Black holes and their information paradox

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The black hole information paradox holds an important place in modern physics, and can have major consequences on our understanding of quantum mechanics and general relativity. In this paper, we provide a discussion on the origin and possible solutions of the information paradox, beginning with the idea of four-dimensional spacetime and its unique feature which contributes to the existence of black holes, followed with a description of the no-hair theorem, Hawking radiation and other properties which make black holes thermodynamic objects. We then describe quantum states and their evolution which results in the information paradox and conclude with some possible solutions with their drawbacks.

Introduction

In 1916, Einstein proposed his general theory of relativity where he suggested that space was not flat but curved and changed our perception of the Universe. He theorized that in the presence of mass, light does not travel in a straight line. Instead, light always takes the shortest path, which is curved. In other words, space in the presence of mass must be curved just like the shortest path on the surface of the earth is curved. This idea led to the discovery of a new celestial body called a black hole; a region of space where the gravitational field is so strong that nothing, including light, can escape[1].

Later, however, it was found that black holes have temperature[2] — a quantitative measure of the average kinetic energy of particles. This presents a problem— for black holes to have temperature they must radiate energy, but the classical description of black hole does not permit energy to escape the hole. The resolution of the problem was presented by Stephen Hawking. He showed that when black holes are treated as quantum objects, certain phenomena such as quantum fluctuations make it is possible for the creation of particle and anti-particle pairs -particles with opposite charge and spin- in empty space (vacuum). He showed that when these pairs of particles are created at the interface of the event horizon one particle can fall back into the black hole while the other escapes outside the black hole, resulting in the black hole radiating (emitting) particles[3]. Since the energy required to produce these particles is derived from the black hole, the escape of one of the particles results in decrease of the black hole's mass. As this process continues, eventually the black hole evaporates

This solution resulted in a bigger problem: a paradox. When a black hole radiates energy and eventually evaporates, there is a fundamental loss of information, i.e., we cannot determine what constituted the black hole before its evaporation. This goes against a fundamental principle of quantum mechanics: information must be conserved. If information is lost, then our understanding of the Universe as described by quantum mechanics would prove to be wrong. However, there are multiple possibilities and information may be conserved. But for that, the rules of relativity such as locality (the idea that objects can only be affected by their immediate surroundings and cannot be instantaneously by objects at a distance) and causality (a concept which describes which events can or cannot affect other events) must be modified. Either way like many previous paradoxes, a solution to the information paradox can change our understanding of the Universe or at least modify it.

In this paper, the goal is to discuss the origin and possible solution of the information paradox. We begin with a description of the idea four-dimensional spacetime and causality in section 2. After which, in section 3, we generalise the concept of spacetime in the presence of objects and gravitational force and explain the prediction and properties of black holes which result in the information paradox. We then describe quantum states and how Hawking radiation results in the paradox in section 4. And conclude in section 5 with some possible solutions of the paradox and their plausibility.

Minkowski Space

Black holes are simple objects. They have a singularity where the entire mass of the Black hole is predicted to exist and an event horizon which behaves like a one-way membrane between the Black hole and the rest of the Universe as objects can fall into a black hole but cannot escape. This simple structure of black holes and their very existence can be originated from the nature of space and time with respect to Einstein's theory of special relativity, also known as theory of four-dimensional spacetime[4]. As the name suggests,

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according to special relativity, space and time are not independent and absolute as assumed in Newtonian mechanics where there are three spatial dimensions and one time parameter. Instead, space and time together create a four-dimensional spacetime continuum in which objects have four coordinates: three spatial coordinates (x,y,z) and one time coordinate(t). And points in space are replaced by points in spacetime called events, represented uniquely by coordinates (t,x,y,z). This four-dimensional flat spacetime continuum is called Minkowski space[4].

