Analyzing Hawking's Black Hole Information Paradox and the Black Hole Firewall Paradox

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***Abstract*— this paper aims at explaining the complicated concepts and phenomenon associated with the Information and Firewall Paradoxes of Black Holes. The research has been described in a manner that explanations can be grasped by people with a rudimentary knowledge of physics as well. For the same purpose, a negligible amount of math has been provided for ease of understanding. The main purpose served by this text is to introduce the quantum nature of the universe to youngsters through the pretext of Black Holes and provide them with a basic understanding of these intriguing subjects. Not all the problems communicated through the course of this paper have been solved, which in fact, makes it a lot more interesting. The hope remains constant that this piece of literature provides the basic insights into quantum concepts to future scientists who in turn contribute to the solving of these problems.**

Keywords*— Black holes; information paradox; black hole firewalls;

I. UNDERSTANDING QUANTUM PHYSICS (SOME BASIC CONCEPTS)

1. Principle Of Equivalence (No Drama): This principle was the most important building block for Einstein's General Theory of Relativity. This states that the gravitational mass of an object is equal to its inertial mass. Simply put, this means that there is no difference between an object undergoing acceleration due to gravity and an object in an accelerating frame of reference. To the observer, the 2 scenarios are indistinguishable. This simple but profound statement has large implications when it comes to Black Holes. Equivalence is also called no drama.

2. Quantum Vacuum: Most of us understand the concept of vacuum in a general sense- empty space. However, quantum vacuum is a bit different and it is, by no means, empty. When a space is considered to be part of a quantum vacuum, virtual particles are coming into of existence in pairs and annihilating one another almost instantaneously. Thus, even a vacuum is bubbling with activity. As these particles are formed from nothing, they have completely opposing properties. Thus, while one particle would have positive charge, spin and mass, the other would have negative charge, spin and mass. As a result, mass and angular momentum are conserved as well.

3. Quantum Entanglement: Einstein had described this phenomena as "spooky action at a distance". The entire concept is beyond the scope of this paper and so, only required sections of this idea have been provided. In the section of Quantum Vacuum you may have observed that particles have opposing properties. Thus, if we were to find and examine one particle, we would know for sure the properties of the other. Thus, it is said that the properties of the particles are entangled with one another and in a broader sense, it can be said that the particles are entangled with each other.

4. Quantum Information: Each and every object around us is made of the same elementary particles: electrons, neutrons and protons (the last two can be further broken down into quarks). Thus, what makes each object around us unique is the way these elementary particles are arranged. This arrangement is encoded in the form of Information. At the quantum level, this is called quantum Information. Quantum Information has been hereby referred to as Information.

5. Locality: Locality is a bit different from the rest of the above explained concepts. We know for a fact that a particle cannot disappear somewhere and reappear somewhere else. It has to travel through space with time to reach its destination. Similarly, a tennis ball doesn't disappear at one side of the court to reappear at the other side and light doesn't appear in the room all at once (though it can seem to do so due to its high speed). This is the property of locality. The effects of an event aren't seen all over the universe all at once, they travel locally to reach different points in space.

6. Quantum Gravity: Gravity is a concept of classical mechanics- a branch of physics handed to us by scientific prodigies like Isaac Newton, James Maxwell and Albert Einstein. It successfully explains and predicts universal phenomena at a macro scale (stars and galaxies). On the other hand, quantum theory- a branch of physics revolutionized by scientists like Erwin Schrodinger and Richard Feynman- satisfies the universe at a micro scale (bosons and quarks). However, the 2 theories have proven to be immensely difficult to combine. We still find ourselves looking for a unified theory of everything that explains all phenomena- micro and macro- successfully. The top contender for the same is string theory, however, this theory too has shown no conclusive indications of being true yet.

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II. INTRODUCTION TO BLACK HOLES

1. What Are Black Holes?

Black Holes are objects in the universe with a mass that approaches infinity. Due to this they have a very high density as a lot of mass is packed into a tiny space. Their high mass provides them with a very high force of gravity.

Each object with a large mass exerts a strong force of gravity (such as Earth and the Sun). However, for each force of gravity there exists an escape velocity. If an object attains this velocity it can break free from this gravitational force. Rockets have to attain the escape velocity of Earth (roughly 11,186 ms^{-1}) to break free from Earth's gravitational pull and enter outer space.

