Commentary on Hawking's No Black Holes

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Abstract

In 2013, the media picked up a technical presentation by Stephen Hawking in which he stated that "There are no black holes." [1] [2] *That's a curious viewpoint from someone who spent much of his career working out the physics of black holes. Unfortunately, the rest of Hawking's presentation was too technical for the media to touch, leaving the general public in need of new mental images to replace all those missing black holes. This paper is an informal discussion of the technical parts of Hawking's paper without undue jargon and math.*

Black holes occur in nature when matter and energy are squeezed into a space so small and dense that the gravity that surrounds it prevents anything from escaping, even light. Nobody has seen a black hole, but we can see things orbit them, so we know they are there, Hawking notwithstanding. We just don't know what it's like inside one. All we can do is take the mathematical formulas of physics that we know work elsewhere, and see what they tell us would happen if we were to squeeze a bunch of matter and energy into an unimaginably small space. And the results are head-scratching. The formulas of relativity tell us one thing; the formulas of quantum mechanics tell us something different. And there's the matter of the *information paradox*.

The information paradox is an accidental consequence of a theory proposed by Hawking in the 1970s. Using quantum mechanics, he showed a way that black holes can lose mass over time. Here's how it happens. The empty vacuum of space isn't really empty – it contains a kind of potential energy called the *vacuum energy* or *zero-point energy*. From this potential energy, pairs of random quantum *virtual particles* spontaneously pop into existence for very brief periods of time, annihilate each other, and disappear again into the vacuum. Suppose a pair of particles appears close to the boundary of a black hole, and one particle falls inside while the other doesn't, forever separated. In the bizarre math of quantum mechanics, the one that dropped inside contributes negative energy to the inside of the black hole and reduces its mass, while adding one particle of mass to the outside universe. Over time, a black hole can disappear through this kind of quantum evaporation. [3] An important point here is that the evaporation is through an absolutely random process.

[1] Audio-video presentation via Skype at a meeting at the Kavli Institute for Theoretical Physics in Santa Barbara, California, in August 2013, `http://www.youtube.com/watch?v=isimsXwilvc` .

[2] A transcript of Hawking's presentation is available on the ArXiv server: "Information Preservation and Weather Forecasting for Black Holes," `http://arxiv.org/abs/1401.5761` . Weather forecasting is Hawking's analogy that the information radiated from a black hole is so scrambled that it's difficult or impossible in practice to measure all the particles' positions and momenta to determine the history of the system, much like trying to model weather.

[3] Microscopic black holes formed in nature would evaporate very quickly. Larger black holes take exponentially longer to evaporate, such that a large black hole could take longer to evaporate than the lifetime of the universe.

I. The Controversy

It is a law of physics that if you know everything about a particle's location and momentum, you could in principle figure out where it came from. It's also a law of physics that this kind of information is never destroyed. The information may become spread out as particles interact with each other, but a particle's present state always betrays its history.

As a black hole evaporates, particles disappear from the interior, and particles appear on the exterior, but the exterior particles are created by a random process that does not have anything to do with the particles that disappeared from the inside. The particles shed by an evaporating black hole cannot in principle or theory carry any information about the particles that were lost. Information is irretrievably lost from the universe, and physics says that can't happen.

This process of black hole evaporation is called *Hawking radiation*. At the time, it apparently did not bother Hawking that he was draining the information out of the universe. Other physicists, most publicly Leonard Susskind of Stanford University, promoted various adjustments to the theories or different interpretations of the mathematics in order to avoid any information loss. [4]

For the mathematically inclined, here is an example of the perplexing results we get from the math. Suppose a photon was traveling directly toward a black hole. As it gets closer to the black hole, the gravitational forces warp space and time in a manner described by the mathematics of special relativity. [5] From those equations, you can derive a measure of how space and time are warped along the path of the photon, [6] and you get some confusing results. The formulas say that the photon will experience time passing at a factor proportional to $\sqrt{\left(1-\frac{R}{d}\right)}$. The R is the radius of the black hole's event horizon, also called the Schwarzschild radius. [7] The little d is the distance remaining between the photon and the center of the black hole. When the photon is still far away and d is some huge number compared to R, then the factor is essentially $\sqrt{(1)}$, which means that time passes for the photon at 1X the usual speed. There are two interesting values of d – when d approaches R, and when d equals zero. The first case represents the photon as it gets close to the event horizon. If it were to reach the horizon where d is the same as R, then the time factor becomes $\sqrt{(1-1)} = 0$, which means that time stops for that photon.

