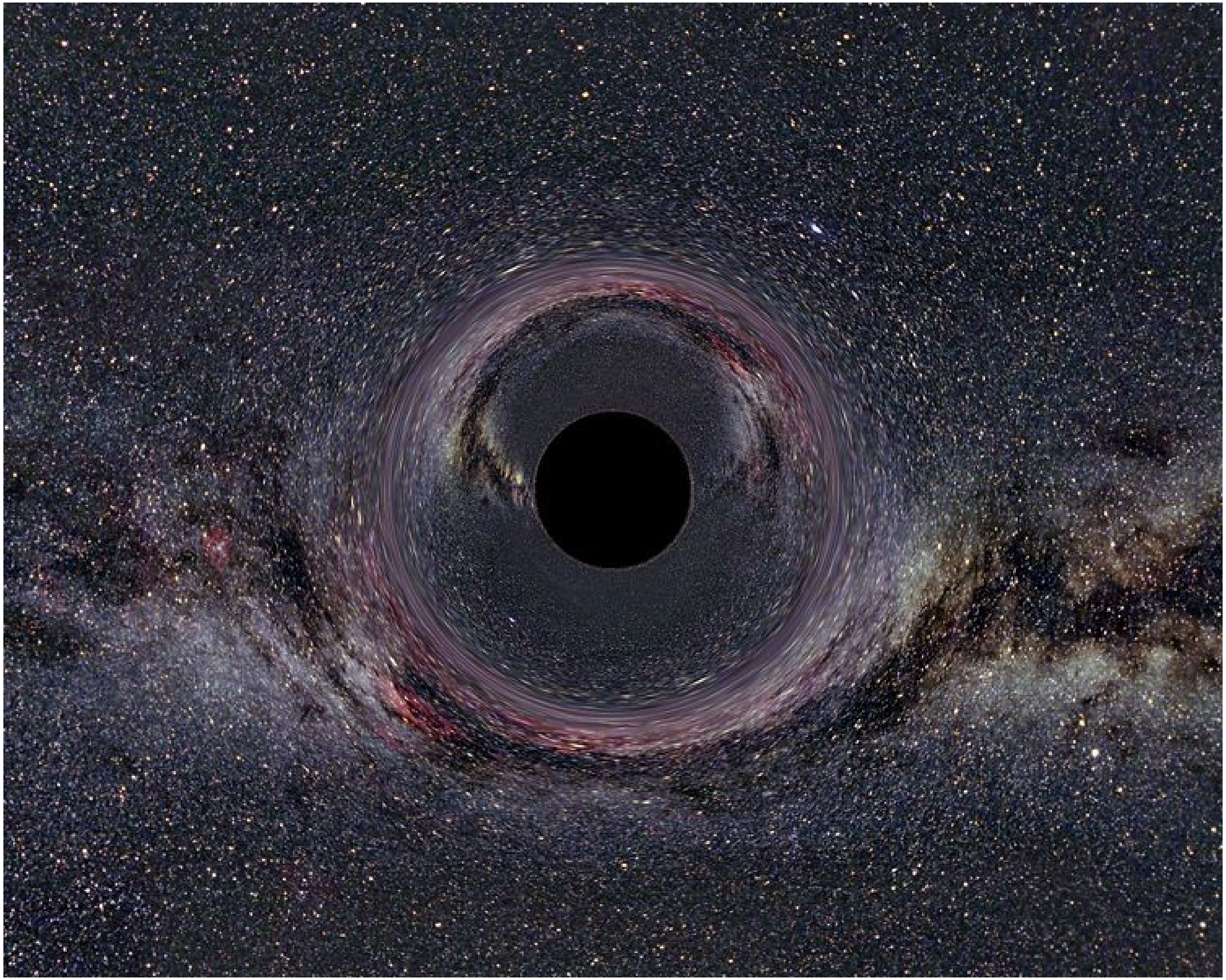
Black Hole Information

Hawking's Greatest Mistake?