In Newtonian mechanics, where there are only three spatial dimensions, the space between two points is described by the Euclidean distance metric (equation 1)

$$ds^2 = (dx)^2 + (dy)^2 + (dz)^2 \tag{1}$$

Where ds is an infinitesimal distance. We can rewrite (equation 1) by introducing the Euclidean metric, a 3 x 3 matrix, given by (equation 2)

$$g_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{2}$$

by introducing the metric, we get,

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu \tag{3}$$

Similarly, in Minkowski space where there are four dimensions, the distances between two events in spacetime is described by the spacetime interval (equation 4).

$$ds^2 = -(cdt)^2 + (dx)^2 + (dy)^2 + (dz)^2 \tag{4}$$

Like the Euclidean metric, we can rewrite (equation 4) by introducing the Minkowski metric, a 4 x 4 matrix representing all four coordinates of spacetime, given by (equation 5).

$$\eta_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{5}$$

By introducing the Minkowski metric, we get,

$$ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu \tag{6}$$

The negative sign in the Minkowski metric indicates that distances in spacetime can be positive, negative or zero. We can classify spacetime with respect to an observer into timelike separated when $s^2 < 0$, spacelike separated when $s^2 > 0$, and lightlike separated when $s^2 = 0$. This has profound implications on determining which events can affect other events, called causality.

To understand this, let us take two coordinates: time coordinate t and distance coordinate x as shown in Figure 1a and place a light source at the origin O. The ray of light emitted by the source is shown by AO and BO. This spacetime diagram is called a light cone and divides spacetime into three regions: future, past and present for an observer as depicted in Figure 1b where we can also observe its conical structure. In the light cone, lines AO and BO represent the trajectory of light in spacetime. From special relativity we know that no object can travel faster than the speed of light. Therefore, it is not possible for an event inside the light cone to affect an event outside the light cone, as it would be a direct violation of the postulates of special relativity.

In other words, if an event occurred at point E inside the light cone, it can affect another event S inside the light cone. But an event E inside the light cone cannot affect event Z or any other event outside the light cone and is said to be spacelike separated from Z. The event E inside the light cone is said to be timelike separated from S and an event on the lines AO or BO is said to be lightlike separated from S.

Minkowski space provides an accurate description of four dimensional spacetime and causality, but it is a special case where spacetime is flat due to the absence of objects and gravitational force which bend spacetime.

Black Holes

When mass is introduced in Minkowski space, a special effect is observed due to the interaction of energy and spacetime described by Einstein's theory of general relativity, also known as the modern theory of gravity. It predicts that the spacetime is not flat as described in Minkowski space, but is curved in the presence of objects resulting in a four-dimensional curved spacetime manifold. Here, the classical interpretation of gravity as an action at a distance is replaced as an effect of spacetime curvature. This curvature of spacetime by energy is expressed by the Riemann curvature tensor (equation 7).

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} - \Lambda g_{\mu\nu} \tag{7}$$

The tensor equates energy in space to the curvature of spacetime. Where, $G_{\mu\nu}$ is curvature tensor, $T_{\mu\nu}$ is energy density tensor, Λ is the cosmological constant which describes the expansion rate of the Universe and is the intrinsic curvature of space in the absence of mass and G is Gravitational constant ($\approx 6.67 \text{ x } 10^{-11}$).

We can also observe the proportional relation between the two quantities in equation 7 where the curvature of spacetime increases with increase in energy density. And as gravity is an effect of curvature, greater the energy density of an object, greater is the gravitational field produced by the object.

An extreme example of this relation between energy, curvature and gravitational field is a black hole, which is formed when the radius (r) of an object is less than the Schwarzschild

