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Resolving the Information Paradox with Probabilistic Spacetime

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Abstract

It has been 50 years since Hawking described the black hole (BH) information paradox. The combination of BH radiation and subsequent BH evaporation was found to take trapped information into oblivion contrary to the law of conservation of quantum information. Numerous attempts have been made since to resolve this paradox. A brief review herein documents how all these attempts have significant shortcomings, meaning the paradox is still unresolved. A relatively new cosmological theory offers a resolution despite not being developed for that purpose. The theory, entitled the probabilistic spacetime theory (PST), starts with an alteration in one basic assumption compared to all current cosmological theories. Spacetime, instead of being seen as a void or container of other entities, is viewed as the most fundamental entity in the universe, composed of energy fragments, and (in keeping with the conservation principle) impermeable to destruction. The potential contribution of the PST in resolving the information paradox is delineated, with the finding that the single change in the conceptualization of spacetime results in the disappearance of the paradox and not information.

Keywords

Information Paradox, Hawking Radiation, Probabilistic Spacetime, Black Holes, Energy Fragment

1. Introduction

In 1972, Bekenstein studied the entropy of black holes (BHs), concluded that BHs slowly radiate energy, and that this energy was completely independent of the initial state of the matter that entered the BH [1]. During the mid-1970s, Hawking supported that analysis, adding that the radiated energy eventually causes the complete evaporation of the BH. Since the radiation causing that evaporation was seen as not encoding the quantum information from the BH interior (because information cannot escape the BH), that interior information would no longer exist once the BH evaporated [2] [3]. Put another way, Hawking drew the conclusion that the radiation can only encode temperature, charge, and angular momentum, but not the wave functions that define the unique states of the matter that fell into the BH. Through the slow but predictable evaporation of BHs, the initial wave functions would remain inside the BH and eventually disappear along with the BH.

This is contrary to the quantum theorem of reversibility/causality, the principle that quantum information cannot be destroyed. The apparently predictable but antitheoretical loss of a BH's quantum information through this evaporation was termed the information paradox.

This paper briefly reviews numerous attempts to resolve that paradox, finding none of them sufficient. A new resolution is then described, one that results from a change in a single underlying assumption underlying the other attempts.

2. Attempts to Resolve the Information Paradox

From 50 years ago through now, many attempts have been made to resolve this paradox. The major ones are briefly reviewed below, grouped under four rubrics that classify the approach taken. The purposes of this review are (a) to document the inadequacy of these explanations and (b) to set the stage for describing how the resolution suggested by a new theoretical application avoids the shortcomings found in previous formulations.

2.1. Modifying Hawking's Computations

Some attempts have used very small corrections to Hawkings' formulations that in aggregate are reportedly enough to account for how information is encoded into the radiating energy [4] [5] [6] [7]. These corrections do not remove the entanglement between the radiation and the BH, however, and thus either do not resolve the paradox or seem to violate the presumed interior structure of BHs [8].

One approach to "correcting" Hawking's calculations concentrates only on the final stage of evaporation when quantum gravity effects are expected to dominate, changing nothing from Hawking's original computations until the final moments of BH evaporation [9] [10] [11] [12]. At that point, all information suddenly escapes. Although this approach keeps classical gravitational effects intact until the BH's near-end, these theories require very small BHs to contain huge amounts of information with very large numbers of internal states. These theoretically required physical states seem quite implausible [13] [14] due to their violation of the Bekenstein bound [15].

A significant "correction" to Hawking's calculation demonstrated that the correlations between the subsystems of outside-the-BH radiation and of the radiation's inaccessible counterparts inside the BH offer a potential resolution to the information paradox [16] [17]. The researchers concluded these correlations account for additional encoded information and do so exactly to the degree that all information was previously thought lost. That analysis was quickly challenged conceptually in two ways: 1) the "failure" to define the paradox in terms of entanglement and 2) the lack of mechanism for how the correlations allow for information recovery [18], with a rebuttal from the original researchers [19]. Subsequent researchers have typically expressed the correlational correction represents progress but have not seen it as sufficiently complete to resolve the paradox due to its lack of mechanism [20] [21] [22] [23].

2.2. Modifying Our Understanding of BH Radiation

A different hypothesis involving the final stage of BH evaporation is that the evaporation simply stops once the BH becomes Planck sized [9] [10]. Information remains stored in a large BH remnant [24] [25]. This process would avoid the paradox as information never is destroyed. However, there is no accepted mechanism that stops Hawking radiation while a BH is macroscopic.