Black Holes

- Black holes are regions of space where gravity is so strong that nothing can escape, at least according to classical physics (the physics of large objects).
- They are believed to form from the gravitational collapse of massive stars that burn out their nuclear fuel.



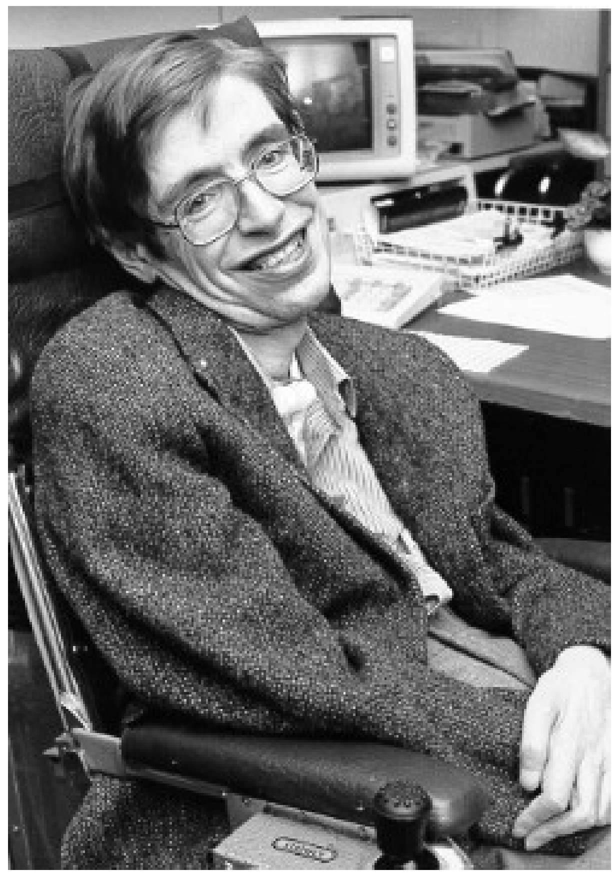
Evolution of Stars

- Stars are held up by the pressure from heat generated by nuclear reactions.
- When low-mass stars like the sun burn out their fuel, they condense to white dwarfs (size of earth).
- Medium-mass stars end up as neutrons stars (tens of kilometers across).
- Very massive stars keep collapsing until light can no longer escape, forming black holes.

Hawking’s Area Theorem

- In 1972 Stephen Hawking discovered how to define a black hole in terms of its surface, the event horizon, defined so that nothing could escape from inside.
- Then Hawking proved that under normal circumstances, the area of the event horizon could not decrease.
- Black holes could only grow.

Stephen Hawking



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Gravitational Radiation from Colliding Black Holes

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It is shown that there is an upper bound to the energy of the gravitational radiation emitted when one collapsed object captures another. In the case of two objects with equal masses m and zero intrinsic angular momenta, this upper bound is $(2-\sqrt{2})m$.

Weber[1-3] has recently reported coinciding measurements of short bursts of gravitational radiation at a frequency of 1660 Hz. These occur at a rate of about one per day and the bursts appear to be coming from the center of the galaxy. It seems likely[3,4] that the probability of a burst causing a coincidence between Weber's detectors is less than $\frac{1}{10}$. If one allows for this and assumes that the radiation is broadband, one finds that the energy flux in gravitational radiation must be at least 10^{10} erg/cm^2 day.[4] This would imply a mass loss from the center of the galaxy of about $20\,000 M_\odot$/yr. It is therefore possible that the mass of the galaxy might have been considerably higher in the past than it is now.[5] This makes it important to estimate the efficiency with which rest-mass energy can be converted into gravitational radiation. Clearly nuclear reactions are insufficient since they release only about 1% of the rest mass. The efficiency might be higher in either the nonspherical gravitational collapse of a star or the collision and coalescence of two collapsed objects. Up to now no limits on the efficiency of the processes have been known. The object of this Letter is to show that there is a limit for the second process. For the case of two colliding collapsed objects, each of mass m and zero angular momentum, the amount of energy that can be carried away by gravitational or any other form of radiation is less than $(2-\sqrt{2})m$.