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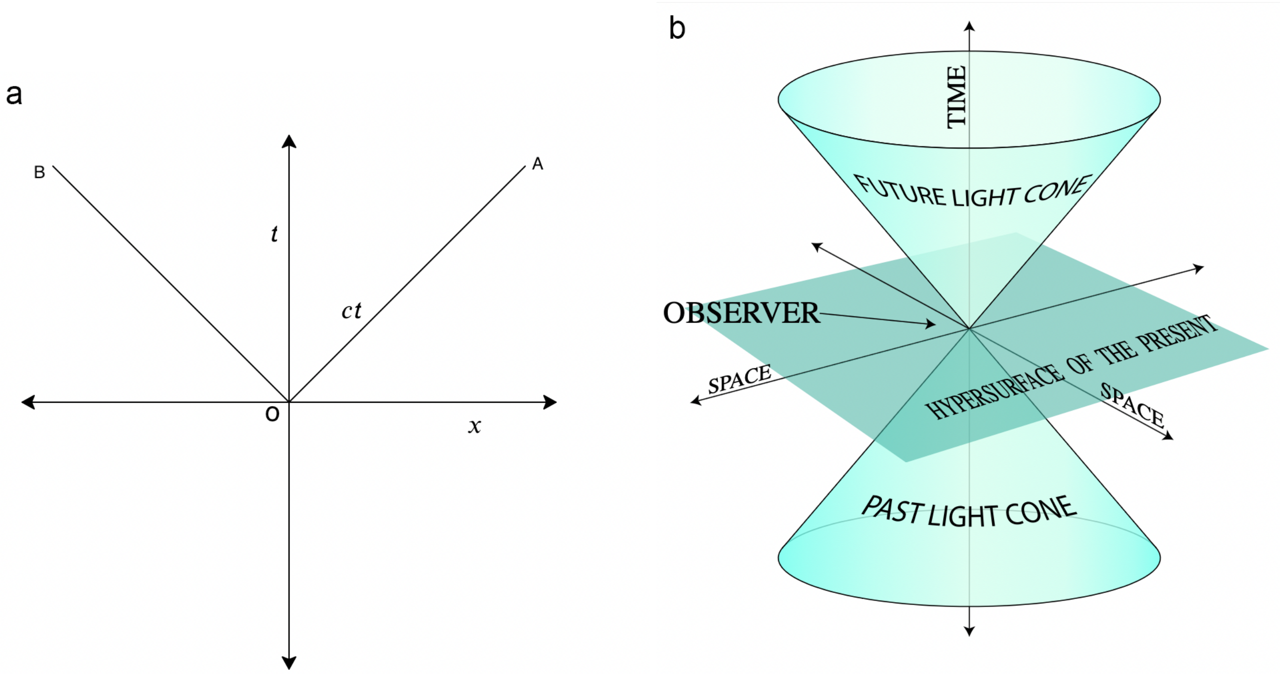

Fig. 1 Light cone | **a)** Two-dimensional light cone diagram and division of spacetime into light-like, space-like and time-like. **b)** Three-dimensional light cone diagram and division of light cone into past, present and future.

radius (equation 8), an equation which predicts the formation of a black hole.

$$r_s = \frac{2GM}{c^2} \tag{8}$$

In principle, since every object has a Schwarzschild radius, as depicted in table 1, theoretically any object can form a black hole if its radius is smaller than the Schwarzschild radius, but natural processes allow the formation of black holes only for stars above the Chandrasekhar's limit– the limit after which a white dwarf star collapses into a black hole ($\approx\ 1.4\ M_\odot$).

General relativity not only predicts black holes but also predicts their structure with the Schwarzschild metric (equation 9), a solution of Einstein's field equations.

$$g = c^2 d\tau^2 = -\left(1 - \frac{rs}{r}\right) c^2 dt^2 + \left(-1 - \frac{rs}{r}\right)^{-1} dr^2 + r^2 d \tag{9}$$

It predicts that a black hole has two parts: the event horizon, which behaves as a boundary between a black hole and the rest of the Universe ($r = r_s$) and the singularity ($r = 0$), where the entire mass of the black hole is predicted to exist, which also indicates that the inside of a black hole is vacuum[5]. When we solve the Schwarzschild metric, we find that the energy is predicted to be infinitely dense, resulting in an infinite curvature of spacetime and a strong gravitational field whose escape velocity- the lowest velocity required by a body to escape the gravitational field of another body- is greater that the speed of light. A consequence of this is the effect of causality. As no object can travel faster than the speed of light, no object, including light, can escape a black hole and no event inside the black hole can affect an event outside the black hole, dividing spacetime into lightlike, spacelike and timelike separated as in a light cone[4]. The inside of a black hole (where $r < rs$) is said to be spacelike separated, outside of the black hole (where $r > rs$) is said to be timelike separated and the event horizon is lightlike separated.

Table 1 Schwarzschild radius of various objects

Object	Schwarzschild radius
Milky way	0.25 light years
Sun	2.9510^{-3} m
Earth	8.8710^{-3} m
Moon	1.0910^{-4} m
Human	1.0410^{-25} m
Planck mass	3.23×10^{-35} m

Apart from their simple structure, black holes have only three known properties: mass, charge and angular momentum. This is due to the no-hair theorem, which states that all information of matter that forms the black hole is lost except

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for the three. This means that we cannot determine the type of matter which constitutes a black hole and therefore cannot determine their origin. For example, if two black holes were formed, one from a massive star and another from a neutron star, both black holes would be similar but vary only in their mass, charge and angular momentum.

