>> # ERROR 404:
FILE NOT FOUND

LOADING...

>> AUTHOR CID: 0

>> WORD COUNT: 2986

>> FILE CONTAINS:

MESSAGE 1:

STATUS= SENT

MESSAGE 2:

STATUS= NOT SENT

RETRY ↻ EXIT ✕

>> BEGIN ENCRYPTED MESSAGE 1: “GENERAL UPDATE”

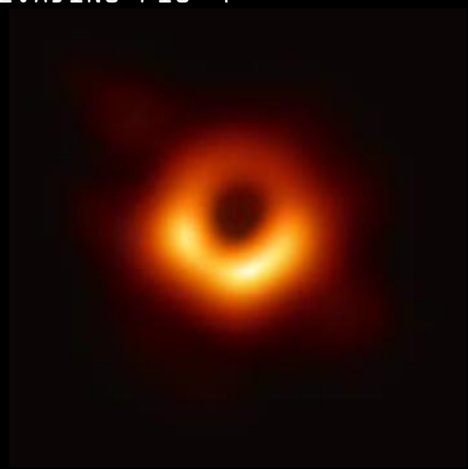
>> 19/06/2071 13:10 P.M.

FROM: INTERGALACTIC EXPLORER (MESSIER 87)

TO: MISSION CONTROL (MILKY WAY)

I don’t mean to alarm you with an unexpected update. I know we were sent on this mission to study quantum fluctuation around the supermassive black hole M87*, Fig. 1, but unfortunately our engines have cut off. We’re currently drifting towards it and haven’t got long before we’re sucked in… but that’s not what I really wanted to say. Instead, I’m here to tell you I’ve solved it! The Black Hole Information Paradox—an idea formed in 1974 that black holes may be deleting information from the universe. The engines have actually been down for weeks now, but I’ve been distracted trying to resolve the paradox while the rest of the crew worked to fix them. All the previous theories were missing a final piece, and I’ve finally figured out what this was.

LOADING FIG. 1



>> Photo taken of M87*’s silhouette in April 2019, using the event horizon telescope.[1]

We’re about 20 minutes from intercepting M87* now, so I’ll quickly remind you guys (almost 100 years later!) of the paradox, before explaining my discovery.

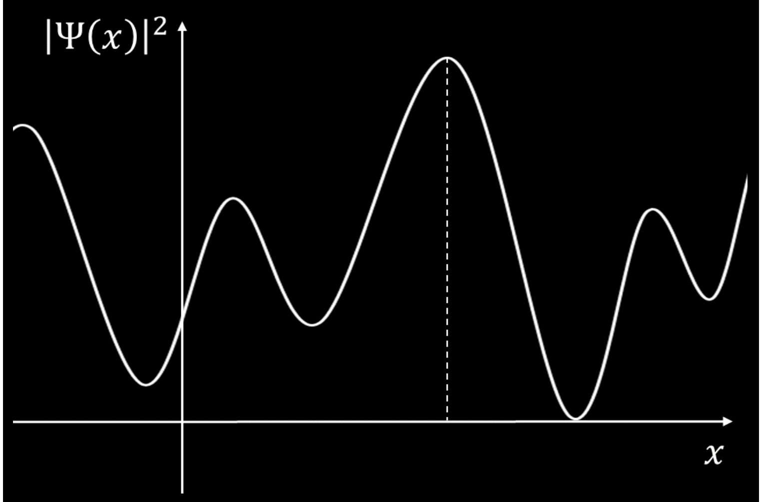
>> QUANTUM INFORMATION...

T MINUS 19 MINUTES TO M87*

The Black Hole Information Paradox is rooted in the concept of information, but what is that actually? Before looking at the idea of quantum information we should first consider what information means in a classical sense. Let’s say I wanted to tell you about how I resolved this paradox: I could send you a message like this, an old-fashioned email, or I could even write you a song. While these all seem like different ideas, they have one thing in common: they are all distinct forms of information. In the same way we use scales to measure mass, information is measured with ‘entropy’. The word entropy gets used a lot, but it has a specific definition in terms of information. If you have studied chemistry, you may have met thermodynamic entropy. This measures the amount of energy per unit temperature that is unavailable to do work in a system. Thermodynamic entropy is linked to information entropy via Landauer’s principle: if information is lost from a system, the observer loses the ability to extract work from it, thereby increasing entropy [3]. So, in information theory, entropy is the amount of uncertainty in a system due to a lack of information.