I assume the validity of the Carter-Israel conjecture[6,7] that the metric outside a collapsed object settles down to that of one of the Kerr family of solutions[8] with positive mass m and angular momentum a per unit mass less than or equal to m. (I am using units in which $G=c=1$.) Each of these solutions contains a nonsingular *event horizon*, two-dimensional sections of which are topographically spheres with area[9]

$$8\pi m[m+(m^2-a^2)^{1/2}]. \qquad (1)$$

The event horizon is the boundary of the region of space-time from which particles or photons can escape to infinity. I shall consider only

Hawking Evaporation

- In 1974 Hawking found that quantum theory, how small objects behave, violates the normal circumstances and allows black holes to shrink.
- Hawking radiation is emitted and causes black holes to evaporate away into a black hole explosion.
- Hawking evaporation is only important for tiny black holes unless you wait very, very long.

Information Loss?

- Black hole radiation does not violate energy conservation, since the energy in the black hole comes out in radiation.
- But Hawking proposed that it violates information conservation, as it appeared that the information that fell into a black hole could not come back out.

Quantum Information

- Quantum theory has the Heisenberg Uncertainty Principle that there is a limit to how well one can know certain pairs of quantities, such as position and momentum (mass times velocity).
- A pure quantum state gives the minimum uncertainty and maximum information possible for a given system.
- A mixed quantum state has less information.

Information Conservation

- In ordinary quantum theory, total information is conserved: Pure quantum states stay pure.
- Information may become spread out so that it is in practice inaccessible, and then the loss of accessible information is called the increase of entropy.
- However, total information is conserved.

Are Black Holes Different?

- It was believed that nothing can escape from black holes, so information that fell in would be totally lost.
- One might think the same about energy, but near a black hole, the energy of quantum matter can be negative, and negative energy going in is equivalent to positive energy coming out in black hole radiation.
- But negative information seems impossible.

Breakdown of Predictability?

- In 1976 Hawking argued that the formation and evaporation of black holes leads to a fundamental loss of information from the universe, a breakdown of predictability, as pure quantum states turn into mixed states.
- One would not be able to predict the maximum allowed quantum information.

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Breakdown of predictability in gravitational collapse*

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The principle of equivalence, which says that gravity couples to the energy-momentum tensor of matter, and the quantum-mechanical requirement that energy should be positive imply that gravity is always attractive. This leads to singularities in any reasonable theory of gravitation. A singularity is a place where the classical concepts of space and time break down as do all the known laws of physics because they are all formulated on a classical space-time background. In this paper it is claimed that this breakdown is not merely a result of our ignorance of the correct theory but that it represents a fundamental limitation to our ability to predict the future, a limitation that is analogous but additional to the limitation imposed by the normal quantum-mechanical uncertainty principle. The new limitation arises because general relativity allows the causal structure of space-time to be very different from that of Minkowski space. The interaction region can be bounded not only by an initial surface on which data are given and a final surface on which measurements are made but also a "hidden surface" about which the observer has only limited information such as the mass, angular momentum, and charge. Concerning this hidden surface one has a "principle of ignorance": The surface emits with equal probability all configurations of particles compatible with the observers limited knowledge. It is shown that the ignorance principle holds for the quantum-mechanical evaporation of black holes: The black hole creates particles in pairs, with one particle always falling into the hole and the other possibly escaping to infinity. Because part of the information about the state of the system is lost down the hole, the final situation is represented by a density matrix rather than a pure quantum state. This means there is no S matrix for the process of black-hole formation and evaporation. Instead one has to introduce a new operator, called the superscattering operator, which maps density matrices describing the initial situation to density matrices describing the final situation.