Though we can differentiate black holes with the three properties, not all black holes possess these properties. Some black holes called Schwarzschild black holes (static black holes) only have mass but no charge and angular momentum and Kerr black holes (rotatory black holes) have mass and angular momentum but no charge.

These black holes which have only three known properties are classical black holes, or black holes which are described only by classical mechanics. But if we introduce quantum mechanics and treat black holes as quantum objects, an entirely new set of properties emerge– thermodynamic properties. One such property is entropy. Since the entropy of an object is the amount of states the internal structure of an object can exist as, its measurement depends on the amount of information possessed by an observer on the object. If we have more information regarding the object, lesser is the entropy of the object[6]. For example, if we consider a container with steam (water in gaseous state), there are multiple number of configurations in which the molecules can be arranged and therefore the container has high entropy, but if we are given the information that the steam is compressed into a smaller section of the container, then there are less number of states in which we can arrange the molecules and therefore, there is less entropy. And due to the no-hair theorem, we cannot obtain information of matter inside the black hole and therefore black holes have maximum entropy.

The entropy considered above is called coarse-grain entropy[7], or entropy which considers only our lack of information about a system[8]. However, as black holes are treated as quantum objects, we must also consider the effects of quantum mechanics and more precisely quantum entanglement. Quantum entanglement is a process where particles that form at the same event in spacetime are correlated with one another. They are correlated in such a way that changing the properties, such as spin, of one particle results in an instantaneous change in the properties of the other particle. In these pairs of particles some information of one particle is possessed by its pair. Since coarse-grained entropy, which is used for all thermodynamic objects, does not consider these correlations, even though black holes are thermodynamic objects we must use a different entropy- von Neumann entropy. von Neumann entropy does not consider the lack of information but the fundamental loss of information and also the correlations of a quantum system. It is given by equation 10.

$$S(\rho) = -Tr \ln \rho \tag{10}$$

Where ρ is the density matrix given by equation 11

$$\rho = \sum_{s} p_s \left|\psi s\right\rangle \, \left\langle \psi s\right| \tag{11}$$

The ability of black holes to have entropy suggests that they are objects with thermodynamic properties, such as temperature, entropy, information, and other similar properties. It was found that there is a relation between the entropy of a black hole and its surface area in which both entropy and surface area increase with time, similar to that of closed thermodynamic systems where energy that cannot be used to do work (heat energy) increases, resulting in increase in entropy[2]. Another such similarity can be found when black holes collide. Under normal circumstances excluding quantum processes, energy inside a black hole cannot escape, due to which black holes cannot do work. But when two black holes collide, they release energy in the form of gravitational waves[9] (ripples in spacetime), ultimately gaining the ability to do work, which is also observed when two closed thermodynamic objects which have lost the ability to do work combine, producing energy and doing work[6].

A consequence of black holes being thermodynamic objects, is that they radiate energy just like any other thermodynamic system. Which means that black holes must have temperature. But the classical description of black holes does not permit energy to escape and consequently does not allow black holes to have temperature. This problem is resolved by Quantum field theory, where energy is predicted to exist in empty space (vacuum), from where particle and anti-particle pairs can be formed and annihilated in a very short period of time due to quantum fluctuations. Such a process is made possible due to the uncertainty principle (equation 12) which allows these pairs of particles called virtual particles to exist for a very short period of time violating energy conservation law.

$$\Delta \mathrm{E} \Delta \mathrm{t} \geq \frac{1}{2}\hbar \tag{12}$$

Even though the entire mass of the black hole is predicted to exist at the singularity, these particle and anti-particle pairs can form and annihilate inside the vacuum of black holes. This is because empty space is not empty but has energy due to curvature as depicted by the Riemann tensor (equation 7). As black holes result in extreme curvature of spacetime, energy exists in the vacuum of black holes and it is possible to obtain virtual particles. This phenomenon does not possess much effect if it occurs inside or outside a black hole, but when it occurs near the event horizon, due to the strong gravitational field, one of the particles goes into the black hole and other towards infinity (outside the black hole). As these particles are formed by the energy inside the black hole, when one of the particle escapes, it reduces the total energy of the black

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hole, resulting in radiation called Hawking radiation, which gives black holes temperature.

