Black Hole Firewalls and the Information Paradox

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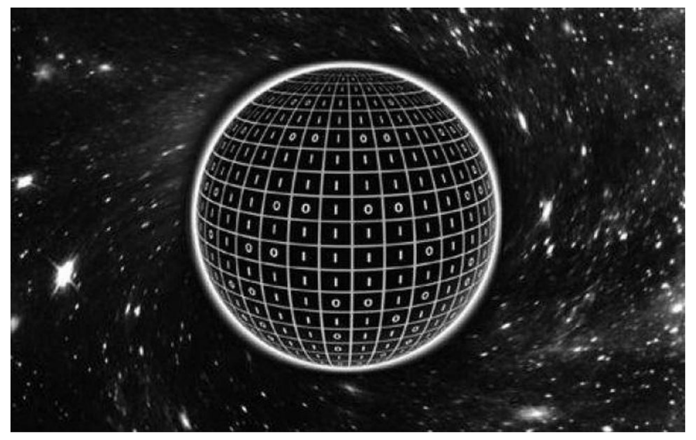


A Brief History and Future of Black Hole Firewall and Information Paradox

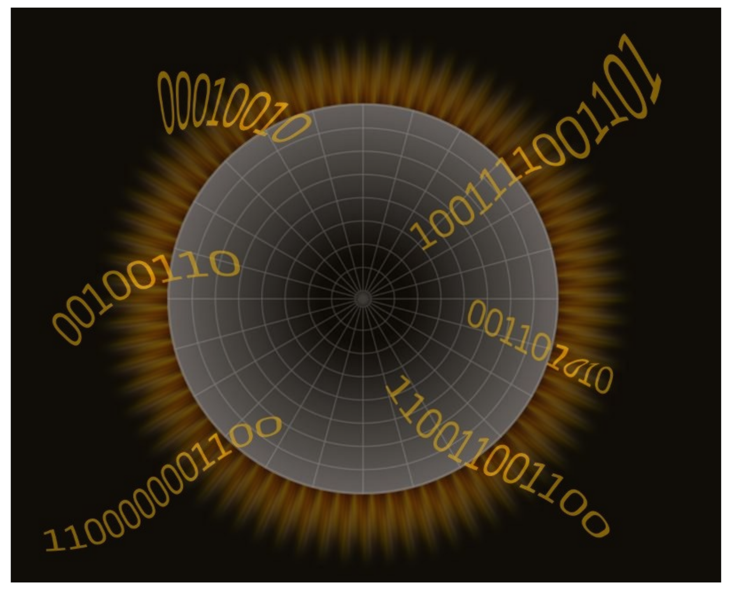
For over 40 years a debate has polarized the science community and has yet to be settled fully. This debate focuses around the concepts associated with the Information Paradox and more importantly, the characteristics of Black Holes. In 1915, Physicist Albert Einstein put forth the Theory of General Relativity which laid out fundamental concepts that dictate how objects, not tangible, function. Years later in 1974, Physicist Stephen Hawking and his colleagues proposed that energy leaves a black hole in the form of radiation, hence bringing about Hawking Radiation[1]. This radiation is associated with a temperature, the Hawking Temperature.

$$T_H = \frac{\hbar c^3}{8\pi k G M}$$

Once his ideas became circulated, many scientists began to pick apart the foundation to see if the structure of his ideas would stand. For the most part the structure held true, but one part dented the foundation. The main problem with Hawking Radiation is that it would destroy information indefinitely, violating the Law of Conservation of Information which states that information cannot be created or destroyed, only transferred. The debate became the question, is Information Conserved? In 1997, the debate enlarged when Physicist John Preskill publically bet against Hawking and his colleague Kip Thorne, stating that information was not lost in black holes. Since the rise of this bet, many scientific papers have been written to try to propose a solution to the paradox, yet none has been successful enough to persuade the physic community as a whole. It wasn't until 2004 that Hawking conceded to Preskill and announced that he believed that information is not lost, yet the reasoning behind this change in thought did not satisfy the community and the debate continued.

One solution that was proposed in 2012 by Physicist Joseph Polchinski and his colleagues[2] was that information is conserved through the existence of a firewall at or near the event horizon of a nonrotating Black Hole. Polchinski comes to this conclusion through the behavior and interaction of particles near a black hole's event horizon. Furthermore, Polchinski states that the energy to break an antiparticle-particle pair entanglement creates a wall of fire around or near the event horizon and information escapes with one of the particles in the formally entangled pair. This created more questions about the existence of a firewall and it became a paradox in it's own and is still being analyzed as seen through many publications over the years.

