Resolving Black Hole Information Paradox: Revisited

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Abstract. Blackhole remnants are one of the most exotic remnants in our universe, leaving behind several unsolved paradoxes. Resolving the black hole information paradox, in particular, can direct us to numerous engrossing discoveries and provide a decent understanding of the unsolved conventional theories. We readdress the notions underlying the paradox explicitly, beginning from the basic principles. Various theories, explanations, conclusions, their advantages and disadvantages in several works of literature regarding the information paradox and black hole entropy are discussed. Recent developments in the interpretation of the black hole information paradox are reviewed. A congenital solution to this contradiction involves the transition of classical physics to quantum physics. At the centre of the black hole, the space-time theory by Einstein’s general theory of relativity fails. The research suggests that the solution obtained from considering the principles of quantum gravity is quite plausible. This approach also gives a decent explanation towards the recondite hypothesis of tunnelling of black holes to white holes and the interior geometries of white holes.

1. Introduction
Black holes are radiating bodies. This thermal body radiation occurs at temperature

\[ T = \frac{1}{8\pi GM} \]  

(1)

At the event horizon, the particles behave queerly. They form particle and antiparticle pairs at the event horizon. One of the particles enters into the black hole and the other will leave the horizon making it a radiating body. This infers that the black hole eventually evaporates with evaporation time

\[ t_{\text{evaporation}} \simeq G^3 M^3 \]  

(2)

This process is known as Hawking Radiation.

Information paradox is one of the most intriguing problems in the black hole physics. This was put forward by Stephen Hawking in the early 1970s. This paradox is a combination of two observations:

(i) The no-hair theorem - states that the black hole settles down swiftly to a state where the region around the horizon is a vacuum.

(ii) The vacuum produces entangled pairs by Hawking process.

The calculations performed by Stephen Hawking and Kip Thorne, using the general theory of relativity and quantum field theory on the Minkowski space-time resulted that any physical information is permanently lost inside the black hole.
Here the information conservation is contravened. The principles of quantum mechanics state that the ‘Information can be scrambled hard but cannot be lost in any case’. This raises controversy with modern physics.

Some scientists, significantly, John Preskill, Leonard Susskind and Gerard ‘t Hooft had many scientific debates with Hawking against the information loss. Many scientists came forward to unravel the paradox with several distinct methodologies and hypotheses. Majority of these hypotheses include quite a few intricacies and numerous penalties due to the infringement of fundamental laws of cognized physics.

2. Proposed solutions and recent developments

There were numerous theories proposed to resolve this paradox by physicists across the world [1–10]. The efforts to get a solution was high but many of them collapsed due to their complications and violation of a few aspects of fundamental physics.

2.1. Information is permanently lost:
This theory states that the information absorbed by the black hole is irretrievable or is lost forever. This conclusion is against the laws of quantum reversibility. Quantum principles convey that information can be scrambled hard but cannot be destroyed or lost in any case. Thus the theory fails.

2.2. Information leaks out of the black hole but takes a long period:
This theory looks satisfactory as the information is retrieved but has a lot of complexities associated with it. The theory requires a black hole to emit information which needs a lot of complicated divergence from classical to semiclassical theory. Thus this explanation is not efficient for solving the paradox.

2.3. Information stored in remnants:
We have theories where Planck sized remnants and long-lived remnants are acquainted to cache the information. Information is stored as Planck sized remnants, thus the issue looks to be solved but to carry the information they need to have infinite internal states. Long-lived remnants do not need infinite internal states but it demands the Hawking radiation to cease before it reaches Planck size black hole which is a violation of semi-classical gravity at macroscopic scales. The A d + 1-dimensional theory of gravity (with a negative cosmological constant) is equivalent to a d-dimensional large N SU(N) gauge theory without gravity. When we try to understand the black hole in AdS/CFT correspondence we find that the information is not lost and there exist no remnants storing the information.

2.4. Fuzzballs theory:
Recent developments in solving the paradox include the fuzzball(string) theory. With the help of small corrections theorem, we can convey that there is a necessity of correction of order unity to low energy physics at the horizon and the fuzzball can be demonstrated as a rationale argument to it. The Witten’s ‘bubble of nothing’ states that Minkowski space which tunnels into a new topology conveys that a collapsing shell can tunnel into a fuzzball state. String theorists found the individual micro-states of black holes and they are worked out in every case to have a fuzzball structure. Fuzzballs are theorized to replace the singularity by a ball of strings. The central idea is that the fuzzball’s quantum data moves out of the black hole in the form of Hawking Radiation. Many scientists find it as a solution to the paradox but it fails to explain the singularity at the beginning of the universe.
3. White holes as a solution to the paradox

White holes are predicted as a part of Einstein's Field Equation. They are opposite to black holes in fairly all the aspects. Black hole evaporation abates the mass and rotational speed of the black hole making it shrink and ultimately disappear. Towards the end of this process, there is an escalated probability of the black hole tunnelling into a white hole. This takes place on the grounds of quantum gravity.