Hawking radiation suggests that black holes radiate, lose energy and eventually evaporate and seize to exist. Another important implication of Hawking radiation is its effect on information.

Information Paradox

Apart from having temperature and radiating energy, black holes exhibit one more property of thermodynamic objects–blackbody radiation[10]. Though hawking radiation is unique to black holes, the radiated particles are primarily photons similar to that of other thermodynamic systems. In other words, like the radiation of the sun, a light bulb and all other thermodynamic bodies, black holes radiate light. But the radiation of a completely evaporated black hole is subtly different from that of other thermodynamic bodies - the quantum state of the radiated photons[10].

Quantum mechanics predicts that energy is not continuous as assumed in classical mechanics but exists is discreet quantities called quantum which can possess only certain magnitudes of energy. It is analogous to a person climbing a staircase. The person can either stand on the first, second or any other step of the staircase, but never between either two steps. And each time the person climbs a step, he will have a greater potential energy. Similarly, if we replace the person with a particle and the steps by different magnitudes of energy called the energy state of the particle, the particle will either exist on the first, second or another energy state but never between either two states and each time the particle gains a fixed magnitude of energy, it goes to the next energy state.

These are called eigenstates, or states that do not evolve into other states in time. But in quantum mechanics it is also possible to have states that evolve by themselves following the dynamics of the time-dependent Schrodinger equation (equation 13).

$$\hbar\frac{\partial}{\partial t}\Psi(r,t) = \hat{H}\Psi(r,t) \tag{13}$$

Such an evolution is a special case when particles have energy between two states, say energy state one $E1$ with the wave function $<p1|E1>$ and energy state two $E2$ with a wave function $<p2|E2>$, where p is the probability of the particle existing in the given state. In this case, the particle exists as a superposition of the two states – half the time it exists in the first energy state and half the time in the second energy state. In other words, it has a fifty percent probability of existing in either two states represented by equation 14.

$$|\Psi\rangle = p1\,|E1\rangle + p2\,|E2\rangle\,. \tag{14}$$

These energy states that can be represented by one or more eigenstates are called pure states and are similar to the state of the initial particles that makeup a black hole and the radiation of other thermodynamic objects. But the radiated particles of an evaporated black hole are in a mixed state - a state that cannot be represented by eigenstates and does not evolve into either one. These states are described by a density matrix (equation 11).

We can observe in equation 11 that unlike pure states, which can be described as two or more individual eigenstates, mixed states are described as a combination of two or more pure states.

This transition of energy from a pure quantum state during the formation of a black hole to a mixed quantum state after its evaporation provides a problem. According to the Schrodinger equation of quantum mechanics (equation 13), a pure state over time evolves into another pure state but not into a mixed state. This is called unitary evolution when there is before and after a hundred percent probability of a quantum state existing as an eigenstate.

But that is not the case in Hawking radiation, where we get a mixed state which violates unitary evolution and the probability is greater that hundred percent. Also, as von Neumann entropy represents the loss of information of a quantum system, for pure states, it is always zero as we possess all the information regarding the state. However, for a mixed state the von Neumann entropy is greater than zero as we do not possess all the information[11]. Therefore, for a black hole to follow unitary evolution, its von Neumann entropy must decrease as it radiates particles and must become zero after completely evaporating.

But contradictory to the above statement, Hawking showed that the von Neumann entropy of a black hole increases with time. He argued that as one of the particles of hawking radiation fall into the black hole, they become inaccessible beyond the event horizon, and result in the increasing von Neumann entropy S_{vn} of a black hole.