Einstein, in his General Theory of Relativity had stated that nothing can have a velocity faster than that of light (the velocity of light is roughly $3x10^8$ ms^{-1}). Thus, if a body were to exert a gravitational force which has an escape velocity greater than that of light, no object- not even light- would be able to escape its gravity. This body is called a Black Hole. As a result, not even light that enters a Black Hole escapes it. This is why, Black Holes appear dark. Black Holes have an exterior boundary called the Event Horizon. Any object that goes past this Event Horizon becomes incapable of defending itself from the gravity of Black Holes.

2. How Are Black Holes Formed?

The stars we see in the night sky were initially formed from collapsing clouds of gas and dust. As the star is formed it enters a state of equilibrium. The nuclear fusion taking place in the star counters the massive gravitational force exerted on the star by its own core. The nuclear fusion taking place inside the star eventually gives rise to the formation of cores consisting of heavier metals (like iron).

Millions of years later, when the energy provided by nuclear fusion gets overpowered by the core's gravity, the star starts to collapse onto itself. It keeps collapsing until all the mass of the star gets packed in a very tiny volume. This star with very high mass and extremely low volume is called a Black Hole.

3. Black Holes and Space-Time:

Take a stretched rubber sheet. Next, drop a bowling ball onto this sheet. You'll notice that at the spot the ball is dropped, a curve is formed. Further, take a few marbles and roll them over the sheet with some velocity. We start to notice that the marbles start circling the bowling ball and eventually fall into it the groove it forms. After this, increase the mass of the placed bowling ball. We find that the curve gets steeper. If we were to reduce the size of the ball and increase the mass we would notice that the curve starts to get steeper and sharper. Theoretically, we could hence approach a size and mass of the ball such that the curve becomes a trench with an end which has a size that approaches zero just before tearing the sheet.

This trench is exactly how a Black Hole looks like. In his Theory of General Relativity, Einstein proposed that the universe was like a stretched rubber sheet called the space-time continuum. All bodies of considerable mass are able to introduce dents in this rubber sheet. Extrapolating on this idea, we find that if an object with high mass and low volume were to be placed on this sheet we would obtain a trench-like groove on the sheet with a very small end-point. This end point in Black Holes is called the space-time Singularity.

4. The Space-Time Singularity:

The most important property of the Singularity is its inevitability. Any object that crosses that Event Horizon will encounter the Singularity mandatorily. It is the point in the Black Hole where the disintegration of the body into its elementary particles is complete. Trying to avoid the Singularity is equivalent to saying that we are trying to avoid next Thursday- it is simply impossible.

III. TOWARDS HAWKING'S INFORMATION PARADOX

1. Hawking Radiation:

Outer space is considered in a state of quantum vacuum. As a result, particles are repeatedly coming in and out of existence. Naturally, this phenomenon also extends to the region near the Event Horizon. This brings upon implications that were first posited by Stephen Hawking. He stated that the virtual particles that come into existence at the Event Horizon are at times, torn apart from one another due to the strong gravitational effects of the Black Hole. Of the positive and negative particles formed due to the Quantum Vacuum, the negative particle succumbs to the Black Hole's gravity and falls towards the Singularity. The positive particle is seen being emitted as radiation from the Black Hole. This is known as Hawking Radiation. The negative particle which enters the Black Hole reduces the Black Hole's mass. As a result Black Holes evaporate over a very long astronomical time frame (for a large Black Hole, time taken to evaporate is of the order 10^{67} years).

2. Stepping Inside A Black Hole:

It is pretty evident that if an object were to cross the Event Horizon, it would eventually be ripped to shreds due to its massive gravity. This process, as Kip Thorne called it, is termed spaghettification. It is theorized that when an object enters the Event Horizon of an astronomically large Black Hole, at first the body experiences nothing. However, as time progresses, the body starts to feel a strong tug. As one end of the body is closer to the Singularity than the other, the body is stretched vertically (as gravity is stronger on the closer end of the body than the farther) and at the same time, it is compressed horizontally. The object is then ripped to shreds and is reduced to its elementary particles.

3. The Information Paradox:

The concept of Information is one of great interest in Quantum Physics. Hence, the question of what happens to Information in a Black Hole was one of great importance. Stephen Hawking had initially theorized that Information is lost inside a Black Hole. However, a fundamental law of Quantum Physics states that Information can never be lost. This called the Law of Conservation of Information.