Nobody has any idea what it means in the real world for time to stop. We don't know for sure what these equations are telling us at the event horizon except that it seems to require forever to get there as viewed by an outside observer. [8] But relativity theory contradicts that and says that the infalling observer would not notice anything unusual about the passing of time or space when falling past the event horizon on the way to the center of the black hole.

Various theories have been proposed to fix the problems and contradictions around the event horizon. One theory proposes some adjustments to the formulas that would cause

[4] Leonard Susskind (2008). *The Black Hole War: My Battle with Stephen Hawking to Make the World Safe for Quantum Mechanics*. Hachette Inc. ISBN 978-0-316-01640-7.

[5] Einstein's gravitational field equations.

[6] The Schwarzschild metric is one such equation.

[7] This is commonly described as the the point of no return if you're traveling near a black hole. If you get closer to the black hole than that, the gravity of the black hole will be so strong that even light can never escape.

[8] It gets even more bizarre. The equations say that the energy that used to move the infalling object through time gets redirected to moving the particle through space in an Escheresque path. An outside observer would see an infalling object move toward the black hole horizon more and more slowly as the object's shape distorts and smears all around the black hole horizon.

infalling matter to explode when it reached the event horizon and dissipate by known physical processes, so no information would be lost. Irretrievably scattered maybe, but not lost in principle. That line of thought is called the *firewall* theory. Hawking didn't care for that approach in his recent paper, and pointed out some ways that it would contradict other well established physics.

Another proposal, known as *black hole complementarity*, avoids the contradictions another way. In this approach, the matter-energy stuff falling in toward a black hole both takes forever to get there as viewed from the outside, while also reaching the interior state. This means that, depending on how you look at it, information about a particle of matter or energy is in some sense both inside and outside of the horizon. It's one of those things that is mathematically precise and intuitively impossible.

If you're falling into a black hole, you'd not notice anything unusual thanks to the effects of relativity, but space and time limitations rob you of any opportunity of ever accessing what an interior observer sees. On the flip side, if you're inside a black hole and you haven't yet evaporated or been pulled apart by gravitational tidal forces, then you'll also not experience anything out of the ordinary because of relativity, and you will never have the opportunity to access your complementary information as seen from outside the horizon. When an observer looks at one side of that coin, the other side is not just invisible, it doesn't even exist in the frame of reference of the observer.

It is in the context of this confusion and controversy that Hawking presented his recent paper. It wasn't meant to reveal significant new science. Rather, it was a position paper in which he officially cast his lot with the black hole complementarity camp and gave his reasons why.

II. What He Said

Here is part of the summary from Hawking's recent paper. It's a good summary; it relates all the important concepts, which we'll try to interpret below.

> The absence of event horizons mean that there are no black holes - in the sense of regimes from which light can't escape to infinity. There are however apparent horizons which persist for a period of time. This suggests that black holes should be redefined as metastable bound states of the gravitational field. It will also mean that the CFT on the boundary of anti deSitter space will be dual to the whole anti deSitter space, and not merely the region outside the horizon.
>
> The no hair theorems imply that in a gravitational collapse the space outside the event horizon will approach the metric of a Kerr solution.

Let's take this one piece at a time.

What does he mean by the "absence of event horizon"? Imagine the eye of a hurricane. There's no *thing* out there in the air that defines the boundary of the eye of the hurricane. The eye is just a temporarily semi-stable atmospheric structure. There's a difference between the atmospheric conditions inside and outside of the eye, and the "boundary" is just wherever the transition happens to be between the interior and exterior conditions. Hawking wants us to think of a black hole boundary in a similar way. What we called the event horizon happens to be where photons on their way outward can never travel past, and it also happens to be where photons traveling inward will never reach. They're really two horizons that happen to be in the same place because both are constrained by the speed of light, but you will only encounter one or the other depending on whether you are inside or outside. Since they are mathematical limits, and because there's no *thing* defining that limit, Hawking suggests that we call that place an "apparent horizon." It's a pedantic distinction, but it allowed him to say that there are no black holes, and that made for great P.R.