Now pretend instead that I had resolved this paradox in a dream, but still wanted to tell you about it. I’d have a little more difficulty, as the information this time is pretty much hidden away in my head. If you’ve ever tried to describe a dream to someone, you’ll know that the memory often changes as you explain it and you’re left only remembering what you’ve just said. We can think of quantum information in this way. It’s some private or secret information, like a dream, that is changed when you try to explain or measure it. Quantum information, measured with von Neumann entropy, is the information about the state of a quantum system, like the position, momentum, or energy of an electron in atom [4]. Systems with no uncertainty, or no 'lack of information', have a von Neumann entropy of 0, as with so-called 'pure states' as we will see.

LOADING FIG. 2



>> Arbitrary wavefunction probability density: dotted line shows most likely position of particle [by author]

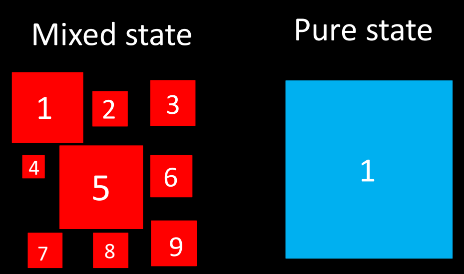
Classically, we can determine the evolution of the state of a ball thrown into the air using Newton's second law, $F = ma$. With just some boundary conditions we could calculate position, acceleration, and almost anything else we would want to know about the ball, at any time. In quantum physics however, our new best friend is the Schrödinger equation, Eq. (1).

$$i\hbar \frac{\partial}{\partial t} \psi_n(x,t) = \hat{H}\psi_n(x,t)$$

>> Eq. (1)

Solving Schrödinger's equation for a quantum system returns the wavefunction $\Psi(x,t)$, a probability amplitude which tells us everything about the system and how it evolves over time. A possible wavefunction probability amplitude is show in Fig. 2. It is in the position basis, meaning we can directly interpret the position of the particle at a given time. $|\Psi(x)|^2$ allows us to determine the probability of finding the particle at each x position. Locations where $|\Psi(x)|^2$ =0 indicate a certain absence of the particle, whereas locations with a large $|\Psi(x)|^2$ value have a high probability of finding the particle there. Repeating a measurement for a quantum system does not give the same value each time, as the particle can be found with any position, momentum, energy etc. described by the wavefunction's probability distribution.

LOADING FIG. 3



>> Shows a mixed state, left, comprised of (an arbitrarily chosen) number of eigenstates with different probabilities (proportional to area of their box). On the right is a pure state of one eigenstate. [by author]

Take the classical example of the ball again, at each point in its trajectory it is in a specific state, which we call the different 'eigenstates'. Each state has well-defined momentum, position, or energy values, or 'eigenvalues'. Because of the probabilistic nature of quantum mechanics, quantum systems can have an arbitrarily large number of eigenstates. A system like this is in a mixed state, Fig. 3. A pure state is a system described by a single eigenstate such that there is no quantum uncertainty, with a von Neumann entropy of zero. When measuring the energy of an electron, for example, in a mixed state there is a chance you will measure the different eigenvalues with different probabilities, e.g. maybe 10eV only once, but 100eV many times. However, in a pure state you are guaranteed a single measurement outcome: the specific eigenvalue to the eigenstate. It might be 10eV again, but for every measurement. In an open system a pure state can evolve to a mixed state when information is lost to the surroundings by process of decoherence, analogous to energy being lost to surroundings by friction in classical systems [6].

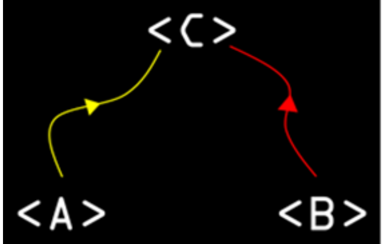
>>UNITARITY Time evolution of the wavefunction is unitary, meaning probability is conserved (the probabilities of every existing eigenstate sum to 1) [5]. Integrating over all space for $|\Psi(x)|^2$, at a certain time t_1, therefore must give 1 due to normalisation, Eq. (2).

$$\int_{-\infty}^{+\infty} |\psi(x,t_1)|^2 \, \mathrm{d}x = 1$$

>> Eq. (2)

Unitarity means two states can't evolve into the same state over time, otherwise the probabilities before and after the evolution are not equal. Demonstrated in Fig. 4, if both states A and B evolved to C, afterwards we could not tell which state we began in. From this we can see that the number of quantum states must be conserved for unitary evolution—A and B must evolve into two independent states. This is a fundamental property within quantum mechanics.

