ratory) told us, for example, that in the H–T plane the melting line might lie below the irreversibility line and that the flux lines are in a "glassy" configuration in the region between those lines. Chris Rossel, Y. Maeno and Morgenstern (IBM Zurich Research Laboratory) have observed in the magnetic behavior of Y-Ba-Cu-O a "memory effect" that was first reported in spin glasses. In the IBM Zurich experiment the magnetic field acting on a sample of Y-Ba-Cu-O cooled below the critical temperature was changed after the superconductor had been maintained at fixed field and temperature for a given "waiting" time. At a time comparable to the waiting time the decay curve showing the nonequilibrium magnetization of the superconductor versus the logarithm of time exhibited features, similar to those observed in spin glasses, reflecting the change in the magnetic field. The Zurich group thinks that the giant-flux-creep picture for the magnetic properties of the oxide superconductors is valid only for short time scales and low temperatures, and that their superconducting-glass theory[9] is needed to explain the newly found memory effect. Morgenstern told us that the Zurich superconducting-glass theory is a generalization of the giant-flux-creep picture valid at higher temperatures and longer time scales.

Because the flux creep is larger for some values of the magnetic field and temperature, currents in some single crystals of the high-temperature oxide superconductors may not persist for as long as they do in conventional superconductors at low temperatures. The magnitude of the effects due to giant flux creep varies in different families of the new superconductors. John Rowell (Bellcore) told us that this means we might have to decide which material is best for each application. For example, according to Theodore Geballe, flux creep resistivity is of no consequence in many applications, such as power transmission.[10]

"Seen in the light of the results on single crystals, the large optical current densities obtained in thin films suggest that some new mechanism for pinning the flux lines operates in the films," Malozemoff said. Chaudhari thinks that because of the short coherence length in the new oxide superconductors, flux lines in good films may be pinned at point defects.[11] In conventional superconductors point defects are considered not to be important for pinning. According to the Zurich group, the mechanism underlying the glassy behavior might also provide the pinning needed for higher critical currents.

—ANIL KHURANA

References

1. K. A. Müller, M. Takashige, J. G. Bednorz, Phys. Rev. Lett. **58**, 408 (1987). A. C. Mota, A. Pollini, P. Visani, K. A. Müller, J. G. Bednorz, Phys. Rev. **36**, 1987.
2. Y. Yeshurun, A. P. Malozemoff, Phys. Rev. Lett. **60**, 2202 (1988). A. P. Malozemoff, T. K. Worthington, Y. Yeshurun, F. Holtzberg, P. H. Kees, Phys. Rev. B **38**, 7203 (1988).
3. C. Rossel, Y. Maeno, I. Morgenstern, Phys. Rev. Lett. **62**, 681 (1989).
4. M. Tinkham, Phys. Rev. Lett. **61**, 1658 (1988).
5. T. T. M. Palstra, B. Batlogg, L. F. Schneemeyer, J. V. Waszczak, Phys. Rev. Lett. **61**, 1662 (1988).
6. P. L. Gammel, D. J. Bishop, G. J. Dolan, J. R. Kwo, C. A. Murray, L. F. Schneemeyer, J. V. Waszczak, Phys. Rev. Lett. **59**, 2592 (1987). P. L. Gammel, L. F. Schneemeyer, J. V. Waszczak, D. J. Bishop, Phys. Rev. Lett. **61**, 1666 (1988).
7. D. R. Nelson, Phys. Rev. Lett. **60**, 1973 (1988). D. R. Nelson, H. S. Seung, submitted to Phys. Rev. B.
8. M. A. Moore, Phys. Rev. B, in press. A. Houghton, R. A. Pelcovits, A. Sudbo, Brown University preprint 1988.
9. I. Morgenstern, A. Müller, G. Bednorz, Z. Phys. B **69**, 33 (1987).
10. S. Jonathan, R. S. Feigelson, D. Gazit, D. Fork, T. H. Geballe, A. Kapitulnik, in *Proc. Applied Superconductivity Conf. 1988*, to be published by IEEE, New York.
11. P. Chaudhari, Jpn. J. Appl. Phys. **26–3**, 2023 (1987).
12. P. W. Anderson, "Just Exactly What Do You Do, Dr. Anderson?" Abigail and John Van Vleck Lecture, University of Minnesota, unpublished.