Because of evaporation by quantum processes, black holes, unlike diamonds, are not forever. Like hurricanes, they form through natural processes, they're somewhat stable for a while, and they dissipate. Exactly what is it that forms and dissipates? It's the disturbance in the geometry of spacetime that temporarily forms a natural boundary where, due to the speed limit of light, photons on either side have no way to reach the other side, yet they share a dual existence. The result is that a person falling into a black hole would see a different world than seen by an outside observer.

A black hole, then, is just all appearance. When you concentrate matter-energy in the densities of a black hole, gravity increases, the paths of photons get wonky, and eventually the extreme warp in the geometry of space fades away as the black hole evaporates. That's all a black hole is: an extreme curvature in spacetime around a point of extreme gravity. This is why Hawking suggests that we think of a black hole as a "metastable bound state of the gravitational field" rather than an object.

Next, Hawking says that "the CFT on the boundary of anti deSitter space will be dual to the whole anti deSitter space...." The "CFT" refers to *Conformal Field Theory*, a particular mathematical model of quantum field theory. For our purposes, the exact model isn't as important as the relationship of the boundary conditions to the interior conditions. The "dual" refers to complementarity as described earlier. This is Hawking saying that the quantum mechanical stuff that happens at the horizon of a black hole is correlated with 100% of the interior. This is a another way of saying that everything inside a black hole is complementary to something on the boundary, and all the quantum mechanical stuff that happens to the matter-energy smeared around the boundary is correlated with all the matter-energy stuff in the interior.

Anti-deSitter space refers to a particular mathematical model of spacetime used in quantum mechanics. The salient point here is not the exact math model, but that Hawking believes that the interior of a black hole conforms to our best quantum mechanical theories for otherwise normal space. That means that the space inside the black hole horizon is quantized in small units that cannot be further subdivided. [9] From this we can calculate just how much matter or energy or information we can stuff into a black hole.

Finally, Hawking states that "no hair theorems imply that... the space outside the event horizon will approach the metric of a Kerr solution." The term "no-hair" refers to the viewpoint that a black hole can be completely characterized by a small handful of parameters. The *Kerr model* is a specific model of thermodynamic dissipation outside the black hole, and the main point is that the black hole dissipates matter-energy approaching a maximally chaotic way that scrambles, smears, and scatters the matter-energy information outside the horizon but does not destroy it. The complement of that on the inside is that the information is packed in a minimally small volume.

Replacing some of Hawking's text with simplifications and interpretations, his summary can be rewritten as,

Black hole event horizons are places

[9]That's how we used to describe atoms, then we found out they are composite. The fundamental units of space are of *Planck* size, which is as small compared to an atom as atoms are compared to the size of the Earth. We don't know much about that scale of the universe. For now we assume that space doesn't exist in sizes smaller than Planck units.

of extreme spacetime curvature, so we should think of black holes as just temporary curvatures in spacetime due to gravity. Black holes can evaporate. Matter-energy stuff that appears to eternally approach a black hole horizon is completely correlated with the stuff inside in a quantum complementary way. From one frame of reference, you experience the horizon in one way, while from a different frame of reference, you experience it in a contradictory way, but never both. Information gets spread around the horizon and may be scattered thermodynamically, but because of complementarity, never lost from the universe.

III. Conclusion

In summary, Hawking endorsed black hole complementarity to avoid the paradox of information loss due to Hawking radiation.

We have to admire the elegance and mystery of nature using contradictions to glue the universe together. Einstein appreciated contradictions. Some of the mathematical formulas used in Einstein's first theory of relativity (he had two) were already invented by others, but the formulas weren't understood because they gave contradictory answers to simple questions. Einstein's brilliance was to suggest that perhaps the universe was, in a fundamental way, contradictory, and thus he proposed the theory of relativity. [10] And then along came quantum mechanics with so many contradictions that even Einstein couldn't make peace with it.

Quantum mechanical math has successfully predicted contradictions that we can measure in laboratory experiments to extraordinary accuracy. The theories, the mathematical models, and the experimental results all prove that the true nature of our universe, our home, is literally beyond anything we can imagine.

[10] The contradiction in the special theory of relativity relates to our intuitions about space and time. We think that space and time are made of very different stuff, but relativity shows us that space and time are intimately related in a way that is described mathematically as a geometric relationship. One consequence is that two observers might not agree on the concept of "simultaneity." Two events that appear to happen simultaneously to one person might not appear to happen simultaneously to a different observer.