Science Fair Information Paradox on Hawking Radiation

Idea Of Hawking Radiation -(Jan 2-3)

A black hole is a region of space-time with an event horizon from which nothing can escape. Hawking radiation makes black holes behave like hot objects that very slowly lose mass, eventually evaporating. If a black hole fully evaporates via Hawking radiation and the outgoing radiation carries no imprint of what fell in, then all that information is permanently erased.

- Hawking radiation is a quantum effect near black holes, where anti-particle pairs at the event horizon lead to black holes very slowly losing mass and energy over time.
- What appears to be empty space is actually filled with fluctuating quantum fields that produce anti-particle pairs.
- Near a black hole's event horizon, one of these particles can fall in, which is negatively charged, while the other escapes, which is a photon, making the black hole lose a tiny amount of energy and mass. This is called Hawking's radiation.

Role Of Einstein and Hawking

- Einstein's work on space-time curvature predicts black holes, while Hawking's work applies quantum field theory to these curved backgrounds, leading to the prediction that black holes can radiate.

Consequences For Black Holes

- Because Hawking's radiation carries away energy, the black hole mass diminishes over an extremely long time, leading to the idea that black holes can actually evaporate.
- The effect is described as incredibly small for astrophysical black holes. This means that any complete evaporation would take far longer than the current age of the universe.

Why This Matters in Physics

Hawking radiation is a bridge between quantum mechanics, thermodynamics, and general relativity. Understanding this process is very important for resolving deeper puzzles, such as what happens to information that falls into a black hole.

- Hawking radiation only exists when both quantum mechanics and general relativity are considered together.
- The negative energy particle falls in; the positive energy one escapes as radiation; and the black hole loses energy/mass.
- Very small black holes from the early universe could be evaporating now, but no Hawking radiation signal has been detected yet.

Hawking radiation, therefore, is still a theoretical prediction. However, experiments in lab systems show promising, similar effects.

Paradoxes

- Evaporation appears to destroy information about the matter that formed in a black hole.
- This leads to the Information Paradox: After complete evaporation, nothing seems to encode the initial state.

Universe Today Podcast - Does Hawking radiation even exist? (Jan 24-26)

Hawking Radiation is not universally accepted, as it's a hypothesis made by Steven Hawking and has not been detected yet.

- Every aspect of Hawking Radiation aligns with the theory of how black holes function.

- Detecting Hawking Radiation is quite difficult because of time scales and the distances between us and black holes. For time scales, most black holes will take millions or billions of years to evaporate enough radiation to be visible in space. In space, everything is so vast and distant that it's extremely difficult to collect data from places outside our solar system and the universe.

- One of the theories created to detect Hawking Radiation was through primordial black holes w(black holes which were created close to the time of the theorized Big Bang). Smaller primordial black holes will generate more Hawking Radiation and are closer to being fully evaporated.

- Another theory is through colliders and how smashing atoms together can create a black hole for a short amount of time. These theorized black holes could evaporate in a detectable Hawking Radiation. It will be tested soon in the Large Hadron Collider. Theoretically, the Large Hadron Collider could produce microscopic black holes, if extra dimensions exist, but these would immediately evaporate due to Hawkings Radiation.

Although Hawking Radiation follows all of our known scientific laws, it has not been confirmed by scientific theory. The steps of testing the hypothesis and verifying our theory remain.

? - How it works

- Quantum fluctuations: "empty space" has tiny particle-antiparticle pairs that constantly pop in and out of existence
- At the event horizon, one particle falls in, and another can escape
- The particle that falls in reduces the black hole's energy
- Smaller black holes are hotter and therefore emit more radiation

Black Hole Radiation Information Paradox (Feb 4)

In Stephen Hawking's original theory, Hawking Radiation is predicted to be completely thermal, so the information that goes in never comes out of the black hole and is lost. This causes a conflict in Quantum Mechanics. Quantum Mechanics says that information can never be destroyed. As long as you know the state of every particle in the system, you should be able to see how it started. This is called unitarity.