However, a recent finding in 2019[12] discovered that the von Neumann entropy increases initially as predicted by Hawking but decreases after the black hole begins to evaporate. It was shown that unlike Hawking's approach where the total entropy of a black hole was determined with respect to the event horizon (equation 15),

$$S_{bh} = \frac{(Area)_{hor}}{4{l_p}^2} + S_{matter} \tag{15}$$

the von Neumann entropy is determined by the area of a different surface, given by equation 16[11 7]. It is a surface similar to the event horizon in equation 15 but with one difference– it is the minimal value and can also exist inside the black hole. This allows us to not separate the entangled particles of Hawking radiation as the event horizon does.

$$S_{vn} = min \left[\frac{(Area)_{hor}}{4l_p^2} + S_{matter} \right] \tag{16}$$

It was also shown that due to the black hole evaporation this surface shrinks with time and as the von Neumann entropy is directly proportional to the surface (as shown in equation 16), it also decreases. Therefore, as S_{vn} is decreasing and unitary evolution is not violated as a black hole evaporates, the evaporation of the black hole is not a problem until the entire black hole evaporates, after which all the particles that previously constituted a black hole are in a mixed quantum state and the von Neumann entropy is greater than zero. Here, even though von Neumann entropy of an evaporating black hole is decreasing to zero, the von Neumann entropy of an evaporated black hole is not zero. This results in a fundamental loss of information as we cannot determine the exact quantum state of all the particles that constituted the black hole.

Quantum mechanics is built on the principle that information is conserved; it can neither be created nor destroyed. As quantum mechanics does not allow information to be lost but quantum process when applied to black holes results in information loss, they contradict each other and ultimately result in a paradox- the information paradox. This paradox is an example of the incompatibility of quantum mechanics and general relativity. A black hole, described by general relativity, when treated as a quantum objects fails to follow the rules of quantum mechanics – unitary evolution. Thus, the black hole information paradox is a problem that arises from the inconsistency of quantum mechanics and general relativity.

Solutions of the Information Paradox

The paradox still stands unresolved, but there have been many proposed solutions varying from the idea of encoded information in the radiated particles to the prospect of a baby universe, each trying to resolve the paradox.

Information is Encoded in Hawking radiation

The first resolution is that, similar to all other thermodynamic systems where information is encoded in thermal radiation, the information of a black hole must be encoded in Hawking radiation[10].

Though this is expected, as a black hole is a thermodynamic body, there is a problem in this approach. The radiated particles are different from that of other bodies- they are entangled with one another. In these pairs of particles some information of one particle is possessed by its pair. And in Hawking radiation one of the particle falls inside the horizon and the other to infinity (outside the event horizon). Their correlation must be maintained even after their separation by the event horizon to conserves information. But as black holes have no-hair and it is not possible to derive any information of the particles except for their mass, charge and spin, it raises the question as to how a black hole manages to conserve this correlation.

One possible explanation is that causality is violated and information is transferred between the pair of particles at a speed greater than the speed of light. Or a more subtle approach that does not violate the principles of relativity is that there is some mechanism[10] (yet unknown) that destroys the information possessed by the particle that falls into the black hole, which makes it possible for the emitted particle to possess all the information. This is called the unique state. When an object has a unique state all the information is radiated and the object does not possess any information.

Information is given out in a burst

As the above solution violates causality, we can consider another approach in which instead of information being encoded in Hawking radiation, it is conserved inside the black hole until it gradually evaporates to Plank size (theoretically the smallest possible size of a system) after which the entire information is given out in a burst[10 13]. And as the size of the black hole is really small ($\approx 1.616255\,(18) \times 10^{35}\ m$), unlike in the previous solution, it neither violates causality nor locality.

This approach does not violate the principles of relativity or quantum mechanics but it poses a problem. While the energy of a Planck size black hole is very small, the information is present in large magnitudes. Initially a black hole is very large and has a large amount of information. And as the information is not emitted in radiation and remains inside the black hole, a Planck size hole has low energy but high quantities of information. The only possible way to emit such quantities of information is not by a sudden burst but by a very slow process of radiating energy that exceeds the lifespan of the Universe. This gives rise to long-term remnants of black holes from which we may not be able to retrieve complete information in practice[10 13].

Also, thermodynamic objects with finite size and energy can contain only certain limit of information given by the Bekenstein bound (equation 17).

$$S \leq \frac{2\pi kRE}{\hbar c} \tag{17}$$

Where, S is the entropy of the object, K is Boltzmann's constant, R is the radius, $\hbar$ is Planck constant and c is the speed of light in vacuum.