Though the standpoint of the Physicist in question has changed over the years, it will continue to change until a general answer is reached. The future of this debate could lead scientists to link the two branches, General Relativity and Quantum Mechanics, for the first time. One direction that is in the favor of the idea of a firewall existing is through gravitational waves. Proposed recently is that black holes that have radiated half their mass away have the right conditions for a firewall to exist. The way that we can detect these firewalls is through gravitational waves[3]. A firewall would smear the event horizon of a black hole and create a distorted region that traps photons and gravitational waves. The waves and photons bump around in this region and create echos in the waves when they leave, these echos can be detected and can determine if a black hole has a firewall or not. This would happen in the occurrence of two black holes merging, just what LIGO has been detecting since 2015. Since the discovery of the 2016 echos, five cases have been studied to find the same thing and to further prove the existence of firewalls.



Schwarzschild Metric and the Trajectory of Photons Near the Event Horizon

In the presence of a nonrotating black hole, spacetime is described by the Schwarzschild Metric:

$$(ds)^2 = (cdt\sqrt{1-\tfrac{2GM}{rc^2}})^2 - \left(\frac{dr}{\sqrt{1-\frac{2GM}{rc^2}}}\right)^2 - (rd\theta)^2 - (rsin(\theta)d\emptyset)^2 \qquad (1)$$

One consequence to General Relativity is that massive objects with great gravitational potential interact with time and cause a time difference to occur between two observers at different points in spacetime. The Schwarzschild Metric describes the proper time between two events which take place at the same point in space so that

$$\mathrm{r}, \theta, \emptyset = \text{constant} \qquad \mathrm{dr}, \mathrm{d}\theta, \mathrm{d}\phi = 0$$

For these conditions, Schwarzschild Metric becomes $ds = cdt\sqrt{1-\frac{2GM}{r^2}}$. The proper time between the two events is then given as

$$d\tau = \frac{ds}{c} = dt\sqrt{1-\frac{2GM}{rc^2}},$$

This shows that, $d\tau < dt$, and time slows down in the local region of this mass. Each term in the metric describes the space time outside an uncharged and nonrotating mass, the terms being time, radius, and the two rotational components. When considering a mass whose radius is without change, $dr = 0$, the second term becomes the standard equation for calculating the event horizon of a nonrotating and uncharged black hole, the Schwarzschild Radius.

$$R_s = \frac{2GM}{c^2}$$

An important factor that defines the Schwarzschild Radius is that this value results in $d\tau = 0$ and therefore defines the event horizon of a black hole[4]. The metric itself describes the spacetime around a mass M but can be used to figure out the path a photon takes, and each term plays a part in the probability of a photon falling into the event horizon or falling into orbit around a black hole. When a photon falls into orbit around the central mass, it orbits in a region called the photon sphere.

When moving in the ϕ direction, $dr = 0$, $d\theta = 0$, and $\theta = \pi/2$ along with $ds = 0$ for a photon. These conditions being stated, the metric changes to only the first term and the fourth term. By applying these conditions to the metric, the radius of a stable orbit can be derived.

$$0 = \left(cdt\sqrt{1-\frac{2GM}{rc^2}}\right)^2 - \left(\frac{0}{\sqrt{1-\frac{2GM}{rc^2}}}\right)^2 - \left(r(0)\right)^2 - \left(rsin\left(\frac{\pi}{2}\right)d\phi\right)^2$$

$$rd\phi = cdt\sqrt{1-\frac{2GM}{rc^2}} \rightarrow r\frac{d\phi}{dt} = c\sqrt{1-\frac{2GM}{rc^2}} \qquad (2)$$

From the metric the coordinate speed for light moving in the ϕ direction. Taking the derivation further, the orbital radius for a photon around a mass M can be found through the coordinate speed for a circular orbit of radius r around the mass M.

$$v = \sqrt{\frac{GM}{r}}$$

Setting this equation given equal to equation (2), the radius of a photons orbit could be solved for.

$$\sqrt{\frac{GM}{r}} = c\sqrt{1-\frac{2GM}{rc^2}}$$

$$\frac{GM}{c^2}\cdot\frac{1}{r} = 1 - \frac{2GM}{c^2}\cdot\frac{1}{r} \rightarrow \frac{GM}{c^2} = r - \frac{2GM}{c^2}$$

Using $R_S = \frac{2GM}{c^2}$ the substitution can be made

$$\frac{1}{2}R_S = r - R_S$$

With the substitution, the radius for the stable orbit of a photon around a mass M can be solved for[4].

$$R_p = \frac{3GM}{c^2} = 1.5R_s$$

The metric can also be used to describe spacetime and particles that are not photons. When a particle is drawn into the event horizon the information that the particle carries disappears into the black hole. This directly violates the Law of Conservation of Information along with the core principle of Quantum Determination. The Law of Conservation of Information states that information cannot be created nor destroyed, only transferred while Quantum Determination states that the value of a wave function at one point in spacetime should be determined its value at all future and past points. The wave functions carry information about the particle it represents, and the value of the wave function everywhere is necessary to know the probabilities of its value anywhere. With the evolution of the wave function determined by the unitary operator and this unitarily implies that information must be preserved and cannot be lost. With information being lost, the question arises for particles that spontaneously occur in pairs around a black hole.