- General Relativity says that anything that crosses a black hole's event horizon is gone forever.
- The Problem**:** Hawking's original math suggested that the radiation coming out was "thermal"—meaning it was completely random and carried no information about the stuff that fell in (like a book, a star, or an astronaut).

The Paradox**:** If the black hole disappears and the radiation it left behind is random, the information that fell in has been erased from the universe. This violates the fundamental laws of physics.

Basic String Theory (Feb 10)

String theory is a concept that merges quantum mechanics and Albert Einstein's general theory of relativity. It turns subatomic particles like electrons into string-like structures that can be wrapped around to turn into a circle.

- These strings can vibrate, creating a particular shape
- Each mode of vibration is theorized to correspond to a particle with properties such as mass or charge
- String theory is heavily connected to the holographic principle. String theory can count the microscopic state of some black holes, as the idea turns the event horizon into a specific configuration of strings.
- This leads to the conclusion that the number of states depends on the area of the black hole's surface rather than volume, which is exactly what the holographic principle states: "The information in a region of space is stored on its boundary."

Unfortunately, there is little to no evidence that suggests that string theory is real. It remains a relevant theory used to explain the nature of the world around us, but is completely theoretical.

Theories surrounding the paradox

1. ***The holographic principle*** (https://arxiv.org/abs/hep-th/9409089) -February 14

The concept is that once an object falls into a black hole, its "data" doesn't just vanish into the center; instead, it's encoded onto the surface of the event horizon. Holography is the idea that the 3-dimensional world is a "hologram", hence the name, in which information is encoded on a 2-dimensional surface.

- Though this theory sounds strange, it's backed by the fact that black hole entropy scales with surface area (the event horizon). It makes this theory follow black hole thermodynamics.
- The holographic principle is backed by string theory, in which a higher-dimensional gravitational system can be described by a lower-dimensional, non-gravitational theory.
- This conclusion is found from the theory that the number of states depends on the area of the black hole's surface rather than volume.

2. ***The black hole firewall*** (https://arxiv.org/abs/1207.3123) - February 14

To keep the math of quantum mechanics consistent, some physicists argue that the event horizon isn't a smooth point of no return, rather it is a seething wall of high-energy particles. The firewall proposal, which was introduced by Ahmed Almheiri, Donald Marolf, Joseph Polchinski, and James Sully(AMPS), works, as it includes the concept of unitarity, which ensures that information is not lost when the black hole vanishes. This is achieved by an outgoing Hawking photon that is entangled with all the radiation emitted earlier. It sacrifices the equivalence principle of general relativity to save quantum unitarity.

3. ***Black Hole Complementarity*** (bhcomplementarity_PSA_sub.pdf) - February 15

A theory proposed by Leonard Susskind, Lárus Thorlacius, and John Uglum, theoretical physicists in the 1990s. It focuses on the idea of different perspectives not being able to contradict each other and how information is never destroyed, but no perspective can access both copies.

- From the outside, the information looks stretched on the event horizon, and matter never seems to go inside the black hole. The information seems to be encoded on the horizon and later in Hawking Radiation. Tiny correlations encode the information in quantum-gravity corrections but aren't visible to an observer.
- On the inside, the quantum state of the matter continues inward, and the information goes inside the black hole.
- The two different descriptions don't match, so there is no one answer about the information that doesn't violate quantum mechanics. However, no observer can access both descriptions.

The Complementarity theory basically states that the information is both on the horizon and inside the black hole, but no one sees a violation of physics.

4. ***Soft Hair*** (Physics - Black Holes Have Soft Quantum Hair) - February 16

A theory made by Stephen Hawking, Malcolm Perry, Andrew Strominger, and Sasha Haco in 2016. It proposes the idea that low-energy quantum excitations (photons and gravitons) on the event horizon can store information.

