The Nature of Space and Time

Two relativists present their distinctive views on the universe, its evolution and the impact of quantum theory

by Stephen W. Hawking and Roger Penrose

In 1994 Stephen W. Hawking and Roger Penrose gave a series of public lectures on general relativity at the Isaac Newton Institute for Mathematical Sciences at the University of Cambridge. From these lectures, published this year by Princeton University Press as *The Nature of Space and Time,* SCIENTIFIC AMERICAN has culled excerpts that serve to compare and contrast the perspectives of the two scientists. Although they share a common heritage in physics—Penrose served on Hawking's Ph.D. thesis committee at Cambridge—the lecturers differ in their vision of quantum mechanics and its impact on the evolution of the universe. In particular, Hawking and Penrose disagree on what happens to the information stored in a black hole and on why the beginning of the universe differs from the end.

One of Hawking's major discoveries, made in 1973, was that quantum effects will cause black holes to emit particles. The black hole will evaporate in the process, so that ultimately perhaps nothing of the original mass will be left. But during their formation, black holes swallow a lot of data—the types, properties and configurations of the particles that fall in. Although quantum theory requires that such information must be conserved, what finally happens to it remains a topic of contentious debate. Hawking and Penrose both believe that when a black hole radiates, it loses the information it held. But Hawking insists that the loss is irretrievable, whereas Penrose argues that the loss is balanced by spontaneous measurements of quantum states that introduce information back into the system.

Both scientists agree that a future quantum theory of gravity is needed to describe nature. But they differ in their view of some aspects of this theory. Penrose thinks that even though the fundamental forces of particle physics are symmetric in time—unchanged if time is reversed—quantum gravity will violate time symmetry. The time asymmetry will then explain why in the beginning the universe was so uniform, as evinced by the microwave background radiation left over from the big bang, whereas the end of the universe must be messy.

Penrose attempts to encapsulate this time asymmetry in his Weyl curvature hypothesis. Space-time, as Albert Einstein discovered, is curved by the presence of matter. But space-time can also have some intrinsic bending, a quantity designated by the Weyl curvature. Gravitational waves and black holes, for example, allow space-time to curve even in regions that are empty. In the early universe the Weyl curvature was probably zero, but in a dying universe the large number of black holes, Penrose argues, will give rise to a high Weyl curvature. This property will distinguish the end of the universe from the beginning.

Hawking agrees that the big bang and the final "big crunch" will be different, but he does not subscribe to a time asymmetry in the laws of nature. The underlying reason for the difference, he thinks, is the way in which the universe's evolution is programmed. He postulates a kind of democracy, stating that no point in the universe can be special; therefore, the universe cannot have a boundary. This no-boundary proposal, Hawking claims, explains the uniformity in the microwave background radiation.

The physicists diverge, ultimately, in their interpretation of quantum mechanics. Hawking believes that all a theory has to do is provide predictions that agree with data. Penrose thinks that simply comparing predictions with experiments is not enough to explain reality. He points out that quantum theory requires wave functions to be "superposed," a concept that can lead to absurdities. The scientists thus pick up the threads of the famous debates between Einstein and Niels Bohr on the bizarre implications of quantum theory.