The space above the central singularity, is assumed to be the black hole region where the matter and the energy gets trapped and below, is the white hole i.e, the anti-trapping region. As we arrive at the singularity, temporal coordinate within the hole i.e, the Schwarzschild radius rs, decreases and the curvature increases. The classical approximation becomes unreliable as the curvature comes up to the Planckian values. Quantum gravity effects are anticipated to bound the curvature. Consider the line element

$$ds^2 = -\frac{4(\tau^2 + l)^2}{2m - \tau^2} d\tau^2 + \frac{2m^2 - \tau^2}{\tau^2 + l} dx^2 + (\tau^2 + l)^2 d\Omega^2$$

(3)

where $l << m$. The line element represented defines a genuine Riemannian space-time having no singularities and no divergences. The curvature is bounded. For $l << \tau < 2m$ the line element is well approximated by taking $l = 0$. We get

$$ds^2 = -\frac{4\tau^4}{2m - \tau^2} d\tau^2 + \frac{2m^2 - \tau^2}{\tau^2} dx^2 + \tau^4 d\Omega^2$$

(4)

For $\tau < 0$, it is the Schwarzchild child inside the black hole. We can see this going through the Schwarzchild child coordinates i.e,

$$t_s = x \text{ and } r_s = \tau^2$$

(5)

For $\tau > 0$, it is the Schwarzchild child inside the white hole. Here $\tau$ is a constant (geometrically) space like surfaces foliate the black hole. Therefore equation (3) represents the transition of geometry from black hole to white hole across a region of Planckian but bounded curvature.

According to the Hawking radiation, the black hole size should shrink to Planckian size in the period of

$$\tau_{bh} \simeq \frac{m_0^3}{\hbar} \text{ and } \Delta \tau \simeq \sqrt{\hbar}.$$  

(6)

Here the probability density becomes unitary thus the B region is expected to be the region of white holes. By calculating the interior volumes and also considering the past geometries we get

$$\tau_{wh} \simeq \frac{m_0^4}{\hbar^2}.$$  

(7)

This shows that the white holes are of Planckian size and are long lived. The total entropy should be released thus the white hole should be long-lived. This helps the information to escape with low frequency obeying the bounds on maximal entropy of the volume. The modes of the short wavelength are exponentially blue-shifted along the horizons of the white holes; this indicates the instabilities of the white holes. Using non-perturbation quantum gravity more importantly considering the no trans-planckian perturbation all the instabilities of the white holes lose their existence.

These white holes can provide an acceptable solution to the information paradox which is pondering since Hawking proposed that black holes evaporation. They can also provide a proper way to understand the big bang. They can provide a solution to the current energy and matter in the universe. They can provide a model to provide a cycle of the black hole.
4. Conclusion
Black hole information paradox was overwhelming many scientists since the late 20s. Many theories are put forward to solve the paradox. But many collapsed due to the complexities and violating few laws of modern physics. Few theories are still under development to explain the known physics. Hawking radiation or the black hole evaporation leads us to the quantum tunnelling of the black holes to white holes. The entropy of the black hole can be released through the white holes as described. This approach can provide a proper solution to the black hole information paradox with comparison to the other approaches till today. This model can also solve multiple problems like the origin of the initial singularity and the big bang and also the current energy and matter in the universe can be formed from some previous black hole. Further development in the theories regarding the understanding of the black hole – white hole physics can improve our vision regarding quantum gravity and quantum space and time.

References
[1] Stoica O C 2018 Adv. High Energy Phys. 2018 4130417
[2] Gurevich I 2014 Open J. Microphys. 4(3) 21-5
[3] Bianchi E, Christodoulou M, d’Ambrosio F, Haggard H M and Rovelli C 2018 Class. Quantum Gravity 35(22) 225003
[4] Rovelli C and Vidotto F 2018 Universe 4(11) 127
[5] Martin-Dussaud P and Rovelli C 2019 Class. Quantum Gravity 36(24) 245002
[6] Barceló C, Carballo-Rubio R, Garay L J and Jannes G 2015 J. Phys. Conf. Ser. 600(1) 012033
[7] Olmedo J, Saini S and Singh P 2017 Class. Quantum Gravity 34(22) 225011
[8] Potvin G D 2006 Singularity resolution and the black hole information paradox (Toronto: University of Toronto)
[9] Giusto S and Mathur S D 2010 J. High Energy Phys. 07 9
[10] Bojowald M 2003 Gen. Relativ. Gravit. 35(11) 1877-83