It is considered in Quantum Physics that each event that occurs in the universe can be reversed, at least in principle. For example, if we were to make curd out of milk (which is a chemical process), Quantum Physics suggests that we could turn the curd back to milk if we had the Information of each particle involved in the event. A simple implication of this phenomenon is that each event has a unique outcome. If we were to conduct 2 different events, we will have 2 different outcomes. The slightest of changes in the conditions of the event will also give separate unique outcomes which will be revealed by the Information of the particles in the outcome.

Extending this concept to a Black Hole, we find a contradiction. Each object is made of the same elementary particles and hence, each object will be reduced to the same particles on reaching the Singularity. Thus, different objects will yield the same end products and so, different events will give us the same outcome. So, there is no way to know what makes the Black Hole and what went inside even when it evaporates. This presents us with a conflict with Conservation of Information. Stephen Hawking had proposed that Information was indeed lost inside a Black Hole. He said that Information was in principle radiated out of the Black Hole via Hawking Radiation but it is too scrambled to make sense out of. Kip Thorne agreed with Hawking. However, John Preskill- a celebrated particle physicist at California Institute of Technology- wasn't impressed with this theory. He stated that this Information could be accessed in methods not known to man yet. He felt that physicists would have to come up with a theory of quantum gravity to decrypt this Information. For the same reason, John Preskill, Stephen Hawking and Kip Thorne had famously made a bet to as to who will be proven right in the future.

IV. THE MENU OF HELL

1. Joe Polchinski's Assessment:

In Quantum Physics, 3 rules are held dear by physicists. These are: Equivalence, Conservation of Information and Locality. With his work, the physicist Joe Polchinski, proved that if we accept Stephen Hawking's theories of Black Holes to be correct, one of these 3 precepts would have to be negated.

2. The AMPS Argument & Black Hole Firewalls:

This contradiction arose when Polchinski conducted a few thought experiments along with a few colleagues to examine the underlying assumptions in Hawking's theory.

These assessments arose out of a contradiction in Quantum Theory by physicists Don Page and Leonard Susskind. They stated that the particle emitted as Hawking Radiation at exactly half the lifetime of the Black Hole would have to be entangled with all the particles ever radiated by the Black Hole. This idea was at odds with the principle of Monogamy, which states that a particle cannot be entangled with more than one independent quantum system.

An important solution given at the time to resolve the above mentioned contradiction was to account for the presence of a hot wall of radiation at the Event Horizon; a firewall. However, this meant sacking Einstein's Principle of Equivalence.

The idea of sacrificing one between Equivalence, Conservation of Information and Locality shook the world of physics. This was called the "menu of hell". Physicists couldn't agree which one should be incorrect and a number of different solutions were offered for the same. However, scientists weren't able to come up with a common theory agreed upon by everyone. A few of them have been listed below.

V. SOLUTIONS:

1. Giving Up Conservation of Information:

The easiest way to look at this is that perhaps Information is actually permanently lost in a Black Hole. However, even if this is the case, no one yet has been able to come up with a consistent theoretical framework for this to be correct.

2. Sacrificing Equivalence:

According to the principle of Equivalence, a body entering a large Black Hole would experience nothing unusual before the effects of gravity kick in (except for the fact that the rest of the universe will move in fast forward with respect to it). If we were to give up Equivalence, we would be able to conclude that this isn't really the case.

We know that Black Holes emit radiation. This radiation is viewed in the form of low energy photons coming out of the Black Hole. If Equivalence weren't present, we would be able to say conclusively that the body won't even get the chance to be spaghettified. It would be burnt by a wall of radiation at the Event Horizon itself. This is because, the origin of the low energy photon can be traced back to a high energy photon at the Event Horizon. Thus, a wall of fire would be present just inside the Event Horizon (as all low energy photons emitted can be traced back to the Event Horizon).

3. Dethroning Locality:

Keeping in mind the large repercussions of yielding Equivalence and Conservation of Information, it is speculated that locality is the answer to our problems. In fact, a number of thought experiments and theories have been developed discussing the implications of sacking locality.

VI. THOUGHT EXPERIMENTS AND FIREWALLS:

After Black Hole firewalls were proposed, a number of scientists came up with theories to compete with this hypothesis. None of these theories have gathered any substantial proof and it is ever so likely that the true nature of Black Holes hasn't been theorized yet. A few of the most popular theories have been provided below.