LOADING FIG. 4



>> Shows how if both quantum states A and B evolve to C, we cannot know which state we started with, violating unitarity. [by author]

>> CONSERVATION OF INFORMATION...

T MINUS 13 MINUTES TO M87*

Now we have a better understanding of what quantum information is, we can look at its conservation. Conservation of quantum information is a consequence of unitarity; the wavefunction undergoes unitary time evolution preserving the number of quantum states, which in turn, preserves quantum information. Processes that cause the wavefunction to evolve between pure and mixed states do not conserve information as they do not conserve the number of states. This has an important implication for the Black Hole Information Paradox.

You may, as I did, wonder how this conservation law extends to classical information—mainly to see exactly what falling into a black hole means for us! In search of an answer, I reached out to Prof. Samuel Braunstein, who proved information conservation in 2000, for some more insight [7,8]. In an email from Braunstein:

> >> 'This is an important question ... Ordinary classical logic is not reversible, but it can always be simulated (even efficiently) by logically reversible classical processes. By construction, information is retrievable from a reversible process. This may be at the theoretical level if the process is only logically reversible, but it may also be at the practical level, if the process is also physically reversible.' [9]

Essentially, this means that destroying the information of a classical system, such as reducing a piece of paper to ash, for example, does not destroy the information it held. By analysing everything about the system, like the ash particles, smoke, and energy given off etc. the paper could *theoretically* be reconstructed. No information was lost, it was just made harder, maybe even impossible, to access. As Braunstein states, it may be practically impossible to retrieve the classical information from a physically irreversible process, but it is possible on the theoretical level, which is all this conservation law needs. So, currently, it's not looking too good for us...

>> INFORMATION PARADOX...

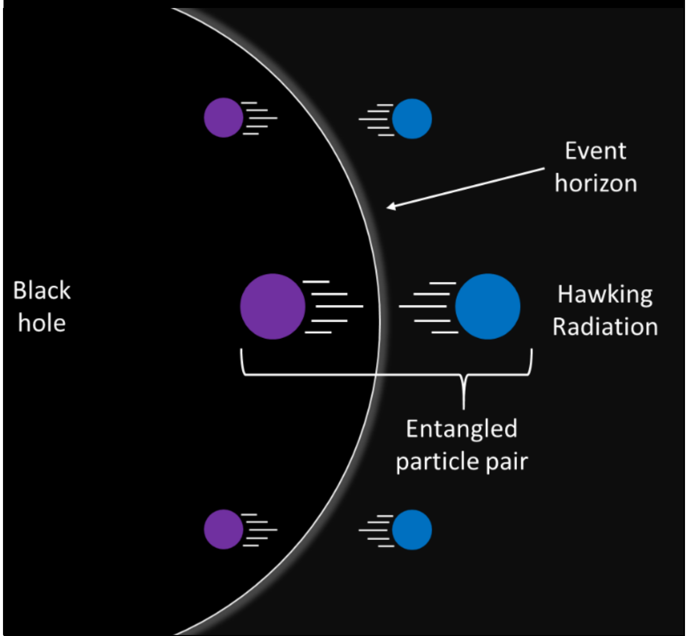
T MINUS 10 MINUTES TO M87*

Now we understand this important law within quantum mechanics stating that information can never be lost, we can now look at how black holes appear to violate this. The information paradox has sparked debate since the mid-1970s when it was posed by Prof. Stephen Hawking, and arose as a result of attempts to combine quantum mechanics with general relativity.

You've probably heard of black holes; regions of spacetime with gravity so large that even light cannot escape their pull. The most common type of black hole are stellar ones, which are formed when massive stars collapse in on themselves [10]. While being hugely complex to describe mathematically, the no-hair theorem of general relativity states that black holes at equilibrium are characterised by only three parameters: mass, electric charge and angular momentum [11]. Essentially, once something falls into a black hole, we cannot know anything about what it was except these three things. It appears that any other information about the matter swallowed is lost. However, so long as the black hole exists, the information can persist within it, even if it is not physically accessible. This was all fine until Hawking discovered that black holes emit radiation, causing them to slowly 'evaporate' away, eventually resulting in their death—seemingly destroying all the information they contained.