—The Editors

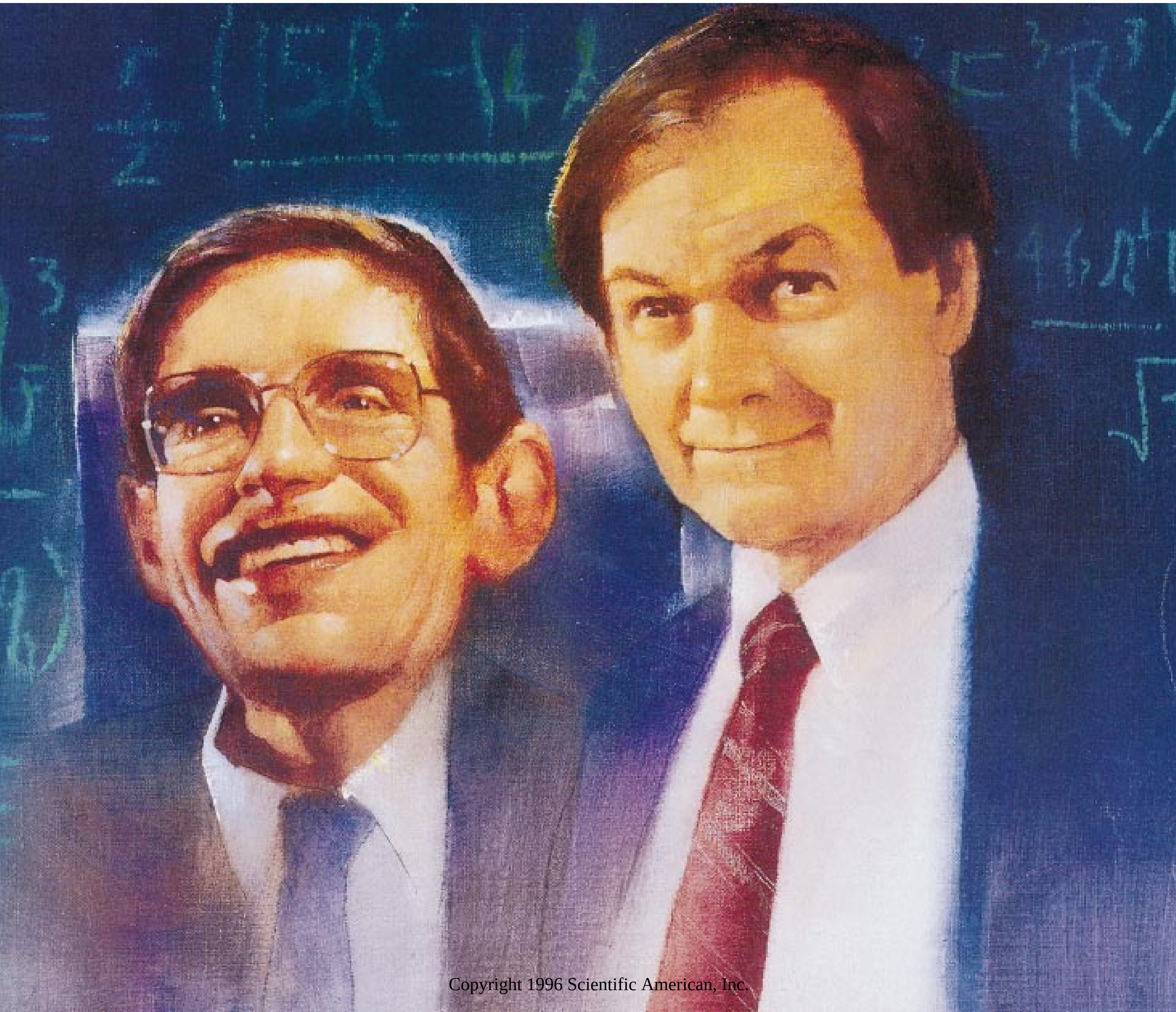
PAINTING BY ROBERT HUNT

Stephen Hawking on quantum black holes:

The quantum theory of black holes…seems to lead to a new level of unpredictability in physics over and above the usual uncertainty associated with quantum mechanics. This is because black holes appear to have intrinsic entropy and to lose information from our region of the universe. I should say that these claims are controversial: many people working on quantum gravity, including almost all those who entered it from particle physics, would instinctively reject the idea that information about the quantum state of a system could be lost. However, they have had very little success in showing how information can get out of a black hole. Eventually I believe they will be forced to accept my suggestion that it is lost, just as they were forced to agree that black holes radiate, which went against all their preconceptions…

The fact that gravity is attractive means that it will tend to draw the matter in the universe together to form objects like stars and galaxies. These can support themselves for a time against further contraction by thermal pressure, in the case of stars, or by rotation and internal motions, in the case of galaxies. However, eventually the heat or the angular momentum will be carried away and the object will begin to shrink. If the mass is less than about one and a half times that of the Sun, the contraction can be stopped by the ***degeneracy pressure*** of electrons or neutrons. The object will settle down to be a white dwarf or a neutron star, respectively. However, if the mass is greater than this limit there is nothing that can hold it up