And as a Planck-size black hole is very small and has low energy it needs to violate the Bekenstein bound to possess arbitrarily large amounts of information.

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Information is stored in a Planck-size remnant

One way to overcome the above violations is to consider that the semiclassical theory of gravity (an approximation of quantum gravity from which hawking radiation is formulated) fails for Planck-size remnants[10]. This is true because of the size of the remnant. Due to its small size, it can be considered as a particle. And quantum process, such as quantum fluctuations, can have drastic implications on particle. And as we do not have a comprehensive theory of quantum gravity, we cannot exactly predict what happens to a Planck-size remnant. But we can consider a possibility in which quantum process terminate Hawking radiation and give rise to stable Planck-size remnants in which information is conserved.

This solution does not violate the Bekenstein bound or casualty but has one major obstacle. In order to conserve an arbitrarily large amount of information, due to their relatively small size, Planck-size remnants must possess infinite number of internal states[10 13].

One suggestion to overcome this problem is that a large black hole can leave behind an infinite number of these remnants so that each one has a finite number of states.

Information is conserved in Large-size remnants

Another possibility is that, as the entropy of a black hole called the Bekenstein-Hawking entropy depends on the size of the event horizon (the surface area) and increases with the increase in the surface area (given by equation 18)

$$S_{bh} = \frac{\pi A k c^3}{2hG} \tag{18}$$

we can say that instead of a stable Planck-size remnant, we have a large remnant whose surface area increases with the increase in entropy and consequently with the increase in information. This solution does not require infinite internal states but has one major problem- in order for a large stable remnant to be greater than Planck-size it needs to violate semiclassical theory of gravity, specifically Hawking radiation, to not radiate energy as it predicts that blackholes must radiate energy in the form of Hawking radiation.

Information is encoded on the event horizon

Another solution can be developed from the previous argument that the entropy of a black hole depends on the size of its event horizon and not its volume- the holographic principle.

It arises from the AdS/CFT conjecture, also known as the gauge/gravity duality, which states that it is possible to encode information of d+1 dimensional objects (three-dimensional) in a d-dimensional space (two-dimensional surface), similar to how a hologram stores information of three-dimensional objects on a two-dimensional surface. According to the conjecture, the information of a black hole, a three-dimensional object, does not fall into the black hole with the in falling particle of hawking radiation but is copied onto the event horizon, a two-dimensional surface, forming a stretched horizon[14]. This allows the information to exist in a lightlike space, not violating causality or unitary evolution, resolving the paradox.

According to quantum mechanics and more precisely the no-cloning theorem, information cannot be copied. But in the holographic principal information is copied onto the event horizon. At first it may seem like the no-cloning theorem is being violated, but that is not the case. This is because even though there are two sets of the information- one outside the event horizon and one inside, at any given time both copies cannot be observed by one single observer. It was argued that one copy is only seen by an observer falling into the black hole while the other by an observer outside the black hole[14]. This is called the black hole complementary. It tells us that as the copies of information cannot be observed and transmitted between two or more observes, the no-cloning theorem is not violated, and unitary evolution is possible.

Even though the holographic principle and black hole complementary are successful in not violating causality or unitary evolution, they do have their drawbacks, one of which is the violation of locality.

Information is conserved in a Baby Universe

There is one more possibility in which information can be conserved by neither radiating nor containing information but sending it to another Universe called ‘Baby universe’[10]. Though this possibility is very rare, it is still possible due to the singularity that exists inside a black hole. As the singularity is infinitely dense, an extreme curvature of spacetime is possible which can extend into another Universe through the Einstein-Rosen bridge or a wormhole (Figure 2). According to this approach the information that falls into a black hole passes through the worm hole into another Universe, which unlike ours, is small in size (from which it gets its name, ’Baby Universe’).

And as this universe is causally disconnected from ours, information is lost in our Universe but is conserved in another. The most attractive feature of this solution is that it does not violate any principle except that it is difficult to prove its existence.