I. INTRODUCTION

Gravity is by far the weakest interaction known to physics: The ratio of the gravitational to electrical forces between two electrons is about one part in 10^{43}. In fact, gravity is so weak that it would not be observable at all were it not distinguished from all other interactions by having the property known as the principle of universality or equivalence: Gravity affects the trajectories of all freely moving particles in the same way. This has been verified experimentally to an accuracy of about 10^{-11} by Roll, Krotkov, and Dicke[1] and by Braginsky and Panov.[2] Mathematically, the principle of equivalence is expressed as saying that gravity couples to the energy-momentum tensor of matter. This result and the usual requirement from quantum theory that the local energy density should be positive imply that gravity is always attractive. The gravitational fields of all the particles in large concentrations of matter therefore add up and can dominate over all other forces. As predicted by general relativity and verified experimentally, the universality of gravity extends to light. A sufficiently high concentration of mass can therefore produce such a strong gravitational field that no light can escape. By the principle of special relativity, nothing else can escape either since nothing can travel faster than light. One thus has a situation in which a certain amount of matter is trapped in a region whose boundary shrinks to zero in a finite time. Something obviously goes badly wrong. In fact, as was shown in a series of papers by Penrose and this author,[3-8] a space-time singularity is inevitable in such circumstances provided that general relativity is correct and that the energy-momentum tensor of matter satisfies a certain positive-definite inequality.

Singularities are predicted to occur in two areas. The first is in the past at the beginning of the present expansion of the universe. This is thought to be the "big bang" and is generally regarded as the beginning of the universe. The second area in which singularities are predicted is the collapse of isolated regions of high-mass concentration such as burnt-out stars.

A singularity can be regarded as a place where there is a breakdown of the classical concept of space-time as a manifold with a pseudo-Reimannian metric. Because all known laws of physics are formulated on a classical space-time background, they will all break down at a singularity. This is a great crisis for physics because it means that one cannot predict the future: One does not know what will come out of a singularity.

Many physicists are very unwilling to believe that physics breaks down at singularities. The following attempts were therefore made in order

Is Black Hole Evaporation Predictable?

- In 1980 I noted Hawking’s argument used quantum theory for the black hole radiation but not for the black hole itself.
- We didn’t (and still don’t) know fully how to use quantum theory for a black hole.
- Therefore, his argument for information loss was not completely convincing.
- Black holes might not lose information.

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Is Black-Hole Evaporation Predictable?

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If black-hole formation and evaporation can be described by a superscattering operator which is CPT invariant, then it can be described by an S matrix which maps pure initial states into pure final states. Thus black holes may be in principle no more unpredictable than other quantum phenomena.

Because gravity provides an attractive force between all forms of matter having positive energy densities, it apparently can lead to a breakdown of physics in which the attraction increases without limit. Such a breakdown, called a singularity, has been shown to occur when matter collapses into a black hole according to the classical theory of general relativity.[1]

It has been thought, according to the Penrose cosmic censorship hypothesis,[2,3] that all singularities that form would be hidden from view inside black holes. Then physics outside would remain predictable, i.e., uniquely determined by the data on some suitable Cauchy hypersurface in the past. However, Hawking found that quantum mechanics allows particles to come out of black holes,[4] so that "even an observer at infinity cannot avoid seeing what happens at a singularity."[5] Furthermore, the emitted particles carry away energy from the black hole and so presumably cause it to shrink and eventually to disappear at a momentarily naked singularity.

Hawking thus argued that the formation and evaporation of black holes would introduce a new level of unpredictability into physics.[5] Part of the information about the system would be lost down the holes. In quantum mechanical terms, a pure initial state would result in a state partially going down the holes and partially remaining outside, so that the final state outside would be a mixed state described by a density matrix. Hawking concluded that one could not describe the process by an S matrix mapping pure states to pure states but must introduce a superscattering operator which maps initial mixed states to final mixed states.