DEGENERACY PRESSURE
No two electrons or neutrons can occupy the same quantum state. Thus, when any collection of these particles is squeezed into a small volume, those in the highest quantum states become very energetic. The system then resists further compression, exerting an outward push called degeneracy pressure.



and stop it continuing to contract. Once it has shrunk to a certain critical size the gravitational field at its surface will be so strong that the ***light cones*** will be bent inward.... You can see that even the outgoing light rays are bent toward each other and so are converging rather than diverging. This means that there is a closed trapped surface....

Thus there must be a region of space-time from which it is not possible to escape to infinity. This region is said to be a black hole. Its boundary is called the event horizon and is a ***null surface*** formed by the light rays that just fail to get away to infinity....

[A] large amount of information is lost when a body collapses to form a black hole. The collapsing body is described by a very large number of parameters. There are the types of matter and the ***multipole moments*** of the mass distribution. Yet the black hole that forms is completely independent of the type of matter and rapidly loses all the multipole moments except the first two: the monopole moment, which is the mass, and the dipole moment, which is the angular momentum.

This loss of information didn't really matter in the classical theory. One could say that all the information about the collapsing body was still inside the black hole. It would be very difficult for an observer outside the black hole to determine what the collapsing body was like. However, in the classical theory it was still possible in principle. The observer would never actually lose sight of the collapsing body. Instead it would appear to slow down and get very dim as it approached the event horizon. But the observer could still see what it was made of and how the mass was distributed.

However, quantum theory changed all this. First, the collapsing body would send out only a limited number of photons before it crossed the event horizon. They would be quite insufficient to carry all the information about the collapsing body. This means that in quantum theory there's no way an outside observer can measure the state of the collapsed body. One might not think that this mattered too much, because the information would still be inside the black hole even if one couldn't measure it from the outside. But this is where the second effect of quantum theory on black holes comes in....

[Quantum] theory will cause black holes to radiate and lose mass. It seems that they will eventually disappear completely, taking with them the information inside them. I will give arguments that this information really is lost and doesn't come back in some form. As I will show, this loss of information would introduce a new level of uncertainty into physics over and above the usual uncertainty associated with quantum theory. Unfortunately, unlike Heisenberg's uncertainty principle, this extra level will be rather difficult to confirm experimentally in the case of black holes.

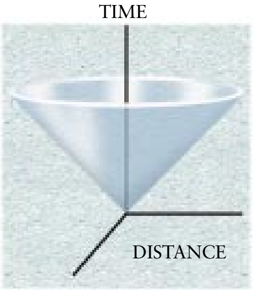
Roger Penrose on quantum theory and space-time:

The great physical theories of the 20th century have been quantum theory, special relativity, general relativity and quantum field theory. These theories are not independent of each other: general relativity was built on special relativity, and quantum field theory has special relativity and quantum theory as inputs.

It has been said that quantum field theory is the most accurate physical theory ever, being accurate to about one part in about 10^{11}. However, I would like to point out that general relativity has, in a certain clear sense, now been tested to be correct to one part in 10^{14} (and this accuracy has apparently been limited merely by the accuracy of clocks on Earth). I am speaking of the Hulse-Taylor binary ***pulsar*** PSR 1913 + 16, a pair of neutron stars orbiting each other, one of which is a pulsar. General relativity predicts that this orbit will slowly decay (and the period

LIGHT CONES

To depict space-time, physicists routinely plot time on a vertical axis and space on a horizontal. In this scheme, light rays emanating from any point in space fan out along the surface of a vertical cone. Because no physical signal can cover more distance in a given time than light can, any signals originating at that point are confined within the volume of the light cone.