1. The Holographic Principle:

This is perhaps the most outrageous idea that emerges out of understanding Black Holes. This is the idea that lays the foundation for the notion that we are living in a simulation.

It is observed that whenever any object enters a Black Hole, the Black Hole slightly expands. Due to this, there is also an increase in the surface area of the Event Horizon. It has been proposed that all the Information of the bodies entering the Black Hole are compressed into 2 dimensions and are stored on the surface of the Event Horizon itself. This implies that all the Information of the universe has the potential of being compressed into a dimension lesser than what we perceive. This way Information is encoded on the surface of the Black Hole itself.

However, this theory leaves the door open for a very troubling possibility. Building on this idea we can say that perhaps, all the Information of the observable universe- including us- is actually present on a flat screen and the objects we perceive as 3 dimensional is actually just 2 dimensional Information being perceived as a hologram.

Rather than going against the laws of physics, this notion goes against the constraints of intuition, which is what makes it overly intriguing.

2. Black Hole Complementarity:

In 1927, Neils Bohr postulated that each particle had sets of complementary properties that couldn't be measured simultaneously at any point in time. This was known as the Bohr Complementarity Principle.

Similarly, there exists a proposed complementarity principle for Black Holes as well. This idea states that there can exist 2 complementary explanations (that is to say, very different explanations) for the event of a body entering a Black Hole as long as both observers can never compare their observations

Leonard Susskind stated that to an in falling observer, nothing special would happen at the Event Horizon. The body would simply float towards the inevitable Singularity. However, to an observer watching from outside, the body would never actually cross the Event Horizon. This happens due to the extreme effects of gravity of the Black Hole. The time dilation caused by the Black Hole makes it seem as if the in falling body has slowed down and it would take an infinite amount of time for the body to actually enter the Black Hole (as seen from outside).

Instead of crossing the Event Horizon, the body would be absorbed by a membrane present just outside this horizon. On the other hand, the first observer would move towards the Singularity and would notice no change in space or time as compared to the rest of outer space.

3. ER=EPR:

Albert Einstein, Nathan Rosen and Boris Podolski (EPR) were 3 physicists who first laid Entanglement at the center stage of Quantum Physics. Shortly after this hypothesis was made, Einstein and Rosen (ER) came up with another theory. They stated that keeping in mind the flexible nature of space-time, it is a theoretical possibility of having bridges that connect 2 widely positioned locations in space-time. These bridges were called Einstein-Rosen Bridges and later came to be known as wormholes. It is also speculated that Black Holes are essentially the gateways to these wormholes.

Studying these 2 concepts, Leonard Susskind postulated that the 2 concepts- Entanglement and wormholes- were essentially the same. He posited that these wormholes were present between all pairs of entangled particles. This meant, in practice there are virtual bridges that extend across space-time that connect all entangled particles.

VII. CONCLUSION:

Black Holes, by large, are one of the most misunderstood concepts in physics today. A brief overlook reveals Black Holes to be a highly complicated species of the universe. However, what one fails to understand is that Black Holes provide a gateway to understanding the most fundamental aspects of the physical and quantum world.

It takes large amounts of time (amounts we don't even have units for) for Black Holes to evaporate and so it remains uncertain as to whether humankind will ever be able to examine the remains of a Black Hole (if there are any). This paves the way for crazy theories that force us to examine the most basic assumptions in science.

Each and every measurable quantity and physical concept boils down to 2 very fundamental absolutes: space and time. Einstein's Theory of Relativity played a huge role in the modern understanding of the 2 concepts. In fact, this theory successfully unified these two. Further, the development of Quantum Physics, mechanics and astrophysics provides deeper insights into these absolutes. But, what if we have been mistaken all along? Einstein provided a framework for space and time to be dynamic- it can be twisted and turned and warped. Thus, can we say that something a lot more fundamental is at work here? Is there another quantity we haven't been aware of that further constitutes space and time? There's a good chance that this field of study would dramatically

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violate all of Quantum Physics. But, Quantum Physics too was a dramatic violation of Classical Physics, which in turn had violated previous schools of thought.

The search for such a quantity might finally bring us the answers to science's biggest questions- quantum gravity, the Information Paradox and whatnot. In a way, Black Holes are actually the simplest entities in the universe, it's just that we have been looking at them all wrong.

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