- Even though Stephen Hawking initially proposed the idea that information is destroyed, he helped generate a new solution in which the event horizon's photons and gravitons can store information. Then they can release the information back out as the black hole evaporates.
- It also indirectly challenges Einstein's general theory of relativity, which states that black holes are only described by their mass, charge, and angular momentum.
- Despite this, there is one major contradiction. As the black hole evaporates and shrinks, it must lose hair because the entropy of the hair cannot be greater than the entropy of the black hole. Once a black hole becomes very small, its limited amount of hair may be insufficient to maintain the necessary information decoupling.

5. ***Black Hole Remnants*** (The Case For Black Hole Remnants) - February 16

This idea takes a different approach to the information paradox as it proposes that the black hole never fully evaporates and stops shrinking at an extremely small size. The black hole will leave behind a dense object that contains the information.

- It centralizes on the idea that evaporation will stop because quantum-gravity effects become stronger at a small-scale.
- However, scientists criticize that remnants would require an infinite number of internal states to store random information, raising stability concerns.
- There are various theories on how a black hole can become a remnant. One of them being that evaporation stops when the black hole reaches Planck mass (the small mass point at which gravity becomes strong at the quantum level).

It is an interesting take on the paradox, as it changes the end state but does not drastically affect the way the event horizon works.

6. ***ER=EPR, Einstein-Rosen bridges*** (Compressed EPR Paradox link) - February 17

Proposed by Maldacena and Susskind, the ER = EPR theory might just be the most fascinating. The idea is that EPR (entanglement) and ER (wormholes) aren't separate, but each entangled particle-pair is connected by a small, non-movable wormhole. In the context of Hawking Radiation, the radiation is "entangled" with the interior of the black hole, meaning that there are wormhole connections between the radiation and the black hole. These wormholes allow information to still be stored in the entanglement between the black hole and its radiation.

- Entangled pairs are basically connected particles that have no visible link.
- If the emitted Hawking Radiation is entangled with the particle that fell into the black hole, it has a wormhole connection between the two.
- The theory is that the information is encoded inside the wormhole's structure, and as evaporation occurs, the information is never lost.

Although fascinating, this idea lacks evidence from quantum gravity and questions how spacetime emerges from entanglement networks.

7. ***Information Loss* - February 17**

This is the original theory created by Stephen Hawking when he first proposed Hawking Radiation. It created ideas as to how Hawking Radiation could exist without conflicting with quantum mechanics. In this idea, the thermal radiation that is released from black holes will no longer contain the information encoded in the matter that originally fell in. Therefore, if the black hole completely evaporates through Hawking Radiation, information is lost.

(Feb 25-28)

The Holographic Principle	*Supporting Information:*
	
	• Provides a solution to the information paradox and preserves unitarity
	
	• Is extremely supported by string theory
	    ○ It claims that the information in a region of space is stored on its boundary.
	
	• Supported by AdS/CFT
	    ○ Anti-de Sitter/Conformal Field Theory
	
	• It follows the Bekenstein-Hawking entropy formula (S=A/4)
	    ○ Suggests information is stored on the horizon
		Information Challenging:
		
		• Is based on a completely theoretical concept
		
		• Ads/CFT applies to a specific universe (anti-de Sitter space), so it may not apply to others.
		
		• Does not explain how information escapes in Hawking Radiation, only describes the fact that it's encoded on the horizon.
		
		• If this theory is true, it suggests that reality is all holographic
		    ○ Not experimentally verified