NULL SURFACE

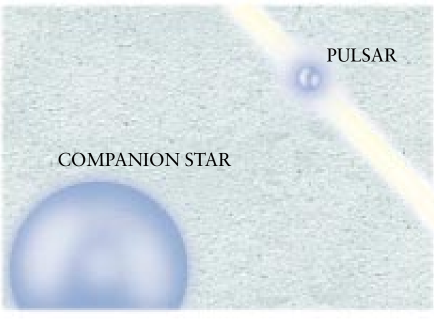
A surface in space along which light travels is known as a null surface. The null surface surrounding a black hole, called an event horizon, has the shape of a spherical shell. Nothing that falls inside the event horizon can come back out.

MULTIPOLE MOMENTS

The dynamics of an object can be summarized by determining its multipole moments. Each moment is calculated by dividing an object into tiny elements, multiplying the mass of each element by its distance from the center zero, one or more times, then adding these terms for all the elements. A sphere, for example, has a monopole moment, whereas a dumbbell has a dipole moment, which allows it to acquire angular momentum easily.

PULSARS

Some dying suns collapse into neutron stars, massive objects made entirely of densely packed neutrons. Rapidly rotating neutron stars become pulsars, so called because they emit pulses of electromagnetic radiation at astonishingly regular millisecond-to-second intervals. A pulsar sometimes orbits another neutron star, forming a binary pair.



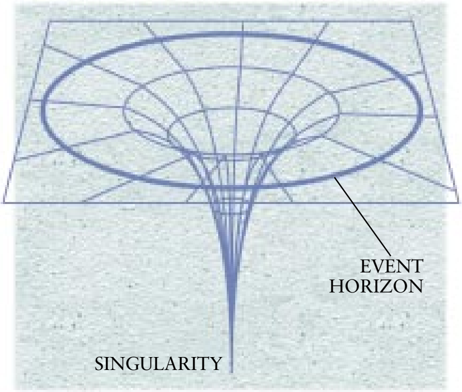
ILLUSTRATIONS BY LAURIE GRACE

shorten) because energy is lost through the emission of gravitational waves. This has indeed been observed, and the entire description of the motion…agrees with general relativity (which I am taking to include Newtonian theory) to the remarkable accuracy, noted above, over an accumulated period of 20 years. The discoverers of this system have now rightly been awarded Nobel Prizes for their work. The quantum theorists have always claimed that because of the accuracy of their theory, it should be general relativity that is changed to fit their mold, but I think now that it is quantum field theory that has some catching up to do.

Although these four theories have been remarkably successful, they are not without their problems….General relativity predicts the existence of space-time ***singularities.*** In quantum theory there is the "measurement problem"—I shall describe this later. It may be taken that the solution to the various problems of these theories lies in the fact that they are incomplete on their own. For example, it is anticipated by many that quantum field theory might "smear" out the singularities of general relativity in some way….

SINGULARITIES

According to general relativity, under certain extreme conditions some regions of space-time develop infinitely large curvatures, thus becoming singularities where the normal laws of physics break down. Black holes, for example, should contain singularities hidden inside the event horizon.



I should now like to talk about information loss in black holes, which I claim is relevant to this last issue. I agree with nearly all that Stephen had to say on this. But while Stephen regards the information loss due to black holes as an extra uncertainty in physics, above and beyond the uncertainty from quantum theory, I regard it as a "complementary" uncertainty…. It is possible that a little bit of information escapes at the moment of the black hole evaporation…but this tiny information gain will be much smaller than the information loss in the collapse (in what I regard as any reasonable picture of the hole's final disappearance).

If we enclose the system in a vast box, as a thought experiment, we can consider the phase-space evolution of matter inside the box. In the region of ***phase space*** corresponding to situations in which a black hole is present, trajectories of physical evolution will converge and volumes following these trajectories will shrink. This is due to the information lost into the singularity in the black hole. This shrinking is in direct contradiction to the theorem in classical mechanics, called Liouville's Theorem, which says that volumes in phase space remain constant….Thus a black hole space-time violates this conservation. However, in my picture, this loss of phase-space volume is balanced by a process of "spontaneous" quantum measurement in which information is gained and phase-space volumes increase. This is why I regard the uncertainty due to information loss in black holes as being "complementary" to the uncertainty in quantum theory: one is the other side of the coin to the other….