2.3. Modifying Our Understanding of Information Storage

The "soft-hair" solution [26] [27] posits particles with no rest mass (e.g., photons and gravitons; these being called "soft particles") can store initial state information and do so within BHs. This explanation requires four-dimensional asymptotically flat space but cannot be applied to BHs in either anti-de Sitter space (a description used in quantum gravity theories such as string theory and M-theory) or other dimensions [27].

Some models of gravity allow for the formation of baby universes. The information paradox could be resolved if information is stored in a baby universe separate from our own [10] [28]. The predictions from these models, however, are currently untestable.

The BH complementarity hypothesis [29] [30] [31] [32] posits that infalling information is both reflected at the event horizon and passes through the event horizon and cannot escape. According to this hypothesis, the information is not duplicated, just not invariantly localized. The result is that no observer can confirm both perspectives simultaneously. Someone outside a BH can only be aware of the reflected information because the time dilation at the event horizon (EH) prevents seeing the material enter the BH. Similarly, an observer falling into a BH can only be aware of the information also falling inside. This complementarity is said to be a feature of the quantum mechanics of noncommuting observables, the process of observation being key. The main issue with this explanation [33] [34] is that no space-like surface contains duplicated quantum information.

2.4. Modifying Our Understanding of BH Geometry

The "fuzzball" proposal promoted by Mathur and colleagues during the early

2000's [35] [36] [37] and researched further during the following decade [38] [39] [40] [41] views BHs (retitled in this theory as "fuzzballs") as an extreme form of degenerate matter, with the whole entity consisting of strings (from string theory). Within this model, the BH is a very tight collection of strings and the entire EH is like a mist (when viewed on the order of a few Planck lengths) composed of these strings. Quantum information that falls into the fuzzball is not trapped inside but instead reaches up to the fuzzball's surface. The BH's radiation then carries away this information, which is encoded in correlations among the outgoing quanta. This contrasts with the usual understanding of the EH as having no structure. The main criticism of the fuzzball solution to the paradox is the lack of mechanism that can generate such a structure at the EH [42].

Also hypothesizing a structure at the EH is the "firewall" proposal [43]. This attempt at resolving the paradox indicates there is a "wall" of high energy quanta at the EH that facilitates the informational escape. The proposed mechanism for the formation of this firewall is that the entanglement between infalling particle and the outgoing particle of virtual pairs gets immediately broken, and in the process releases a huge amount of energy causing the BH firewall. That resolution, however, requires a violation of Einstein's equivalence principle (stating free-falling and floating in empty space are indistinguishable) [44]. In essence, to address the information paradox with the firewall solution, physicists would need to abandon or at least alter a main tenet of general relativity. Additionally, while the firewall hypothesis has been described as indicating echoes would be found in gravity waves stemming from BH mergers (due to the bouncing of radiation in the vicinity of the fuzzy EH) [45], no significant evidence for such echoes have been found in LIGO data [46].

The holographic principle [more specifically the anti-de Sitter/conformal field theory (Ads/CFT) duality] states that the informational content of all the objects that have fallen into the BH might be entirely contained in surface fluctuations of the event horizon [47]. This principle has been used to avoid the information paradox within the context of string theory, if no information is inside the BH, there is no information trapped inside when the BH evaporates. A significant problem in applying the holographic principle to resolve the information paradox is that classical solutions to the Einstein equations allow values of the entropy larger than an area law and hence larger than the entropy values of BHs [35] [48].

Another attempt to resolve the paradox stems from a perspective stated by Hawking many years after labeling the information paradox; that event horizons do not form; only apparent horizons do [49]. Starting with the supposition that the collapse of matter does not continue past the apparent horizon (by matter's coalescing onto the apparent horizon), analyses showed there would be no event horizon, no external radiation, and no singularity (forming a quasi-static object instead) [50] [51]. Without an event horizon and external radiation, no information would be lost. However, the analyses reportedly hinge on how the quasi-static object (which weakens gravity due to negative energy) may form as the end state of the collapse of matter while considering only reasonable energy conditions and regular initial data. This issue was labeled as crucial by one of the researchers for this hypothesis to be considered well-founded [50] but it has yet to be addressed.