Black Hole Firewall	*Supporting Information:* • Provides a solution to the information paradox and preserves unitarity • The AMPS paper argues that the event horizon must not be smooth and must instead be a violent "firewall" of high-energy particles.	*Information Challenging:* • Violates Einstein's equivalence principle, which is a fundamental part of general relativity. • Relies on assumptions • Creates a new question: "Why would the consistent event horizon become a region full of energy?"
Black Hole Complementary	*Supporting Information:* • Provides a solution to the information paradox and preserves unitarity • Avoids new questions by limiting what one observer can see • Supported by the holographic principle, as it suggests information is stored outside.	*Information Challenging:* • Lacks any mathematical evidence to support it ○ It's seen as a philosophical solution rather than a clear scientific one • No observer being able to see both descriptions gives no deep explanation. • The information is essentially cloned, which violates the no-cloning theorem
Soft Hair	*Supporting Information:* • Provides a solution to the information paradox and preserves unitarity • It fits perfectly with known physics and quantum mechanics	*Information Challenging:* • Once a black hole becomes very small, its limited amount of hair may be insufficient to maintain the necessary information decoupling. • Unknown whether "soft hair" can store enough information • Critics argue that it only stores limited information, not the full quantum state of matter

Black Hole Remnants	*Supporting Information:* ● Provides a solution to the information paradox and preserves unitarity ● Follows various frameworks/models ○ Quantum gravity scenarios predict that evaporation can be stopped.	*Information Challenging:* ● Would possibly need an infinite number of internal states despite a small mass. ○ The high amount of information in a small mass would cause instability. ● Conflicts with Hawking Radiation calculations ○ Original calculations claim that evaporation continues until fully gone. ● There isn't a specific way the black hole will turn into a remnant, leaving more open questions
ER = EPR **Einstein-Rosen bridges**	*Supporting Information:* ● Provides a solution to the information paradox and preserves unitarity ● Follows holographic theoretical models ● Karl Schwarzschild found that along with the "front", which is the black hole, the math naturally contained a second, "mirrored" part, an anti-black hole, or a white hole. ● In 1935, Albert Einstein and Nathan Rosen realized that these two regions could be mathematically joined with a "bridge."	*Information Challenging:* ● Extremely unstable. It collapses or pinches off faster than even a beam of light can travel through it. ● To prevent the throat from closing, the bridge would need to be held together by a form of matter with negative energy density. ● The original Einstein-Rosen Bridge is "dynamic," meaning that it doesn't just sit there like a tunnel. ● John Wheeler and Robert Fuller proved that an Einstein-Rosen Bridge grows and collapses so fast that even a single photon moving at the speed of light cannot pass through.
Information Lost	*Supporting Information:* ● Avoids Firewall paradox ● Mathematical Simplicity ● Hawking relied on the "no-hair" theorem, which states that a black hole is characterized entirely by its mass, charge, and angular momentum. ● Since all other information is swallowed and the black hole eventually evaporates, the resulting radiation contains no record of what fell in.	*Information Challenging:* ● Doesn't provide a solution to the black hole information paradox and doesn't preserve unitarity. ● Contradiction with known physics ● If quantum mechanics is correct, this argument must be wrong because it leads to an impossible outcome.

Problem - Not using - December 28, 2025

Hawking Radiation is a theory describing the process of black holes emitting radiation over time and consequently losing mass. The idea of Hawking Radiation has been entertained for decades, yet more theories are established as the years go by. This project addresses these propositions and will determine which of them is the most likely to be real based on various laws of physics and formulas created by scientists. The research aims to also clear misconceptions about the original theory made by Steven Hawking, as misinformation about it has been spread throughout the scientific community.

New Problem? - February 7, 2026

Black holes are celestial bodies in which the gravity is strong enough that almost nothing can escape. In 1974, Stephen Hawking theorized that black holes emit a glow, called Hawking Radiation, due to quantum effects at the event horizon. However, this radiation seems to be entirely thermal, meaning it carries no information about the matter that originally fell into the black hole. This conflicts with basic quantum mechanics, as it states that information cannot be destroyed. This project aims to compare various theories about the Information Paradox and find the most reasonable solution.

Method - February 10, 2026

As finding new data on the Information Paradox is not feasible without substantial funding and resources, these steps will focus on existing data and on comparing theories based on scientific principles.