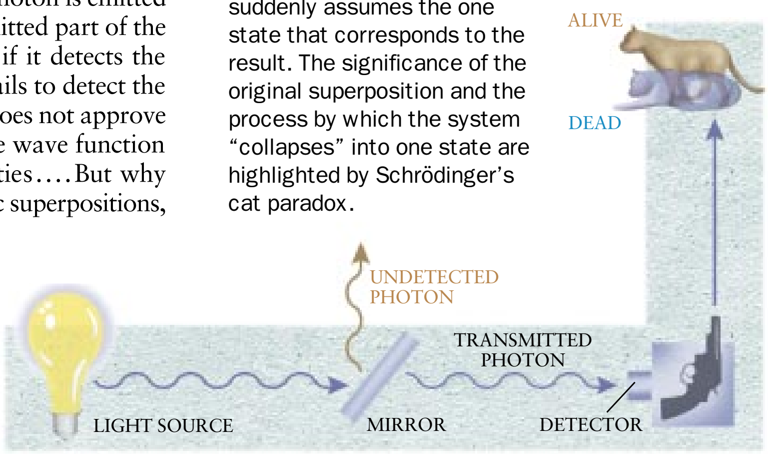
PHASE SPACE

A phase-space diagram is a mathematical volume of many dimensions formed when coordinate axes are assigned to each of the distance and momentum values of each particle. The motion of a group of particles can then be represented by a moving element of volume in phase space.

[Let] us consider the ***Schrödinger's cat*** thought experiment. It describes the plight of a cat in a box, where (let us say) a photon is emitted which encounters a half-silvered mirror, and the transmitted part of the photon's wave function encounters a detector which, if it detects the photon, automatically fires a gun, killing the cat. If it fails to detect the photon, then the cat is alive and well. (I know Stephen does not approve of mistreating cats, even in a thought experiment!) The wave function of the system is a superposition of these two possibilities….But why does our perception not allow us to perceive macroscopic superpositions, of states such as these, and not just the macroscopic alternatives "cat is dead" and "cat is alive"?…

SCHRÖDINGER'S CAT

Penrose invokes a thought experiment originally invented by Einstein and used by Erwin Schrödinger to study the conceptual knots tied by wave functions. Prior to a measurement, a system is assumed to be in a "superposition" of quantum states or waves, so that the value of, say, the momentum is uncertain. After a measurement, the value of a quantity becomes known, and the system suddenly assumes the one state that corresponds to the result. The significance of the original superposition and the process by which the system "collapses" into one state are highlighted by Schrödinger's cat paradox.



I am suggesting that something goes wrong with superpositions of the alternative space-time geometries that would occur when general relativity begins to become involved. Perhaps a superposition of two different geometries is unstable and decays into one of the two alternatives. For example, the geometries might be the space-times of a live cat, or a dead one. I call this decay into one or the other alternative objective reduction, which I like as a name because it has an appropriately nice acronym (OR). How does the Planck length 10^{-33} centimeter relate to this? Nature's criterion for determining when two geometries are significantly different would depend upon the ***Planck scale,*** and this fixes the timescale in which the reduction into different alternatives occurs.

Hawking on quantum cosmology:

I will end this lecture on a topic on which Roger and I have very different views—the arrow of time. There is a very clear distinction between the forward and the backward directions of time in our region of the universe. One only has to watch a film being run backward to see the difference. Instead of cups falling off tables and getting broken, they would mend themselves and jump back on the table. If only real life were like that.

The local laws that physical fields obey are time symmetric, or more precisely, ***CPT (charge-parity-time) invariant.*** Thus, the observed difference between the past and the future must come from the boundary conditions of the universe. Let us take it that the universe is spatially closed and that it expands to a maximum size and collapses again. As Roger has emphasized, the universe will be very different at the two ends of this history. At what we call the beginning of the universe, it seems to have been very smooth and regular. However, when it collapses again, we expect it to be very disordered and irregular. Because there are so many more disordered configurations than ordered ones, this means that the initial conditions would have had to be chosen incredibly precisely.