WHY IS THE COSMOLOGICAL CONSTANT SO VERY SMALL?

A blatant discrepancy between theory and observation can be seen as a promising spur toward deeper understanding. But the gap between theory and measurements of the cosmological constant was too much of a good thing. If one expresses this fundamental parameter of cosmic geometry as the inverse square of a length, it is clear from observation of distant galaxies that this length is, at the very least, a billion light years. The quantum field theory of the elementary particles, however, could not allow a length much larger than 10^{-33} cm—the Planck length—unless one invoked a seemingly miraculous and totally implausible cancellation of elementary-particle parameters.

The cosmological constant may well be identically zero. That is in fact what most astrophysicists prefer. But from the viewpoint of modern particle theory, its observational upper limit is 120 *orders of magnitude* too small. "The discrepancy is so bad that for a long time it didn't bear thinking about," recalls Steven Weinberg (University of Texas). But in the last year things have changed. Last spring Sidney Coleman (Harvard) circulated his provocatively titled preprint, "Why there is Nothing Rather Than Something: A Theory of the Cosmological Constant,"[1] which argued that quantum tunneling between separate universes by way of tiny "wormholes" would make the cosmological constant vanish identically. A month earlier, Thomas Banks (University of California, Santa Cruz) had concluded, from somewhat similar arguments, that the cosmological constant must be finite, but very small.[2]

Coleman's paper, in particular, quickly aroused considerable excitement and theoretical activity. Objections and alternative formulations have been put forward, and Coleman and Banks themselves are by no means convinced that Nature deigns to follow their schemes. Nonetheless there is now real optimism among cosmologists that the new wormhole calculus, applied to the appropriate "wavefunction of the universe," might well yield a solid explanation for the vanishing (or near vanishing) of the cosmological constant.

Vacuum energy

In Einstein's original 1916 formulation, the field equation of general relativity reads

$$R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R = -8\pi G T_{\mu\nu}$$

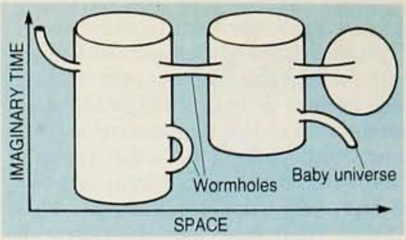
where R, g and T are, respectively, the curvature, metric and energy–momentum tensors, and G is Newton's gravitational constant. This minimal covariant formulation, however, does not allow for a static cosmological solution, any more than does Newtonian gravitation. In those days, before the general Hubble expansion of the universe had been observed, Einstein favored a static cosmological model. As an afterthought, therefore, he added a term $-g_{\mu\nu}\lambda$ to the left-hand side of the field equation, calling the new, undetermined parameter λ the "cosmological constant." A positive λ would introduce an effective general repulsion to counterbalance the collapsing tendency of gravity and thus make a static solution possible. Once the redshift measurements began to show that the universe is anything but static, Einstein wrote to Hermann Weyl: "If there is no quasi-static world, then away with the cosmological term."

But modern quantum field theory makes it very difficult to dismiss the cosmological constant. Adding λ to the Einstein field equation has the same effect as assigning an energy density $\lambda c^4/8\pi G$ to the vacuum itself. The observational upper limit on this vacuum energy density, as determined from the absence of any obvious cosmic curvature at large distances, is roughly 10^{-4} GeV/cm^3. On the other hand, summing the zero-point energies contributed by the vacuum fluctuations of the elementary-particle fields gives an energy density of something like 10^{+114} GeV/cm^3. Even if one restricts one's attention to the zero-point energies of quantum chromodynamics, the field theory of the quarks and their strong interaction, one still gets a vacuum energy density of 10^{+37} GeV/cm^3.