In this Letter I will show that if black-hole formation and evaporation can be described by a superscattering operator which is CPT invariant,[6] then it can be described by an S matrix. Arguments will be made that this is a plausible assumption, though it cannot be proven outside a consistent theory of quantum gravity. Thus black holes may be in principle no more unpredictable than other quantum phenomena. Other possibilities will also be discussed.

Following Hawking's argument in principle if not in detail, let $|X_a\rangle$, $|Y_b\rangle$, $|Z_c\rangle$ be orthonormal bases for Hilbert spaces H_1, H_2, H_3 of incoming states on the initial hypersurface (before the black-hole formation), hidden hypersurfaces (around the black holes that form and disappear), and final hypersurface (after the black-hole evaporation), respectively. Let $|\bar{X}_a\rangle$, $|\bar{Y}_b\rangle$, $|\bar{Z}_c\rangle$ be

Early Debate on Information

- In the early 1980s, not many people paid attention to Hawking’s and my debate.
- General relativists mostly supported Hawking’s position that information could not escape from black holes.
- Particle physicists generally supported my position that black holes would obey standard quantum theory and not lose information.

1993 Opinions about BH Info

- It's lost: 25 votes; I thought 30% likely.
- It comes out with the Hawking radiation: 39 votes; I thought 35% likely.
- It remains accessible in a BH remnant: 7 votes; I thought 5% likely.
- Something else: 6 votes; I thought 30% likely.

It’s lost.

- This is the view that the information that falls into a black hole never comes out and disappears from our universe if the black hole decays away.
- It would be like the decay of positronium into two photons (both spinning right or both spinning left), a state of definite zero total angular momentum, going into a mixed state of one photon of uncertain angular momentum if one photon totally disappeared.

It comes out with the Hawking radiation.

- This was (and still is) my main view that somehow the information comes back out while the black hole is shrinking.
- One would have to violate classical general relativity, but one might suppose that quantum gravity could provide the right violation.

It remains accessible in a black hole remnant.

- This is the view that black holes don't completely decay away but retain the information in some small object that persists.
- Somehow the black hole would have to stop evaporating before it disappeared, which seems conceivable but unlikely.

Something else occurs.

- Maybe the other possibilities envisaged do not cover what actually happens.
- Perhaps quantum theory is not the correct description.
- Or perhaps quantum theory should be reformulated not in terms of quantum states that evolve from before to after.

Information in Black Hole Radiation

- In 1993 I showed that if the information does come out in the Hawking radiation, it would be initially so slow that one could never see it by the usual methods of analysis (perturbation theory).
- The information could be very subtly encoded in correlations between all the radiation emitted.

Information in Black Hole Radiation

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If black hole formation and evaporation can be described by an S matrix, information would be expected to come out in black hole radiation. An estimate shows that it may come out initially so slowly, or else be so spread out, that it would never show up in an analysis perturbative in M_{Planck}/M, or in $1/N$ for two-dimensional dilatonic black holes with a large number N of minimally coupled scalar fields.

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Hawking's calculation of thermal emission from a stationary classical black hole [1,2] soon led to a major unresolved puzzle concerning quantum mechanics and gravity: What happens to a pure quantum state that collapses to form a black hole which emits approximately thermal radiation? Hawking proposed [2] that the black hole would eventually disappear completely and that the resulting state of radiation, like a precisely thermal state, would be mixed. In other words, information would be permanently lost down the black hole, and there would be no S matrix to take an initial pure state to a final pure state.

It was soon objected [3,4] that this conclusion is not justified by the classical or semiclassical approximation for the black hole used to derive it, and that, in its original form at least, it violates a strong form of CPT invariance [4]. A number of alternative possibilities were given [4]. The main options now under active investigation seem to be that either most of the information comes out with the bulk of the radiation to give an S matrix [4–7], or most of the information goes into a long-lived [8,9] or absolutely stable remnant [10], or else information is lost from our universe as Hawking proposed [2]. For recent reviews of the problem, see [9,11–15].