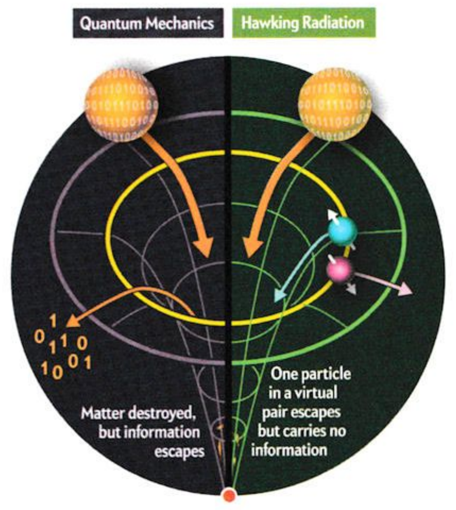
Quantum Entanglement and Particle Pair Annihilation

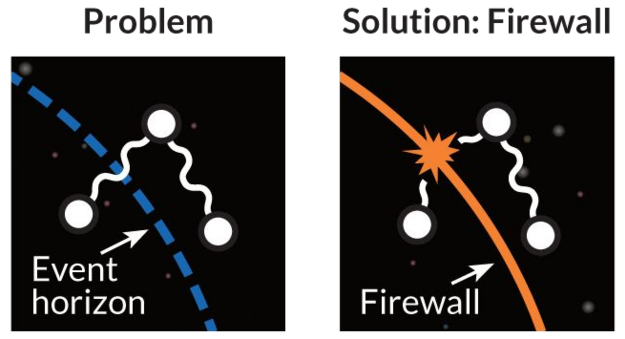
Instead of space being completely empty, which would lead to having a perfect vacuum, the space is filled by virtual particle-antiparticle pairs that randomly occur in space. These short lived pairs do not violate the Conservation of Energy because the time elapsed between the recombining and annihilation is significantly short. This is allowed through the Quantum Field Theory and the existence of these particles in a vacuum is subtly seen on a spectra as a Lamb Shift. In the 1970's Stephen Hawking suggested and pondered the idea of a virtual pair created at the event horizon of a black hole and what would happen in such a case[5]. The entanglement of the pair would be broken, leaving one particle to disappear into the black hole and one to escape as an unannihilated particle, escaping as a particle of radiation.

These virtual pairs that occur are entangled by their wave function, creating a monogamy relationship between the two particles that cannot be broken under the principle of Quantum Entanglement. This principle states that two entangled qubits, A and B maximally correlated quantumly cannot be correlated at all with a third qubit C[6]. With this being said, there are ways that particle polygamy could exist. The principle of monogamy entanglement becomes a problem with pairs created near or at the event horizon of a black hole.

In the occurrence that two entangled particles are created at or near the event horizon, the entanglement between the two wave functions of the particles is broken. One of the entangled particles crosses the event horizon and disappears into the black hole while the other escapes the event horizon, unannihilated, and becomes a particle of radiation. The particle that becomes radiation finds a new partner and violates monogamy. To satisfy the problem of polygamy, the entanglement between the particle that fell into the black hole and the particle that became radiation is broken. With the wave functions entanglement being broken, it is no longer possible to determine the probability state of the radiation particle, and the information of the former partner is lost forever. This only happens to black holes that have radiated away half their mass and are is needed for the second entanglement to occur.

The energy to break the entanglement of a pair of particles is large enough to evoke a firewall at the event horizon. Joseph Polchinski and his colleagues at the University of California in 2012 proposed the existence of a firewall[2], but many were reluctant to accept. Having a firewall exist at the event horizon would violate General Relativity which states that an object moving across a black hole's event horizon would feel no changes occur. Any object that is to cross the event horizon is incinerated by the firewall before the tidal forces would dismantle the object.





Firewall Paradox and Black Hole Thermodynamics

Joseph Polchinski and his colleagues at the University of California in 2012 proposed the existence of a firewall, but many were reluctant to accept this idea. The paper[2] had three conditions that could not be all true about a black hole and the solution given was the existence of a firewall.

The first condition is that Hawking Radiation is not an ideal black body but instead is in a pure non-thermal state. This deals with the concept of unitarity which states that a pure state cannot become a mixed state. The pure state of the Hawking Radiation would be the entangled pairs that occur and disappear randomly[7]. When the radiation is in a mixed state, the entanglement of the pair is broken and the information is lost due to the inability to describe the state of a system.

The second condition talks about how events can only influence nearby objects and points in space. This is valid up to a specific distance far from a black hole's event horizon and singularity, where physics breaks down. This being said, one thing that must stay valid is that information must be conserved. To obey the conservation of information, the second condition also states that information is conserved through being carried away by Hawking Radiation.