One conceivable way out of this dilemma is to imagine that these unavoidably enormous contributions of the particle fields to the vacuum energy density are precisely canceled by a "fundamental" λ of negative sign, so that the "effective" λ seen by the astronomers becomes negligible. But this would require absurdly fine tuning of the fundamental parameters of particle physics to make the two terms cancel to 118 (or perhaps only 41) decimal places.

Prearrangement or precognition

Such fine tuning of parameters is particularly hard to imagine in the context of the earliest moments of the universe. This difficulty is generally referred to as "the problem of prearrangement." It is assumed that ordinary quantum field theory already governed physics soon after the Planck time (10^{-43} seconds after the Big Bang). Thus one could, in principle, have measured all the fundamental constants during the 10^{-35}-second inflationary epoch that followed the Planck time. (See the article by Andrei Linde in PHYSICS TODAY, September 1987, page 61). But, as Coleman formulates the prearrangement problem, "how could [these parameters] have known to adjust themselves so [precisely] that when everything settled down, λ would [turn out to] be zero?" The actual zero value of the cosmological constant would have been completely masked by the enormous energy density and curvature of the metastable inflationary phase. It's far more puzzling, Coleman explains, than finding at the end of the year that the gross receipts of a large supermarket chain match its total expenditures to the last penny.



A manifold of large universes connected by wormholes. The ends of truncated wormholes that make no such connection are called baby universes. The horizontal plane represents 3 space dimensions and the vertical axis represents imaginary, "Euclidean" time.

In Coleman's wormhole scenario, this sort of implausible prearrangement is replaced by what he calls precognition. An expanding universe is one possible classical solution of the Einstein field equations. But so are two independent universes, or three, or as many as you like. These many-universe solutions would be of no interest, Coleman told us, if one universe could have no effect on any other. It is quantum tunneling through wormholes that provides the connection between these otherwise completely separate universes. Wormhole solutions of this kind have been formulated in recent years by Andrew Strominger (University of California, Santa Barbara), Steven Giddings (Harvard) and Stephen Hawking (Cambridge University), but the prehistory of the idea goes back to a suggestion by Freeman Dyson (Institute for Advanced Study, Princeton) in the mid-1970s. These topological fluctuations of 4-dimensional space–time are, however, quite different from the earlier 3-dimensional wormholes of John Wheeler.

A wormhole is a microscopic connection between two large and otherwise smooth regions of space–time. These quantum fluctuations of space–time topology can connect distant regions of the same large space–time manifold, but in Coleman's scheme the principal role is played by wormhole connections between otherwise disconnected space–time manifolds—separate universes. A 3-dimensional spacelike slice through a wormhole (or a truncated wormhole end that fails to make contact with another large manifold) is called a "baby universe." Wormholes can, in principle, be of any size. But Coleman concludes that the contribution of wormholes very much larger than the Planck length is exponentially suppressed.

It makes no sense to speak of these separate universes as having any particular location relative to one another. They do not sit in a larger imbedding space, and the distance between two points in separate manifolds is not defined. Furthermore, the location of a wormhole within a particular manifold is completely uncertain in the quantum-mechanical sense. Therefore a wormhole can convey information only about global averages over the entire extent and history of a universe. The kind of backward time travel Kip Thorne (Caltech) and his colleagues have recently been speculating about[3] involves the very different Wheeler wormholes.

Precognition, as Coleman uses it, addresses the prearrangement problem without invoking knowledge of a particular future moment in the manner of a fortune-teller. A young universe in its inflationary phase can "know about" the physics of older, colder universes that see the cosmological constant directly, because an average over the entire history of the other universe is heavily weighted toward its cool, mature phase. Banks's theory makes this sort of precognition particularly clear.

Does the quantization of gravity require the existence of such wormholes? The answer is somewhat ambiguous because we do not yet have a definitive quantum field theory that includes gravity. But many such theories do have wormhole solutions. As Strominger puts it: "In quantum mechanics almost everything is uncertain. So why should the topology of space–time be fixed?"