The first of these options is in some sense the most conservative, and I have advocated it as the most productive to pursue [4]. However, a number of arguments have been given against this possibility. Hawking's original proposal of a loss of information [2] argued that the semiclassical approximation (which would give a loss of information) is valid until the black hole gets down near the Planck mass, and then there is not enough energy left to carry the information (implicitly assuming no long-lived or stable remnants). Giddings and Nelson [16], and later Giddings alone [12], gave a more detailed version of this argument for a more tractable model of two-dimensional dilatonic black holes with N minimally coupled scalar fields [17].

In this two-dimensional model, the classical equations can be solved exactly [17], and the semiclassical equations can be solved numerically [18], though a full quantum solution for this model or any realistic variant is still out of reach. The semiclassical approximation appears to be good (at least for certain aspects of the problem) until the black hole reaches the strong-coupling regime (the analog of the Planck mass for four-dimensional black holes), by which time the black hole has emitted most of its energy if its initial thermodynamic entropy s_h is large compared to N.

Assuming the validity of the semiclassical analysis until the weak-coupling approximation breaks down, Giddings and Nelson conclude, "The above arguments therefore strongly suggest that within the present model information does not escape until the black hole is very small. Making these rigorous will therefore rule out one suggested resolution of the black-hole information problem, namely, that the information escapes over the course of black-hole evaporation if the effects of the back reaction are included" [16]. Giddings later stated this more cautiously, that "working order-by-order in $1/N$, it is probable that one can construct an argument...analogous to stating that the information does not come out of four-dimensional black holes until they reach the Planck scale" [12].

Here I wish to object that if the information does indeed come out gradually over the entire emission process, it appears likely that the rate of information outflow may initially be so low that it would not show up in an order-by-order (perturbative) analysis, and that the information in the entire emission would be so spread out that it would require too many measurements to be found or excluded by a perturbative analysis.

Suppose the black hole subsystem has dimension $n \sim e^{s_h}$, where $s_h = A/4$ is the semiclassical Hawking entropy [1] of a black hole of area A, and suppose the radiation subsystem has dimension $m \sim e^{s_r}$, where s_r is the thermodynamic radiation entropy. In the spirit of the hypothesis that no information is lost in black hole formation and evaporation, assume that these subsystems form a total system in a pure state in a Hilbert space of dimension mn, with density matrix $\rho_{rh} = \rho_{rh}^2$. If the black hole and the radiation are correlated, each of these subsystems would be in a mixed state,

$$\rho_r = \operatorname*{tr}_h \rho_{rh}, \quad \rho_h = \operatorname*{tr}_r \rho_{rh}, \tag{1}$$