A model receiving significant support gives quasi-normal modes (QNM; oscillations of the BH's horizon) prominent status. Through a process analogous to how energy jumps across levels within the classic (Bohr) view of a hydrogen atom, infalling entangled particles (interior to a BH) ultimately impart their entangled negative energy (and their encoded information) through jumps to the QNM. Once the entangled portion of the wave function (*i.e.*, the information) is within the QNM, the QNM and not an interior particle is entangled with radiation emitted outward at that time. Information that had been internal to the BH escapes as it is already at its horizon [52] [53] [54] [55]. This "Bohr-like" model has received supportive assessments by numerous researchers [56] [57] [58] [59]. Two shortcomings to this model have been described by its developers: 1) they have not specified what happens in the interior spacetime structure, and 2) the model describes BH evaporation until it approaches the Planck distance and mass, but not further. The researchers state a full theory of quantum gravity is required to describe the remaining BH evolution (due to the generalized uncertainty principle). Overall, this model offers a resolution to the information paradox and does so with a specified mechanism (contrary to many of the previously reviewed hypotheses) though that mechanism is not complete.

The proposed resolution to the information paradox gaining the greatest recent support involves replica wormholes [60]-[65]. (Replica wormholes exist in a Wick rotated spacetime, not in original spacetime. In this case, they result from mathematically computing the radiation's entropy by rotating the time coordinate to imaginary values). This hypothesis involves a dramatic reimagining of the interior of BH. Starting with the idea that Hawking radiation is entangled with the particles that fall into the BH (a given for the information paradox), the usually tiny quantum effects on spacetime are thought enhanced by the large entanglement produced by the BH evaporation. This large enhancement produces the possibility of a replica wormhole. Given the path integral for how quantum particles travel includes all possible paths, there is a non-zero probability of particles escaping a BH through such a wormhole where its other end is inside another BH (caused by the same process). Through the temporary wormhole, the BHs swap nearly all their interiors (called "islands"). The original BH's Hawking radiation is no longer entangled with that BH's interior. For any given BH, the entangled entities are all outside the BH. Therefore, no information is lost as that BH evaporates. Two key findings with support for this hypothesized process are 1) that there is sufficient cause for the development of replica wormholes [60] [61] [66] and 2) the replica wormholes are traversable [67] [68].

The replica wormhole resolution of the BH information paradox also involves significant shortcomings:

1) There is no known, or even currently hypothesized mechanism accounting for why information inside a BH, no less the complete island, would either enter or traverse the replica wormhole [63] [69].

2) For the replica wormhole model to work, some low-energy radiation must escape from the BH at its edges. (The islands that traverse the wormhole comprise most, but not all the interior of each hole.) Recent investigations tested the "effective small corrections theorem" and found that if these small corrections were to happen, BHs would not radiate in the way currently understood. Additionally, when examining resultant physical properties from BHs such as topological changes in quantum gravity, the researchers concluded that the physics were not consistent. Their conclusion was that their theorems proved the picture of a BH within the wormhole paradigm was not possible [70] [71].

3) It is not known if replica wormholes represent reality. The mathematical representations could indicate that literal wormholes weave in and out of evaporating BHs; or the equations could simply indicate that spacetime near a BH is nonlocal, the sign of entanglement [69].

4) Finally, even if the required mechanism can be found, and the physics of the interior of BHs can be made consistent, and evidence is found to support replica wormholes can be real, there appears to be another problem in concluding the use of replica wormholes resolve the paradox. The current paradigm is stated in terms of what happens within a pair of BHs – that as one BH evaporates no information is lost because its interior (island) is located inside another BH. But if we take this model to its logical extreme, the original problem shows itself. As the universe approaches its end (in terms of containing differentiated energy sources), and BH after BH evaporates in the universe, alternative places to store their interiors decrease. In this model, by the time the last BH evaporates, all stored information will disappear with it. Unless the principle of conservation of quantum information is thought to break down as BHs disappear (which would end all need to discuss an information paradox), the replica wormhole model seems simply to postpone but not avoid the problem of information loss.

3. The Probabilistic Spacetime Theory

Attempts to resolve the information paradox have been shown to rely on altering how we understand the entities delineated in that paradox; the computation of entropy, the BH radiation, the storage of information, and/or the structure of BHs. Even with those many different approaches, all attempts show significant shortcomings, including the violation of BH geometry, the violation of the Bekenstein bound, the lack of mechanism for the hypothesized structure or process, and the lack of empirical or mathematical analytic support.