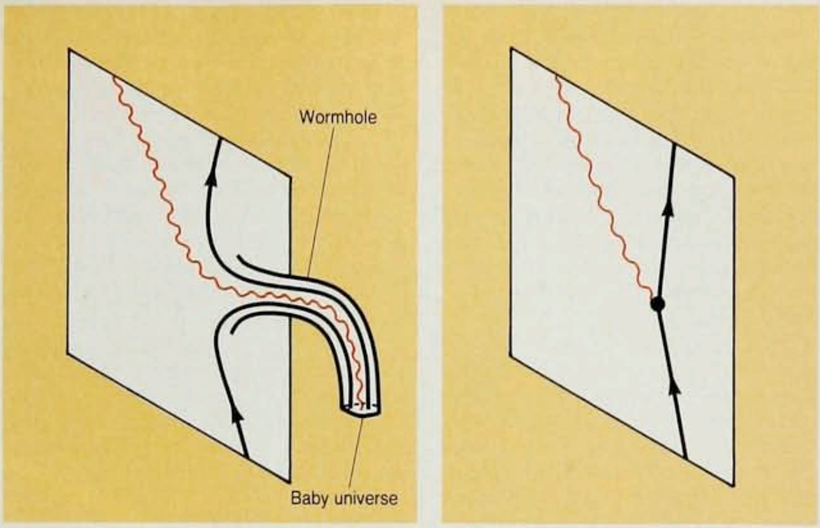
The constants of nature

How does one universe affect the physics in another universe connected to it by a wormhole? Coleman suggests the analogy of adjacent potential wells in ordinary nonrelativistic quantum mechanics. A particle of low energy may be classically confined to its own well, but quantum tunneling allows its wavefunction to probe the neighboring well. Suppose the particle is a boson. Then the presence or absence of a second, identical boson in the other well will, by Bose statistics, affect the wavefunction of the first particle. Thus the "constants of nature," such as the effective mass and spring constant experienced by a particle in a well, are modified by the population of a second well from which it is classically excluded. In Coleman's theory of the vanishing cosmological constant, this is essentially the way in which the constants of nature, as we observe them, are modified by the existence of other universes of which we can never have direct experience.

Two years ago Hawking,[4] Giddings and Strominger,[5] and G. V. Lavrelashvili and coworkers at the Institute for Nuclear Research in Moscow[6] independently argued that wormholes might destroy the large-scale quantum coherence of our universe. It was in an attempt to refute this argument that Coleman, Giddings and Strominger developed the new wormhole calculus. This refutation, which appeared a year ago in Coleman's paper "Black Holes as Red Herrings: Topological Fluctuations and the Loss of Quantum Coherence,"[7] is widely accepted as a convincing demonstration that wormholes do not destroy quantum coherence.

But, Coleman pointed out in this "Red Herrings" paper, they do something else even more spectacular. Wormholes, he concluded, turn the "constants of nature" into dynamical variables governed by some *a priori* probability distribution. That is not to say that λ, or the fine-structure constant, or any other fundamental coupling constant, will vary with time or from one universe to another. They are eigenvalues, like constants of the motion, which are the same for all time and all universes connected by wormholes. But like the result of a measurement on a superposition of eigenstates, the physical value of any one of these constants is predicted only by a probability distribution, which in this case depends on wormhole dynamics. Much the same conclusion was put forward in a paper by Giddings and Strominger[8] that appeared back to back with Coleman's.

Here one confronts an intrinsic problem of applying quantum mechanics to the "wavefunction of the universe." Probability amplitudes are the standard coin of quantum theory. Ordinarily these distributions are interpreted as governing the intrinsically unpredictable outcomes of repeated, identical experiments. But this kind of cosmology does not involve repeatable experiments. "The theory [as of last March] refuses to predict specific values for the fundamental constants; it only gives a probability distribution," Banks explains. It's as if God had performed the measurement once, and the intrinsically random outcome governs all wormhole-connected universes, throughout their histories, with a fixed set of unpredictable but unchanging coupling constants.



An example of how wormholes shift coupling constants. At left, a baby universe gives up a photon (red), an electron and a positron (which looks like an electron going backwards) to a large universe through a wormhole. To an observer who cannot see down to the Planck scale of the wormhole, this looks (right) like an ordinary electron radiation vertex. Thus even if there were no "fundamental" electromagnetic coupling, wormholes would introduce a finite "effective" coupling.