In the 1970s, Prof. Jacob Bekenstein discovered that black holes essentially have their own temperature and entropy in a 'semiclassical' gravity scenario. This is a bridge between the classical and quantum gravity theories [12]. Classical gravity keeps planets in orbit and us in our seats—it predominantly affects matter on large scales. Quantum gravity is a theory yet to be fully developed which combines classical gravity with quantum phenomena. From this black hole entropy, Hawking radiation was discovered.

LOADING FIG. 5



>> Formation of particle-antiparticle pairs at the event horizon leading to Hawking radiation (represented by blue particles) [by author]

>>HAWKING RADIATION

In empty space, quantum fluctuations mean that virtual particle-antiparticle pairs are constantly generating and quickly annihilating one another. These pairs form a pure, entangled state. Entanglement means that the measurement of one particle also informs us about the second particle [13,14,26].

When these virtual pairs are formed at the event horizon of a black hole, one can be trapped by the black hole, while the other is free and forms a real particle or antiparticle, Fig. 5. The event horizon is at the black hole boundary, beyond which nothing can escape the black hole. The causality principle states that anything within it is 'causally disconnected' from the rest of the universe. This means that nothing within a black hole can influence events outside it. The unabsorbed particle carries some energy, and therefore mass (thanks to $E = mc^2$), away from the black hole. After a very long time the entire black hole mass will have essentially evaporated away. This so-called Hawking radiation is inversely proportional to the mass of the black hole, meaning it is emitted with a greater intensity the smaller the black hole gets. But most importantly, it is apparently independent of the information inside [15]. The entangled pairs initially form a pure state together, but when only looking at the black hole's unabsorbed particles making up the radiation, they are now in a mixed state.

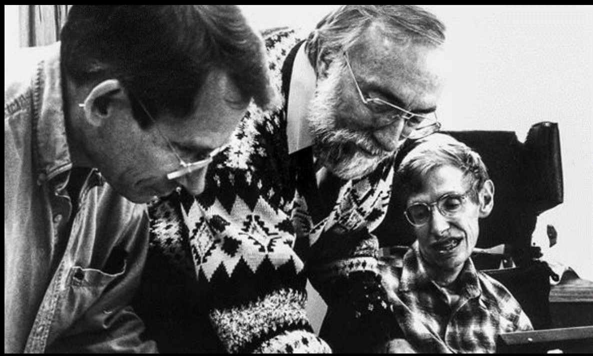
This presents us with a challenge. If any quantum system in a pure state was thrown into a black hole, and after it's evaporation all that remains is the radiation that's always in a mixed state, we have a problem. As we know, evolving from a pure state to a mixed state is non-unitary meaning that probability, and therefore information, are not conserved. This is the information paradox: are black holes just an exception to the information conservation law that applies everywhere else?

>> THE BET...

T MINUS 6 MINUTES TO M87*

This paradox has baffled scientists for decades—namely Kip Thorne, John Preskill and, in particular, Stephen Hawking, Fig. 6, who had a reputation for making scientific wagers. For this bet, Thorne and Hawking stated causality meant that the Hawking radiation was independent from its entangled particle inside the black hole, and thus also to the information inside. They argued that information was lost in black holes, while Preskill bet that the causality principle doesn't hold here, and information is not in fact lost [16].

LOADING FIG. 6



>> Preskill (left), Thorne (middle) and Hawking (right). [24]

Before we look at the developments of 2020, whose side are you on?

>> PRESS [A] FOR THORNE/HAWKING

>> PRESS [B] FOR PRESKILL

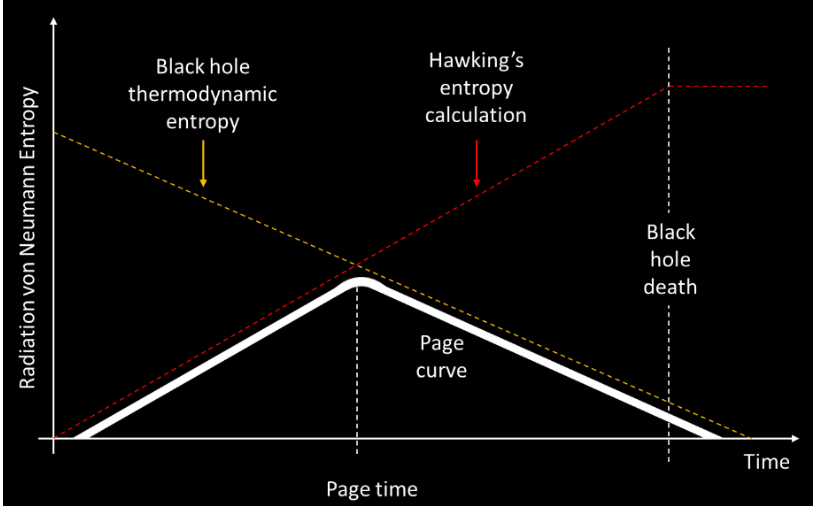
>> THE SOLUTION?...