This paper presents an approach unique to the above. There is one feature intricately involved with BHs and their radiation that has not received focus in trying to explain the information paradox: the nature of spacetime. The previous explanations have viewed spacetime as an irrelevant background to the phenomenon of concern, have neglected it completely or (for the replica wormhole approach) viewed spacetime as a passive vehicle in which information can traverse.

The probabilistic spacetime theory (PST) completely changes the view of the role of spacetime in what happens in the universe [72]. The PST directly rejects the common assumption that spacetime is a void that only contains energy (information) in favor of the idea that spacetime is energy. Each quantum of spacetime is itself a fragment of information. Although the PST was devised for other purposes [72], a straightforward resolution of the information paradox seems to be offered by the PST's reconceptualization of spacetime.

The remainder of section 3 gives a brief explication of the portions of the PST relevant to the information paradox. Section 4 describes the resultant resolution of the information paradox. Included in the latter is commentary about how the PST's resolution of the paradox avoids the shortcomings enumerated above concerning earlier hypothesized resolutions.

3.1. The PST Principles

The PST involves five principles:

1) Spacetime is the fundamental entity of the universe.

2) Once a quantum of spacetime (called a "probability") exists, it cannot be destroyed.

3) All fields are derivative from spacetime (which in volume is called the "probability field").

4) The probability field has phases.

5) Derivatives of the probability field cause it to be self-attractive.

The first principle says the universe is composed of nothing smaller or more fundamental than the quanta of spacetime. In turn, everything that exists, whether energy or mass in form, is derived from it, from gravity to magnetism to massless bosons to mass. The fourth principle indicates that any change in form is reversible. There is no phase of spacetime that is necessarily permanent. These two principles are crucial for addressing the information paradox, though the first one is the key.

3.2. One Changed Assumption

Virtually all cosmological theories portray spacetime as the container for all the entities and fields astrophysicists and cosmologists study: strings, magnetic fields, the Higgs field, etc. Spacetime curvature matters for gravity, time, replica wormholes, etc., but otherwise the essential nature of spacetime is ignored. Virtual particles are seen as coming to exist from (and mutually annihilate back into) spacetime, but cosmological theories consistently view spacetime as having no direct interactions with observable entities beyond being the volume in which they exist and the road on which they travel.

The PST alters this one pervasive assumption. Instead of being a container (or irrelevant) to the things that matter in the cosmos, the PST explicitly states that spacetime is itself a form of energy. Each quantum of spacetime is conceptualized as an energy fragment. There is no such thing as a void in the universe, as any place there is spacetime (or less fundamental entities) there are these energy fragments. They are literally everywhere in our universe. This energy does not "sit" in the volume we call spacetime. This energy is spacetime.

The energy fragment comprising spacetime is probabilistic (mathematical) in form, and like a quantum wave function in the manner it interacts with everything else. The PST refers to each component of spacetime as "a probability" for this reason, to avoid spacetime being viewed as involving particles.

All probabilistic energy, like anything quantum, is inherently nonlocal. The energy is probabilistically shared across all spacetime, meaning across all other probabilities. Likewise, the density (or strength or amount) of energy constantly shifts from point to point, again because of its inherent probabilistic and quantum nature. Analogous to the current understanding of electrons, probabilistic energy does not necessarily move across an intervening distance to be somewhere else but instead is probabilistically found elsewhere without traversing in between. In other words, spacetime is composed of constantly fluctuating energy fragments that are necessarily and invariably interacting among themselves.

3.3. The Probability Field has Phases

Essential to understanding the PST is the idea that the probabilities that comprise spacetime are the most fundamental entity in the universe. Everything else in the universe is derived from probabilities. The fact that virtual particles constantly pop into existence reflects the energy that is spacetime. The swirling energy within spacetime (*i.e.*, across probabilities) results in the magnetism found anywhere we look in the universe [72]. These energetic phenomena occur while spacetime is in its lowest energy or baseline state.

But probabilities also go through phase changes, where the probabilistic energy takes on different forms. With an increase in density of probabilistic energy in a volume, massless gauge bosons form. Photons come to exist in this way. Since the magnetic field is already present everywhere (due to the constant energy fluctuations in the baseline state of spacetime) by the time photons come to exist, they immediately serve as conduits for the electromagnetic field's ability to transmit its electricity and magnetism. Electromagnetism is therefore stronger where spacetime is denser (*i.e.*, in a volume involving more than baseline energy). The strong force transmitters (gluons), however, can come into existence through a phase change before the particles for which they serve as energy transmitters (the fermions, because fermions have mass while gluons do not). Due to this, gluons can exist without the presence of those fermions (in a self-adhesive form called glueballs) [73].