Delta function

Coleman's "Red Herrings" paper had argued that the cosmological constant, like the other fundamental constants, is affected by wormhole connections with other universes in such a way that its value can only be specified by a probability distribution. But he could not specify the form of that distribution, nor had he explained the vanishing of λ.

That explanation came two months later in Coleman's second 1988 paper, "Why There is Nothing Rather than Something." He shows that if one treats the problem in a plausible "dilute-gas approximation," in which the dominant wormholes are one order of magnitude larger than the Planck length, the probability distribution for λ must contain the double-exponental factor $\exp[\exp(3\pi/G\lambda)]$. Thus the *a priori* probability distribution for the cosmological constant is infinitely peaked at $\lambda = 0$. One might say that in the initial measurement that fixed the effective cosmological constant for all times and places, any result other than zero would have been infinitely improbable.

A 1984 paper by Hawking had laid much of the groundwork for this conclusion. Without invoking wormholes, Hawking had derived a single-exponential delta function for the λ probability distribution. But this argument rested rather heavily on assumptions about boundary conditions.

Whether the *a priori* probability distributions of the other fundamental constants also exhibit such delta functions that take away their intrinsic unpredictabilities is not yet clear. Banks, in a recent paper[9] with Igor Klebanov (SLAC) and Leonard Susskind (Stanford), concludes that Coleman's method yields a mass of zero for the pion—"a discouraging result," as the authors put it. In another recent critique,[10] entitled "A Wormhole Catastrophe," Susskind and Willy Fischler (University of Texas) argue that Coleman's assumptions "inevitably lead to the unphysical conclusion that large-scale wormholes materialize in space–time with maximal density." Coleman and Kimyeong Lee (Boston University) have just completed a paper that they believe will successfully answer these critiques. But, for the moment, these issues remain controversial.

Wavefunction of the universe

Coleman's work proceeds from the quantum cosmology developed by Hawking and James Hartle (University of California, Santa Barbara).

Their wavefunction of the universe is a Feynman path integral over all possible configurations of the matter fields *and* the metric. Whereas in ordinary field theory one need consider only the matter fields, in general relativistic cosmology one must also treat the space–time metric itself as a dynamical variable. The integrand of this path integral is, as usual, the exponential of the action—the integral of the Lagrangian over the entire history of the universe.

The path integral, however, is evaluated over space–times of Euclidean (rather than the normal Minkowskian) signature. That is to say, time is treated as an imaginary coordinate. This is a standard analytic-continuation technique. It is employed in quantum tunneling problems, where the square of the momentum is negative in classically forbidden regions and one can thus think of the velocity as being imaginary. But the Euclidean approach is not just a mathematical convenience. It embodies definite cosmological assumptions about the boundary conditions of the wavefunction of the universe.

Banks, on the other hand, employed a Minkowskian formulation for the path integral. Whereas Banks regarded the classical evolution of the universe as the principal contributor to the path integral, Coleman gave precedence to quantum tunneling out of early universes in which classical expansion is forbidden. "I had become a convert to Sidney's view, until I saw the critique of Fischler and Susskind," Banks told us.

In these path integrals, one must integrate not only over the entire history of *our* universe but over the entire manifold of all universes connected by wormholes. The great simplifying trick discovered by Coleman, Giddings and Strominger is that one can throw away the wormholes and replace their effects by probability distributions for the effective cosmological constant and the other fundamental constants of the Lagrangian.

Boundary conditions for the path integrals are an issue. Coleman employed the "no boundary" condition postulated by Hawking and Hartle. "It may be pretty," he writes, "but it is not divinely ordained." Coleman points out that it is possible to make the infinite peak for λ disappear by choosing peculiar boundary conditions. But he argues that this would be another form of implausible fine tuning. "Without wormholes," he writes, "we must fine tune to keep the cosmological constant zero; with wormholes, we must fine tune to keep it nonzero. I believe this is progress."