1. Researching the basic properties of black holes, Hawking Radiation, and scientific theory. This step includes learning the process of Hawking Radiation and understanding antiparticle-particle pairs, thermal radiation's relationship to information, and the event horizon.
2. Recognize how the information paradox works.
3. Identify the various theories surrounding the Information Paradox.
4. Evaluate each identified theory based on scientific principles such as basic quantum mechanics laws.
5. Conclude as to which theory best suits the idea of Hawking Radiation and support it using theoretical and existing evidence.

Research

Will include all of the above, excluding the following: Problem, New Problem, Method, and the pros and cons data chart.

Data

Will include the pros and cons data chart.

Conclusion - March 1-2

Which method do we think is the most realistic?

If the world were a hologram based on code, how much would it really change? The holographic principle has been one of the leading solutions to the information paradox in recent years and is by far the most in-depth theory. Every solution has been completely theoretical, but the holographic principle currently brings the most promise.

Other proposed solutions to the information paradox encounter issues with unitarity and leave major gaps in explanations. Beginning with the firewall idea, it does not violate any principles, but turns the event horizon into a very violent wall of high-energy particles, violating Einstein's equivalence principle. Another theory, black hole complementarity, lacks mathematical evidence and is definitely more of a philosophical approach than a physical one. Soft hair and remnant theories both preserve information by storing it in either event horizon particles or leftover objects, yet they both have an extreme risk of instability. The Einstein-Rosen bridge uses entanglement and wormholes, but the bridges are unstable and pinch off too quickly, and there is still no testable model that shows how these wormholes would carry all the information. Finally, Hawking's original information-loss idea, which consequently led to the information paradox, directly violates quantum mechanics, as the infalling information is destroyed.

On the other hand, the holographic principle is only contradicted by uncertainty, with it not violating any principles and avoiding any new violent effects. The idea is that information is encoded on the event horizon, or the boundary, of the black hole. The holographic principle was first proposed by Gerald 't Hooft and was later developed by Leonard Susskind. First of all, the principle claims that the entropy increases with the surface area of the boundary, unlike previous ideas, which had it grow based on volume. This matches the entropy formula of a black hole , which states that the information a region contains is proportional to a black hole's surface area. Moving on to the more difficult connection, AdS/CFT or Anti-de Sitter Space and Conformal Field Theory. Anti-de Sitter Space can be simplified as a universe with unique properties and negative curvature. Mathematically, it can be represented as the shape of a saddle, opposite to the ordinary, flat, expanding universe. Physicists often use the idea of AdS as a tool for theories, as its properties, such as gravity, are much clearer. Conformal Field Theory, on the other hand, can be described as a set of rules on a lower-dimensional surface. Anti-de Sitter Space and

Conformal Field Theory can be compared to a computer game, where AdS is the game itself, and CFT is the code that describes it. This relates to the holographic principle in the fact that it states that a lower-dimensional world with no gravity can be used to describe a higher-dimensional world with gravity. Although the holographic principle has many more concepts to it, its evidence can be mainly based on its relation to surface area entropy and AdS/CFT.

Wrapping back to Hawking radiation, it says that black holes emit thermal particles that do not hold any information about the matter that fell into the black hole, which violates quantum mechanics. The holographic theory counters this by encoding all 3D volume information on a 2D boundary surface, such as the event horizon, matching the Bekenstein-Hawking entropy formula: where S_{BH} is the Bekenstein-Hawking Entropy, A is the area of the event horizon, k_b is the Boltzmann constant, where c is the speed of light, G is the gravitational constant, and h is the reduced Planck constant. Along with that, string theory counting shows black hole entropy scales with horizon area, not volume, aligning holography and suggesting Hawking radiation carries scrambled information.

Based on our extensive research, we have concluded that the holographic principle is the most likely answer to the information paradox. Alternative solutions either conflict with existing fundamental principles or are shallow explanations as to how the theory would function. The holographic principle is the most in-depth explanation and stretches into several areas of physics while remaining functional.

$$S_{BH} = \frac{k_B c^3 A}{4G\hbar}$$

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