At still greater concentrations of probabilistic energy, the probability field forms the gauge bosons with mass, and all the fermions. The original article presenting the PST [72] describes the process in the following way: "To accomplish the formation of mass, the field must use what has been termed the Higgs field or boson. From the perspective of the PST, the formation of mass is the result of a phase change in the probability field's energy. When enough probabilistic energy is within a local volume of the field, that energy (being at least equal to the Higgs boson) phases into an object with mass. (This is a different emphasis, but conceptually not different from the theory of symmetry breaking associated with the Higgs. Symmetry breaking is viewed as a type of phase change, where an amorphous state becomes uniquely defined.) It is presumed that different amounts of probabilistic energy (coupled with varying interactions with available gluons) are necessary to form the particles with mass in the Standard Model, that energy always being above the energy of the Higgs" (pp. 135-136).

Finally, there is a hypothesized phase change that can only occur inside incredibly intense gravity wells (*i.e.*, BHs, and maybe other extremely dense astronomic bodies such as neutron stars and white dwarfs). This is where the degree of local probabilistic energy is so dense that the distinctness among probabilities asymptotically approaches zero. The "individual" probabilities continue to exist (in keeping with the second principle listed above, basically a restating of the principle that energy cannot be destroyed) but also share their energy across probabilities to their extreme degree. Exactly what this phase looks like is not known, but a reasonable idea, borrowed from Migdal [74], is of a superfluid.

4. The PST and Black Holes

The PST readily accepts the existence of intense gravity wells called BHs and their event horizons to which infalling matter and radiation cannot return once passed. As is well accepted, mass and radiation are stretched and torn apart starting around the time they enter a BH (exactly when being dependent on the size of the BH) and certainly as they approach the core. The tearing apart of mass and radiation results in phase changes in their composite probabilities, ultimately decomposing them back to their original probabilistic spacetime state. As the BH's core is approached, the bunching probabilities approach their maximum density. Even at the core of the most extreme BH, where the degree of overlap of their wave functions is nearly complete, the probabilistic energy fragments necessarily continue to exist. Spacetime is the ultimate and invariable breaking mechanism to a BH's gravitational force. No singularity can ever form because spacetime itself prevents it.

Describing this mechanism further, borrowing from the tenets of general relativity, the intense gravity near the core of a BH is simply an extreme curvature of spacetime. Bringing more spacetime (probabilities) towards that core can only result in one of two outcomes:

1) If there is more "room" for that added spacetime (the term "room" is clear-

ly inexact but is used to convey the idea that more probabilistic energy can exist within a volume), then by stipulation no infinity has been reached.

2) If there is no more "room" for that added spacetime, then nothing in the existing BH core changes except it enlarges. Again, no infinity is suggested.

Either way, at the center of a BH, the only possible interactions among spacetime probabilities are with themselves, but where no probability can be destroyed (made equal to zero), and hence with no pathway to a singularity.

4.1. Resolution to the Information Paradox

The idea that probabilities necessarily continue to exist as such in BHs is crucial in addressing the information paradox. Probabilities are a form of information that are simply a phase change away from all energy and matter with which we are familiar. When the PST states that probabilities cannot be destroyed, the PST is saying this form of information cannot be destroyed.

From the perspective of the PST, infalling material certainly experiences an event horizon beyond which it cannot escape. However, that is only true while the infalling material is in its macro form. Matter and radiation enter a BH, and in that form would forever be trapped.

But they do not remain in that form. They are torn apart into their most fundamental quantum components, probabilities, the essence of spacetime itself. These energy fragments are not bound by the rules of the macro world. The wave function nature of these energy fragments, of spacetime itself, means distances are only measured in likelihoods and without consideration of traversing whatever is in between. The quantum nature of probabilities means they do not need to travel from point "a" (inside a BH) to point "b" (outside a BH) by traversing the intervening distance. The principle of nonlocality means each probability already reaches point "b" while also at point "a". The defining edge of a BH's EH does not exist for the quantum probabilities, as the required velocity to escape a BH is not a relevant consideration. Each probability, analogous to how we traditionally think of spacetime itself, experiences no event horizon (Contrary to the previously reviewed "no event horizon" hypothesis for resolving the information paradox, the PST does not change the geometry of BHs from our usual understanding. The fact probabilities do not experience an event horizon reflects the nature of probabilities, not the nature of BHs).

