic inflation. *Phys. Rev. D* **61,** 023502 (2000).
15. Guth, A.H. & Pi, S.Y. Fluctuations in the new inflationary universe. *Phys. Rev. Lett.* **49,** 1110–1113 (1982).
16. Hawking, S. W. The development of irregularities in a single bubble inflationary universe. *Phys. Lett. B* **115,** 295–297 (1982).
17. Starobinsky, A. A. Dynamics of phase transition in the new inflationary universe scenario and generation of perturbations. *Phys. Lett. B* **117,** 175–178 (1982).
18. Bardeen, J. M., Steinhardt, P. J. & Turner, M. S. Spontaneous creation of almost scale-free density perturbations in an inflationary universe. *Phys. Rev. D* **28,** 679–693 (1983).
19. Hollands, S. & Wald, R. M. An alternative to inflation. *Gen. Rel. Grav*. **34,** 2043–2055 (2002).
20. Albrecht, A. & Sorbo, L. Can the Universe afford inflation? <arXiv:hep-th/0405270> (2004).
21. Carroll, S. M. & Chen, J. Spontaneous inflation and the origin of the arrow of time. <arXiv:hep-th/0410270> (2004).
22. Vilenkin, A. The birth of inflationary universes. *Phys. Rev. D* **27,** 2848–2855 (1983).
23. Linde, A. D. Eternal chaotic inflation. *Mod. Phys. Lett. A* **1,** 81–85 (1986).
24. Linde, A. D. Eternally existing selfreproducing chaotic inflationary universe. *Phys. Lett. B* **175,** 395–400 (1986).
25. Goncharov, A. S., Linde, A. D. & Mukhanov, V. F. The global structure of the inflationary universe. *Int. J. Mod. Phys. A* **2,** 561–591 (1987).
26. Garriga, J. & Vilenkin, A. Recycling universe. *Phys. Rev. D* **57,** 2230–2244 (1998).
27. Dutta, S. & Vachaspati, T. Islands in the Lambda-sea. *Phys. Rev. D* **71,** 083507 (2005).
28. Holman, R. & Mersini-Houghton, L. Why the universe started from a low entropy state. <arXiv:hep-th/0511102> (2005).
29. Farhi, E. & Guth, A. H. An obstacle to creating a universe in the laboratory. *Phys. Lett. B* **183,** 149–155 (1987).
30. Vilenkin, A. Quantum cosmology and the initial state of the Universe. *Phys. Rev. D* **37,** 888–897 (1988).
31. Farhi, E., Guth, A. H. & Guven, J. Is it possible to create a universe in the laboratory by quantum tunneling? *Nucl. Phys. B* **339,** 417–490 (1990).
32. Fischler, W., Morgan, D. & Polchinski, J. Quantum nucleation of false vacuum bubbles. *Phys. Rev. D* **41,** 2638–2641 (1990).
33. Fischler, W., Morgan, D. & Polchinski, J. Quantization of false vacuum bubbles: a Hamiltonian treatment of gravitational tunneling. *Phys. Rev. D* **42,** 4042–4055 (1990).
34. Linde, A. D. Hard art of the universe creation (stochastic approach to tunneling and baby universe formation). *Nucl. Phys. B* **372,** 421–442 (1992).
35. Aguirre, A. & Johnson, M. C. Dynamics and instability of false vacuum bubbles. *Phys. Rev. D* **72,** 103525 (2005).
36. Aguirre, A. & Johnson, M. C. Two tunnels to inflation. <arXiv:gr-qc/0512034> (2005).
37. Alberghi, G. L., Lowe, D. A. & Trodden, M. Charged false vacuum bubbles and the AdS/CFT correspondence. *J. High Energy Phys*. **9907,** 020 (1999); published online 23 June 1999 (arXiv:hep-th/9906047).
38. Hellerman, S. On the landscape of superstring theory in $D > 10$. <arXiv:hepth/0405041> (2005).
39. Adams, A., Liu, X. McGreevy, J., Saltman, A. & Silverstein, E. Things fall apart: topology change from winding tachyons. *J. High Energy Phys*. **0510,** 033 (2005); published online 5 August 2005 (arXiv:hep-th/0502021).
40. Dijkgraaf, R., Gopakumar, R., Ooguri, H. & Vafa, C. Baby universes in string theory. <arXiv:hep-th/0504221> (2005).
41. McGreevy, J. & Silverstein, E. The tachyon at the end of the universe. *J. High Energy Phys*. **0508,** 090 (2005); published online 3 August 2005 (arXiv:hep-th/0506130).
42. Freivogel, B. *et al.* Inflation in AdS/CFT. <arXiv:hep-th/0510046> (2005).
43. Dyson, L., Kleban, M. & Susskind, L. Disturbing implications of a cosmological constant. *J. High Energy Phys.* **0210,** 011 (2002); published online 14 November 2002 (arXiv:hep-th/0208013).
44. Bousso, R. & Polchinski, J. Quantization of four-form fluxes and dynamical neutralization of the cosmological constant. *J. High Energy Phys.* **0006,** 006 (2000); published online 26 June 2000 (arXiv:hep-th/0004134).