The last condition is simply that an infalling object would encounter nothing unusual at the horizon. This obeys General Relativity which states that an object passing through a black hole's event horizon shouldn't feel any difference nor change. This is one fundamental part of General Relativity that is called the equivalence principle.

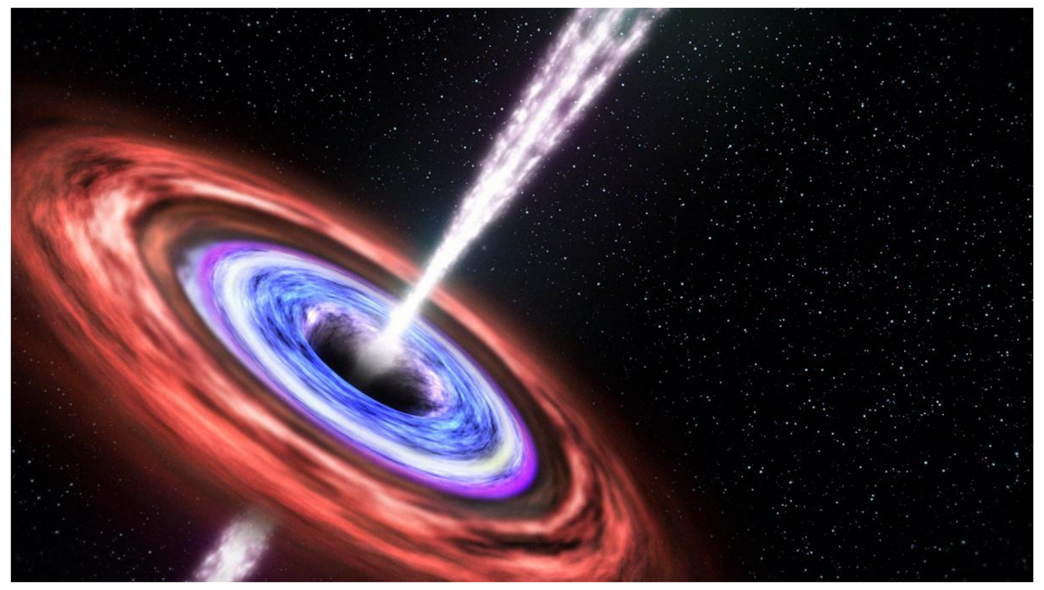
With these three conditions, Polchinski[2] states that they cannot all exist at once and raises the idea to defy General Relativity and conserve information through the existence of a firewall. The problem becomes whether to defy General Relativity or quantum mechanics, becoming the base of the firewall paradox.

A firewall would exist at the event horizon of a black hole and would be the result of breaking the entanglement of a particle-antiparticle pair. There wouldn't be a visible wall of fire, but an invisible wall that burns all matter and particles that could run into it.

The energy to create the firewall would come from breaking an entangled pair of particles that form near the event horizon of a black hole[2]. Breaking entanglement is caused by one of the entangled particles falling into the black hole. The particle that does not fall into the black hole flies off as radiation and is classified as Hawking Radiation. The particle that falls into the black hole is the particle that is required to encode information and carries negative energy. To balance the negative energy falling into the black hole, energy is released, and mass is lost. When this occurs, the black hole shrinks and this violates the area theorem.

The area theorem states that the area of a black hole's event horizon can only increase or not change at all. Ways that black holes lose mass and area is through Hawking Radiation and the firewall emitting energy. Emission of Hawking Radiation causes there to be both a mass and energy decrease, leading to the evaporation of the black hole. When the black hole disappears, it takes with it all the information that it captured through infalling particles.

It should be possible to measure the quantum state of the radiation that comes out of a black hole when an object falls in. Quantum mechanics states under the law of conservation that information must be conserved and cannot be destroyed. To obey quantum mechanics and conserve information, the firewall would need to have information be carried out by quantum correlation among all particles radiated from the black hole.



Information Paradox

The Law of Conservation of Information states that information cannot be destroyed but only transformed. Information is the particular sequence of atoms for an object. A common example of this is how one arrangement of carbon atoms makes coal while a different arrangement could make diamonds. Even when you destroy an object through burning it, there is a way to possibly analyze the atoms to see what the object was previously.

The problem with information is the relationship with black holes. When a particle falls into a black hole, the information is forever lost and irretrievable. Many have made suggestions to how a black hole conserves information, like saying that information is embedded in the event horizon or that it is not destroyed but we cannot access it.

The AMPS firewall gives a solution to the information paradox by having information conserved through quantum correlation[2]. The particle conserves the information about the infalling particle when it finds a new partner and to obey monogamy the entanglement between the initial particles is severed.

References

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