It seems, therefore, that there must be different boundary conditions at the two ends of time. Roger's proposal is that the ***Weyl tensor*** should vanish at one end of time but not the other. The Weyl tensor is that part of the curvature of space-time that is not locally determined by the matter through the Einstein equations. It would have been small in the smooth, ordered early stages but large in the collapsing universe. Thus, this proposal would distinguish the two ends of time and so might explain the arrow of time.

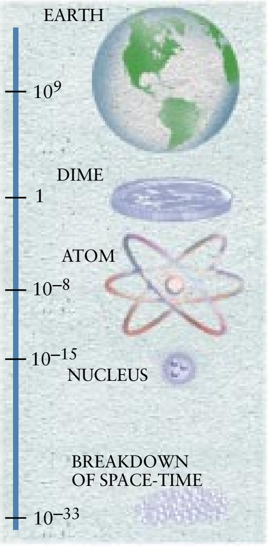
I think Roger's proposal is Weyl in more than one sense of the word. First, it is not CPT invariant. Roger sees this as a virtue, but I feel one should hang on to symmetries unless there are compelling reasons to give them up. Second, if the Weyl tensor had been exactly zero in the early universe, it would have been exactly homogeneous and isotropic and would have remained so for all time. Roger's Weyl hypothesis could not explain the fluctuations in the background nor the perturbations that give rise to galaxies and bodies like ourselves.

Despite all this, I think Roger has put his finger on an important difference between the two ends of time. But the fact that the Weyl tensor was small at one end should not be imposed as an ad hoc boundary condition but should be deduced from a more fundamental principle, the ***no-boundary proposal*....**

How can the two ends of time be different? Why should perturbations be small at one end but not the other? The reason is there are two possible complex solutions of the field equations.... Obviously, one solution corresponds to one end of time and the other to the other.... At one end, the universe was very smooth and the Weyl tensor was very small. It could not, however, be exactly zero, for that would have been a violation of the uncertainty principle. Instead there would have been small fluctuations that later grew into galaxies and bodies like us. By contrast, the universe would have been very irregular and chaotic at the other end of time with a Weyl tensor that was typically large. This would explain the observed arrow of time and why cups fall off tables and break rather than mend themselves and jump back on.

PLANCK SCALE

The Planck scale is an unattainably small distance—related, by quantum mechanics, to an impossibly small time span and high energy—that emerges when the fundamental constants for gravitational attraction, the velocity of light and quantum mechanics are appropriately combined. The scale represents the distance or energy at which current concepts of space, time and matter break down, and a future theory, quantum gravity, presumably takes over.

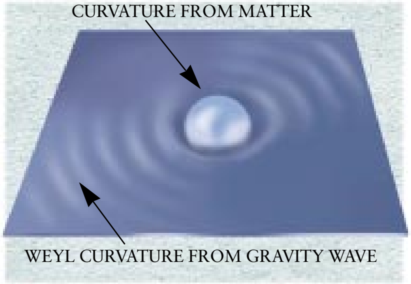


CPT (CHARGE-PARITY-TIME) INVARIANCE

This powerful principle requires that theories describing particles must remain true even when the charge, parity (or handedness) and time simultaneously reverse. In other words, the behavior of a negatively charged electron with clockwise spin moving forward in time must be identical to that of a positively charged positron with anticlockwise spin moving backward in time.

WEYL TENSOR

The curvature of space-time has two components. One derives from the presence of matter in space-time; the other, recognized by the German mathematician Hermann Weyl, occurs even in the absence of matter. The mathematical quantity that describes this curvature is called the Weyl tensor.



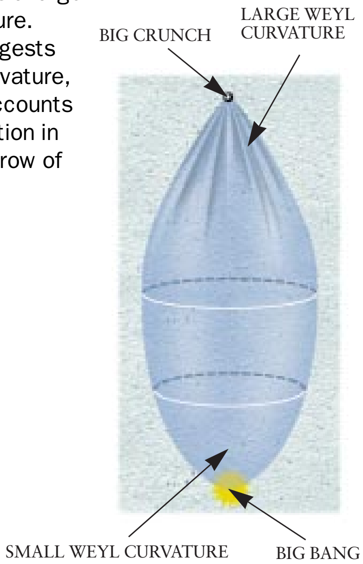
NO-BOUNDARY PROPOSAL

Hawking suggests that the evolution of the universe is explained by the no-boundary proposal, put forth in 1983 by him and James B. Hartle of the University of California at Santa Barbara. The idea that the universe has no boundary places constraints on how the equations of cosmology are solved. Hawking believes these conditions will lead to the ends of the universe being different, thereby determining the direction of time's arrow.