45. Feng, J. L., March-Russell, J., Sethi, S. & Wilczek, F. Saltatory relaxation of the cosmological constant. *Nucl. Phys. B* **602,** 307–328 (2001).
46. Giddings, S. B., Kachru, S. & Polchinski, J. Hierarchies from fluxes in string compactifications. *Phys. Rev. D* **66,** 106006 (2002).
47. Kachru, S., Kallosh, R., Linde, A. & Trivedi, S. P. De Sitter vacua in string theory. *Phys. Rev. D* **68**, 046005 (2003).
48. Douglas, M. R. The statistics of string/M theory vacua. *J. High Energy Phys.* **0305,** 046 (2003); published online 24 April 2003 (arXiv:hep-th/0303194).
49. Ashok, S. & Douglas, M. R. Counting flux vacua. *J. High Energy Phys.* **0401,** 060 (2004); published online 12 January 2004 (arXiv:hep-th/0307049).
50. Linde, A. Inflation, quantum cosmology and the anthropic principle. <arXiv:hepth/0211048> (2002).
51. Vilenkin, A. Predictions from quantum cosmology. *Phys. Rev. Lett.* **74,** 846–849 (1995).
52. Tegmark, M. What does inflation really predict? *J. Cosmol. Astropart. Phys.* **0504,** 001 (2005); published online 12 October 2004 (arXiv:astro-ph/0410281).
53. Aguirre, A. On making predictions in a multiverse: conundrums, dangers, and coincidences. <arXiv:astro-ph/0506519> (2005).
54. Garriga, J., Schwartz-Perlov, D., Vilenkin, A. & Winitzki, S. Probabilities in the inflationary multiverse. <arXiv:hep-th/0509184> (2005).
55. Easther, R., Lim, E. A. & Martin, M. R. Counting pockets with world lines in eternal inflation. <arXiv:astro-ph/0511233> (2005).
56. Tegmark, M., Aguirre, A., Rees, M. & Wilczek, F. Dimensionless constants, cosmology and other dark matters. <arXiv:astro-ph/0511774> (2005).

57. Weinberg, S. Anthropic bound on the cosmological constant. *Phys. Rev. Lett.* **59,** 2607–2610 (1987).
58. Vilenkin, A. Quantum cosmology and the constants of nature. <arXiv:gr-qc/9512031> (1995).
59. Martel, H., Shapiro, P. R. & Weinberg, S. Likely values of the cosmological constant. *Astrophys. J.* **492,** 29–40 (1998).
60. Banks, T., Dine, M. & Motl, L. On anthropic solutions of the cosmological constant problem. *J. High Energy Phys.* **0101,** 031 (2001); published online 26 July 2000 (arXiv:hep-th/0007206).
61. Pogosian, L., Vilenkin, A.& Tegmark, M. Anthropic predictions for vacuum energy and neutrino masses. *J. Cosmol. Astropart. Phys.* **0407,** 005 (2004); published online 26 April 2004 (arXiv:astro-ph/0404497).
62. Arkani-Hamed, N. & Dimopoulos, S. Supersymmetric unification without low energy supersymmetry and signatures for fine-tuning at the LHC. *J. High Energy Phys.* **0506,** 073 (2005); published online 24 May 2004 (arXiv:hep-th/0405159).
63. Arkani-Hamed, N., Dimopoulos, S. & Kachru, S. Predictive landscapes and new physics at a TeV. <arXiv:hep-th/0501082> (2005).
64. Dine, M., O'Neil, D. & Sun, Z. Branches of the landscape. *J. High Energy Phys.* **0507,** 014 (2005); published online 20 January 2005 (arXiv:hep-th/0501214).
65. Fox, P. J. *et al.* Supersplit supersymmetry. <arXiv:hep-th/0503249> (2005).
66. Tegmark, M. & Rees, M. J. Why is the CMB fluctuation level 10^{-5}? *Astrophys. J.* **499,** 526 (1998); published online 12 December 1997 (arXiv:astro-ph/9709058).
67. Graesser, M. L., Hsu, S. D. H., Jenkins, A. & Wise, M. B. Anthropic distribution for cosmological constant and primordial density perturbations. *Phys. Lett. B* **600,** 15–21 (2004).
68. Garriga, J. & Vilenkin, A. Anthropic prediction for Lambda and the Q catastrophe. <arXiv: hep-th/0508005> (2005).
69. Feldstein, B., Hall, L. J. & Watari, T. Density perturbations and the cosmological constant from inflationary landscapes. <arXiv:hep-th/0506235> (2005).
70. Aguirre, A. The cold big-bang cosmology as a counter-example to several anthropic arguments. *Phys. Rev. D* **64,** 083508 (2001); published online 12 July 2001 (arXiv:astro-ph/0106143).
71. Olum, K. D. Conflict between anthropic reasoning and observation. <arXiv: grqc/0303070> (2003).
72. Smolin, L. Scientific alternatives to the anthropic principle. <arXiv:hep-th/0407213> (2004).

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