with a von Neumann or entanglement entropy

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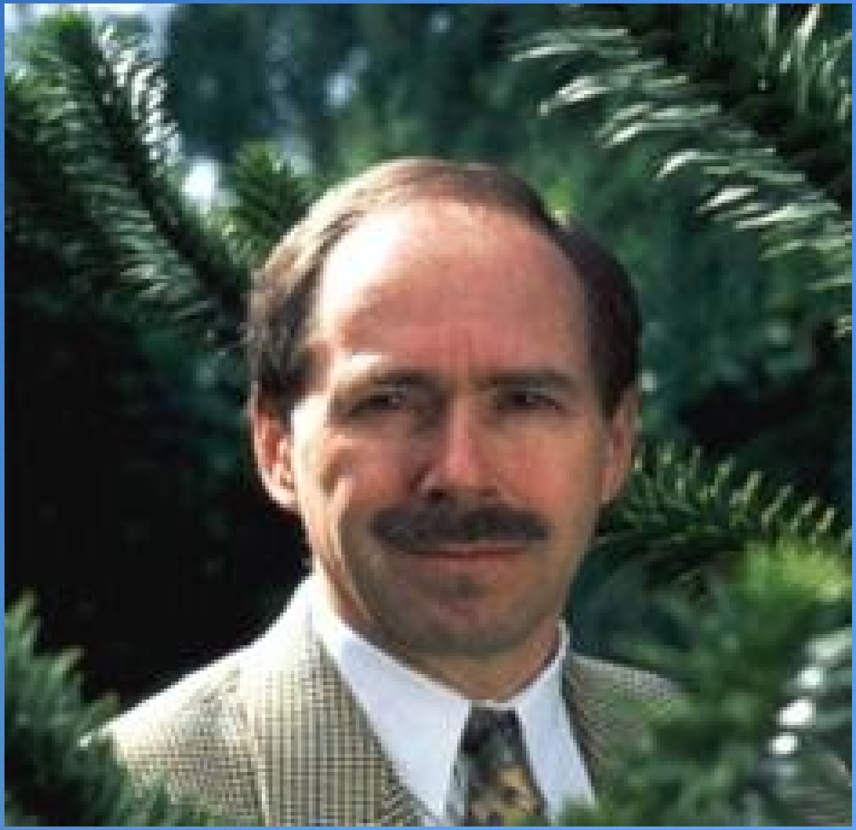
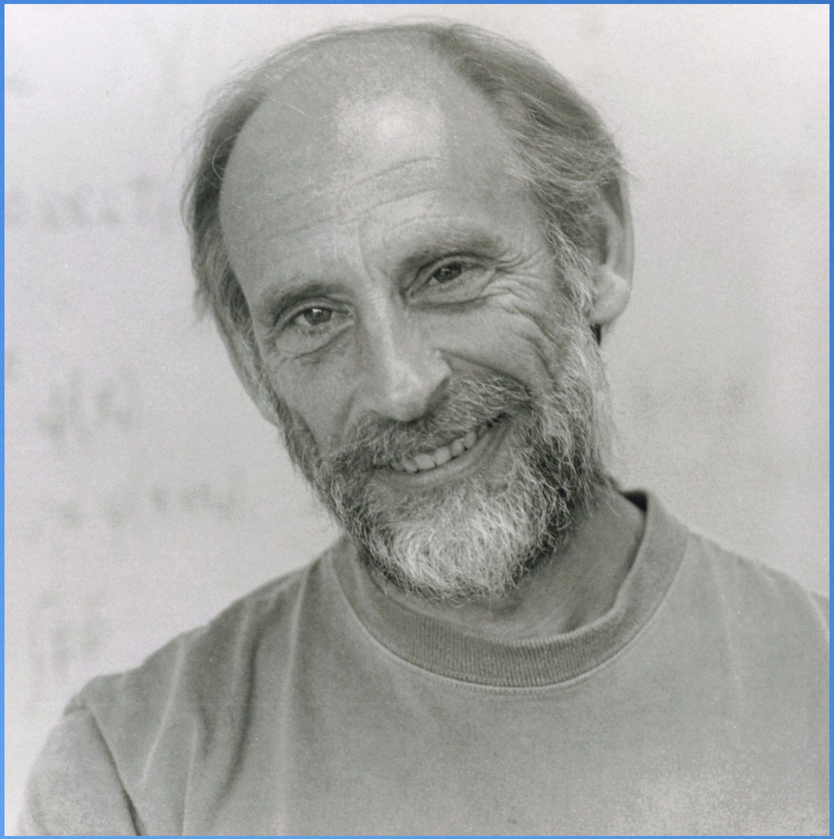
Holographic Principle

- Gerard ‘t Hooft and Leonard Susskind formulated the holographic principle 1993-1995, that the information within a volume is encoded within its surface.
- Then any information that fell into a black hole would remain encoded on its surface (the event horizon).





Black Hole Information in String Theory

- String `theory' is an incomplete set of ideas for a quantum theory of gravity and of all the rest of physics.
- It has made partial analyses of black holes using standard quantum theory.
- Andrew Strominger and Cumran Vafa showed how to account for information in black holes by string theory in 1996.