Penrose on quantum cosmology:

From what I understand of Stephen's position, I don't think that our disagreement is very great on this point [the ***Weyl curvature hypothesis***]. For an initial singularity the Weyl curvature is approximately zero.... Stephen argued that there must be small quantum fluctuations in the initial state and thus pointed out that the hypothesis that the initial Weyl curvature is zero at the initial singularity is classical, and there is certainly some flexibility as to the precise statement of the hypothesis. Small perturbations are acceptable from my point of view, certainly in the quantum regime. We just need something to constrain it very near to zero....

Maybe the no-boundary proposal of [James B.] Hartle and Hawking is a good candidate for the structure of the *initial* state. However, it seems to me that we need something very different to cope with the *final* state. In particular, a theory that explains the structure of singularities would have to violate [CPT and other symmetries] in order that something of the nature of the Weyl curvature hypothesis can arise. This failure of time-symmetry might be quite subtle; it would have to be implicit in the rules of that theory which goes beyond quantum mechanics.



WEYL CURVATURE HYPOTHESIS
The universe just after the big bang has a small Weyl curvature, whereas near the end of time it has a large Weyl curvature. Penrose suggests that this curvature, therefore, accounts for the direction in which the arrow of time points.

Hawking on physics and reality:

These lectures have shown very clearly the difference between Roger and me. He's a Platonist and I'm a positivist. He's worried that Schrödinger's cat is in a quantum state, where it is half alive and half dead. He feels that can't correspond to reality. But that doesn't bother me. I don't demand that a theory correspond to reality because I don't know what it is. Reality is not a quality you can test with litmus paper. All I'm concerned with is that the theory should predict the results of measurements. Quantum theory does this very successfully....

Roger feels that...the collapse of the wave function introduces CPT violation into physics. He sees such violations at work in at least two situations: cosmology and black holes. I agree that we may introduce time asymmetry in the way we ask questions about observations. But I totally reject the idea that there is some physical process that corresponds to the reduction of the wave function or that this has anything to do with quantum gravity or consciousness. That sounds like magic to me, not science.

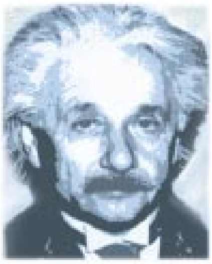
Penrose on physics and reality:

Quantum mechanics has only been around for 75 years. This is not very long if one compares it, for example, with Newton's theory of gravity. Therefore it wouldn't surprise me if quantum mechanics will have to be modified for very macroscopic objects.

At the beginning of this debate, Stephen said that he thinks that he is a positivist, whereas I am a Platonist. I am happy with him being a positivist, but I think that the crucial point here is, rather, that I am a realist. Also, if one compares this debate with the famous debate of ***Bohr and Einstein,*** some 70 years ago, I should think that Stephen plays the role of Bohr, whereas I play Einstein's role! For Einstein argued that there should exist something like a real world, not necessarily represented by a wave function, whereas Bohr stressed that the wave function doesn't describe a "real" microworld but only "knowledge" useful for making predictions.

Bohr was perceived to have won the argument. In fact, according to the recent biography of Einstein by [Abraham] Pais, Einstein might as well have gone fishing from 1925 onward. Indeed, it is true that he didn't make many big advances, even though his penetrating criticisms were very useful. I believe that the reason why Einstein didn't continue to make big advances in quantum theory was that a crucial ingredient was missing from quantum theory. This missing ingredient was Stephen's discovery, 50 years later, of black hole radiation. It is this information loss, connected with black hole radiation, which provides the new twist.

NIELS BOHR



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