T MINUS 2 MINUTES TO M87*

Netta Engelhardt, a physicist who played a large role in the latest developments, describes this paradox in two halves: before May 2019, and after. Initially it was believed that black holes had no entropy, such that if you threw a cup of tea into one, its entropy would eventually disappear with the black hole. This violates the Second Law of Thermodynamics which states that entropy cannot decrease [17,18]. As the astronomer Sir Arthur Eddington succinctly put:

>> "If your theory is found to be against the Second Law of Thermodynamics I can give you no hope; there is nothing for it to collapse in deepest humiliation." [19]

LOADING FIG. 7



>> The theorised 'Page curve' alongside Hawking's entropy prediction. Also plotted is the Black hole's entropy, to show that when both are considered a Page curve emerges. [by author]

However, the apparent Second Law violation was resolved when Bekenstein discovered that black holes have an entropy, also leading to the concept of Hawking radiation in 1974. Hawking calculated that the von Neumann entropy of the radiation keeps increasing as the black hole evaporates, shown in red on Fig. 7. This poses a new issue however, because if a black hole is formed in a pure state with zero entropy, after its evaporation all that remains is the radiation with non-zero entropy—a mixed state. Again, we know this pure to mixed state transition violates unitarity so, as theorised by Don Page in 1992, at some point the entropy of the radiation should start to decrease. He suggested it follow the 'Page curve', shown in white on Fig. 7, decreasing after the 'Page time' at around halfway through the black hole's lifetime. Page outlined what needed to be proven, but it took years for physicists to actually do so. It was long believed that a full theory of quantum gravity is needed to fully explain it, which currently we do not have [20].

This brings us to May 2019: physicists can now prove that the entanglement entropy does follow this curve. It required a new way of quantifying entropy by considering the entropy of the black hole and Hawking radiation together, the entanglement entropy [21]. This led to an understanding that, after the Page time, the Hawking radiation has access to the information inside the black hole as the two are linked via entanglement. The information leaks out in the radiation as shown in yellow on Fig. 7. Here we can see the entropy of the black hole (its maximum information content) slowly decreasing as the information is released back to us. After the Page time, performing measurements on the radiation forms a wormhole which has access to the inside of the black hole, and therefore to the information within [22,25].

>> BEGINNING OF THE END...

T MINUS 1 MINUTE TO M87*

Now all this black hole and wormhole talk sounds exciting, but some physicists are still not convinced that this fully resolves the paradox. When the black hole reaches the final stages of evaporation, it becomes extremely small, comparable to the Planck length. This is where the semiclassical gravity description breaks down and a quantum description is needed. The solution that has been reached does not rely on the quantum gravity theory as expected, and instead could've been reached by Hawking himself. It uses the same quantum and relativistic principles he was familiar with [23]. This is why many physicists believe that in the future a more comprehensive quantum gravity theory will be required to fully explain the paradox. They believe that these developments have just taken the paradox in the right direction, without actually solving it. Essentially, bets are on as to whether 'the bet' is still on…

Whether or not you agree this paradox has been resolved, it is still clear that we have much further to go. We do not yet have the technology to actually extract the information that falls into a black hole, nor do we fully understand what occurs inside one, so effectively this information is lost anyway.

Well that was all back in 2020, but it's 2071 and we finally have a monumental discovery! We're almost at the event horizon now, so I'll have to quickly send my theory. Maybe in the future, after M87*'s Page time, you can reconstruct us all to say thanks!

***************** MESSAGE 1 TERMINATED *****************

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>> BEGIN ENCRYPTED MESSAGE 2: "THE COMPLETE THEORY OF QUANTUM GRAVITY"

>> PROCESSING ERROR...

>> **ERROR 404:** FILE NOT FOUND

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