Support for Holography

- The holographic principle is not yet confirmed, but support came from Juan Maldacena's AdS/CFT conjecture.
- This proposed that a theory of quantum gravity in asymptotically anti-de Sitter spacetime is equivalent to a conformal field theory (CFT) without gravity on a surface a long way away, the boundary of AdS.
- Although this is not proved either, there is an enormous support for it in string theory.

Black Hole Complementarity

- In 1993 Leonard Susskind came up with the idea that as seen from an infalling observer, matter falling into a black hole carries information in with it.
- However, to an observer that stays outside, it appears to stay outside and spread over the horizon.

No Quantum Cloning

- In 1982 Dieks, Milonni and Hardies, and Wootters and Zurek proved one cannot make two copies of an unknown arbitrary quantum state (though if one knows what is definite about it one can).
- Thus one should not be able to have one copy of information inside a black hole and one copy outside.

Problem for Complementarity?

- If an arbitrary quantum state cannot be cloned, how can the information be both inside and on the black hole surface?
- Black hole complementarity argues that no observer can compare complete measurements of both regions to falsify the complementary descriptions.

Slightly Variant Viewpoint

- Quantum cloning forbids making copies of arbitrary information at differ places, but not at different times. (Think of the same information persisting in time.)
- Perhaps quantum uncertainty in the spacetime geometry means one cannot say that inside and outside a black hole are different places rather than times.

Causality

- In quantum field theory in classical spacetime, disturbances cannot travel faster than c, the “speed of light.”
- But if spacetime is quantized (quantum gravity), there may be no definite c.
- String theory is often written as if there were a definite c but faster propagation.

Information Transfer in Quantum Gravity

- If there is no precise limit to the speed of propagation of signals (information), then in principle information could come out from inside a black hole.
- Whether it actually does all come out is not yet really proved, but now the weight of evidence suggests it is.

Hawking’s Concession

- In 2004 Hawking, influenced by a key paper by Juan Maldacena and by his own calculations, changed his mind and decided that information is not lost in black hole formation and evaporation.
- At a conference in Dublin, he conceded a 1997 bet he and my other Ph.D. advisor Kip Thorne had made with John Preskill.

My Reaction

- I regretted not having made a bet myself with Stephen Hawking.
- I thought perhaps I had never expected Hawking to change his mind.
- I also wondered whether it was my moral objection to gambling as a tax on the stupid, but I realized this would not apply to a bet with Hawking.

An Older Bet

- While preparing to lecture on black hole information in Barbados, I found a 1980 letter of mine, that I had bet Hawking!
- After a long search in my boxes piled to the ceiling, I found the bet.
- At a workshop hosted by the 9th richest billionaire in Texas, Hawking conceded.

How Predictable Is Quantum Gravity?

Don Page bets Stephen Hawking one pound Sterling that strong quantum cosmic censorship holds, namely, that a pure initial state composed entirely of regular field configurations on complete, asymptotically flat hypersurfaces will have a unique S-matrix evolution under the laws of physics to a pure final state composed entirely of regular field configurations on complete, asymptotically flat hypersurfaces.

Stephen Hawking bets Don Page \$1.00 that in quantum gravity the evolution of such a pure initial state can be given in general only by a \$-matrix to a mixed final state and not always by an S-matrix to a pure final state.

"I concede in light of the weakness of the \$"
Stephen Hawking, 23 April 2007

Don N. Page

ONE DOLLAR
How Predictable is Quantum Gravity?
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Don N. Page
"I concede in light of the weakness of the $"
Stephen Hawking, 23rd April 2007

Hawking's Greatest Mistake?

- In 1985, Hawking predicted that the arrow of time would reverse if the universe recollapsed.
- I refuted this idea shortly afterward.
- Hawking later called this "my greatest mistake, at least in science."
- However, his apparent mistake about information loss in black holes has generated far more research and is truly much greater.

Summary

- In ordinary quantum theory, information in the entire universe is conserved.
- Stephen Hawking originally suggested that black holes lose information.
- Now Hawking has changed his mind.
- Most think information is conserved.
- But this is not completely proved or understood. Maybe you can help!