Apart from these solutions there have been many attempts to resolve the paradox but none have found a definite solution. And if all the proposed solutions seem to fail, then there are two more possibilities. One is that either information is irretrievably lost and we have to drastically modify our understanding of quantum mechanics or Hawking radiation is not a

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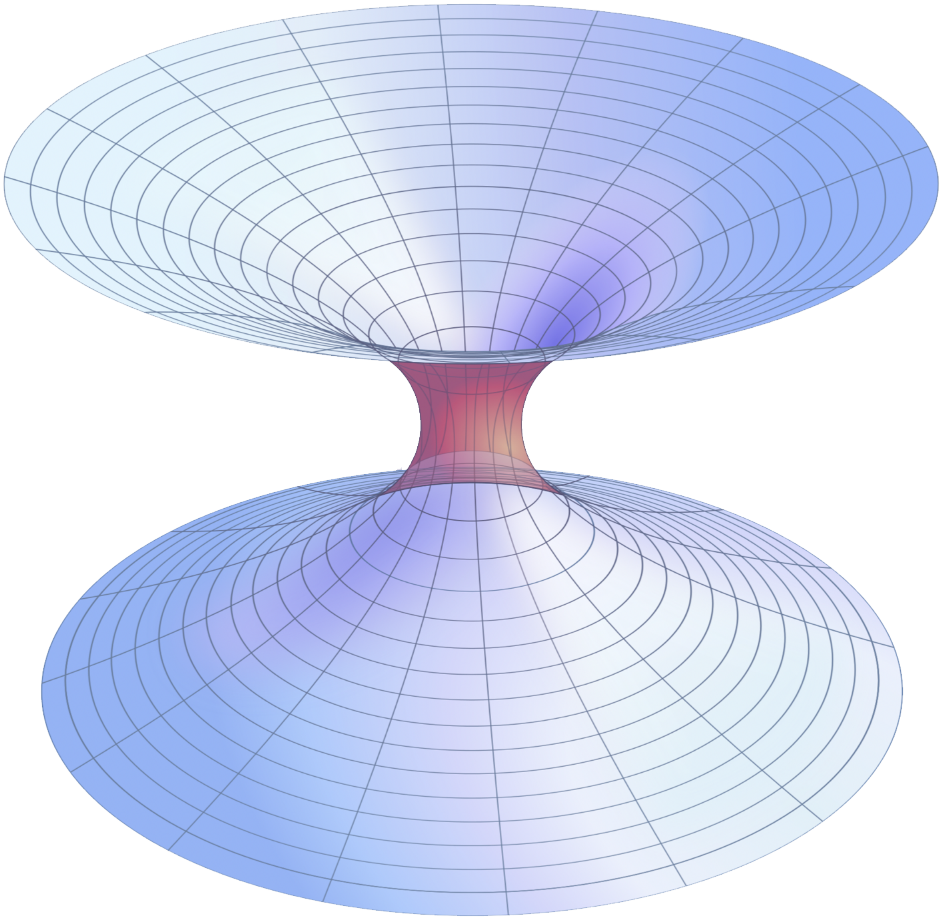

Fig. 2 Wormhole | Embedding diagram of Einstein-Rosen bridge.

real phenomenon and the paradox never existed. But as quantum mechanics and Hawking radiation are really promising theories and work well with our framework of reality, it is possible that if the solutions are incorrect then there are other possibilities that can reveal something unanticipated when discovered.

Discussion

In this paper, we have discussed about the information paradox, beginning with the idea of four-dimensional spacetime and a special case of extreme curvature which results in regions of space from where no object can escape called a black hole. Later we refuted the previous claim and showed that some particles due to quantum phenomena (quantum fluctuations and creation of virtual particles) can indeed escape a black hole called hawking radiation and give them temperature, entropy and make them thermodynamic objects. Apart from giving temperature, we also saw that Hawking radiation attributes a huge problem to black holes called the information paradox and provided a summary of few attempts that have been made to resolve it from which we can deduce three possible outcomes- either locality, causality or unitary evolution must be violated to conserve information[15]. And according to current theories the most plausible conclusion is that causality is violated and the correlation between the radiated particles exists and information is conserved. Either way, there is no telling of what is the solution to the paradox, until maybe the formulation of quantum gravity- a theory which unifies gravity and quantum mechanics. After whose development, we may revise our current theories such as quantum mechanics or theory of relativity or even entirely change our perception of the Universe.

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