Joseph Polchinski (University of Texas) has recently raised a serious technical issue with which Coleman is still wrestling. Polchinski has pointed out that the Euclidean path integral over the wormhole-free manifolds acquires a phase that might eliminate the infinite peak at zero cosmological constant. Stephen Adler (Institute for Advanced Study, Princeton), on the other hand, has recently claimed that one can significantly loosen the requirements of Coleman's method and still preserve the infinite peak in the λ probability distribution.[11] He offers a generalization of Coleman's approach that may clarify its relation to the Minkowskian formalism of Banks.

Anthropic principle

What if the probability distribution for λ is not infinitely peaked? This possibility is made plausible by new work of Fischler, Polchinski and Susskind. If the conclusion of Coleman's "Red Herrings" paper holds up nonetheless, one might be able to explain the observed size of the cosmological constant by the "anthropic principle." This somewhat controversial principle takes the very existence of humanity, or any other sentient beings capable of doing science, to be an important datum constraining the laws of physics. If, for example, different universes or different epochs have different fundamental constants, sentient observers would see only those values of the constants that are consistent with the evolution of such observers.

Coleman's scenario, unlike the one described in Linde's PHYSICS TODAY article, does not allow for a λ that varies with time and place. But if the cosmological constant was indeed determined only by an *a priori* probability distribution, one could argue that if this primordial throw of the wormhole dice had given too inhospitable a value of λ, there would be no cosmologists around to discuss it.

Weinberg has examined the constraints imposed on λ by the anthropic principle in some detail.[12] He argues that the clustering of matter into galaxies is a plausible minimum condition for the evolution of sentient observers. Gravitational clustering puts an upper limit on λ, which acts as a kind of counterforce to gravity. Given the largest redshifts at which we see galaxies, Weinberg argues, the cosmological constant, expressed as a vacuum energy density, could be as large as five hundred times the present cosmic mass density and still permit galaxy formation.

If astronomers find that the cosmological constant is within an order of magnitude of this upper bound, one could plausibly attribute it to the anthropic principle. The observational situation is unclear. Two years ago Edwin Loh and Earl Spillar at Princeton, having found no evidence for cosmic curvature in their galactic redshift measurements, concluded that the cosmic mass density is very close to its critical closure value (10^{-29} grams/cm^3). Imposing constraints of inflationary cosmology on these data, Loh concluded that the cosmological constant is at most one-tenth the mass density—a thousand times too small to be explained by the anthropic principle (see PHYSICS TODAY, May 1987, page 17).

But three orders of magnitude is not nearly as bad as 120. And in any case, the measurements of Loh and Spillar have been disputed. The observed density of luminous matter in the universe is a hundred times less than the critical value. If that were in fact the total mass density, with "dark matter" playing no significant role, inflationary cosmology would favor a vacuum energy density one hundred times greater than the mass density, in good accord with the anthropic principle. Furthermore, a cosmological constant of this magnitude would imply a universe roughly twice as old as one gets with Loh's upper limit or a vanishing λ. Doubling the elapsed time since the Big Bang would resolve the nagging problem of the globular star clusters in our galaxy, which otherwise appear to be older than the universe.

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References

1. S. Coleman, Nucl. Phys. B **310**, 643 (1988).
2. T. Banks, Nucl. Phys. B **309**, 493 (1988).
3. M. Morris, K. Thorne, U. Yurtsever, Phys. Rev. Lett. **61**, 1446 (1988).
4. S. Hawking, Phys. Lett. B **195**, 337 (1987).
5. S. Giddings, A. Strominger, Nucl. Phys. B **306**, (1987)
6. G. V. Lavrelashvili, V. A. Rubakov, P. G. Tinyakov, JETP Lett. **46**, 167 (1987).
7. S. Coleman, Nucl. Phys. B **307**, 867 (1988).
8. S. Giddings, A. Strominger, Nucl. Phys. B **307**, 854 (1988).
9. I. Klebanov, L. Susskind, T. Banks, SLAC preprint R4705 (1988).
10. W. Fischler, L. Susskind, University of Texas Theory Group preprint 26 (1988).
11. S. Adler, Phys. Rev. Lett. **62**, 373 (1989).
12. S. Weinberg, Phys. Rev. Lett. **59**, 2607 (1987). ■