Therefore, as a BH evaporates due to Hawking radiation, two things happen both of which mean information that fell into the BH does not evaporate with it. First, the BH radiation (which forms at the EH) can be encoded with information from material that fell into the BH. The spacetime from which the radiation develops has a non-zero likelihood of involving energy from an "internal" probability that at one time was infalling material. The PST dictates that some "Hawking radiation" involves encoded information from inside the EH.

The second process is the more important to the paradox, however. In this process, two mechanisms involving contrary effects occur simultaneously. First, as described by Hawking, the radiation from a BH is entangled with its BH interior counterpart, and the cumulative effect of continual radiation is an increasing degree of BH entangled entropy. Initially, although the probabilities existing as the interior of a BH have their quantum characteristic of nonlocality, their likelihood of reaching outside a BH is quite small (though non-zero). However, as a BH evaporates, the volume of probabilities that are more likely to reach "outside" increases both cumulatively and at an increasing rate [The increase in rate is due to the basic principle that different densities (pressures) seek equilibrium if not prevented from such. A BH is composed of very dense (or clumped or curved) spacetime. As the gradient in densities between the remaining BH probabilities and the spacetime outside the BH increases (that is, as the EH shrinks), the probabilities from the very dense spacetime inside the BH become more and more likely to intermingle with the spacetime surrounding the BH (that is, to be more likely found on the outside of the BH instead of the inside)]. This is not just information escaping the BH, but the movement of entangled entropy to outside the BH. Overall, while one mechanism, the ongoing radiation at the EH, continues to work towards increasing the BH's entangled entropy, the second mechanism of "escaping probabilities" works in the contrary direction, towards lowering the entropy by transferring entangled portions of a BH's interior to its exterior.

At a point about midway during the evaporation of the BH, the number of escaping probabilities start to lower the BH's entangled entropy more than new radiation increases it. (The rate of "escape" becomes greater than the decreasing area of the EH can produce entangled radiation.) The BH continues to shrink as the process of radiation continues but the rate of escaping probabilities becomes overwhelming (again due to the combination of the increasingly very high-density gradient and the increasing proximity of the EH). The BH's entangled entropy continues to decrease to zero as the BH disappears, exactly as the last "internal" probability becomes more likely to be external.

Overall, information entering a BH experiences the following process. Infalling mass and radiation are increasingly stretched and torn resulting in their returning to their fundamental probabilities. These in turn can escape the BH due to the combination of their quantum nature and the increasing likelihood of locating outside the BH provided by the shrinkage of the BH and the increasing gradient of energy density difference. No matter the size of the BH, its process of shrinking (which was seen as the cause of the information paradox) is exactly what ensures all internal probabilities eventually become external. (The two processes just described, being the encoded radiation and the more significant "relocating" of probabilities, are the PST's explanation of the mechanisms behind the previously reviewed finding that correlations between Hawking radiation and entangled BH entropy result in no loss of information [16] [17]. The main criticism found in that review was the lack of mechanism explaining how the correlation prevented information loss.) All infalling information continues to exist beyond the life of the BH. Most importantly, as the information is simply in a phase change, the original form of the (wave function) information is (theoretically) retrievable. Therefore, from the perspective of the PST, there is no information paradox because there is never any loss of information.

4.2. Entangled Entropy, the Page Curve, and the PST

About 30 years ago, the relationship between BH shrinkage and entangled entropy was discerned, a relationship called the Page curve [75]. The entangled entropy of an evaporating BH initially grows until halfway through its shrinkage, but then decreases to the point of reaching zero when the BH evaporates.

As just described, the PST predicts exactly that outcome including an explanation of the underlying process that is its cause. The PST posits there are two counterforces at work, one increasing entangled entropy and the other decreasing it. Their differing rates over time result in the directional change in the curve. And as parsimony would suggest, the work of the first directly relates to why and when the second force overcomes the first, ultimately bringing what had been a rising degree of entangled entropy down to zero. There are no other intervening forces or even a new construct needed for the existing theory to explain the Page curve.

5. Discussion

Previous attempts to resolve the BH information paradox involved altering the computation of entropy, adding structures within BHs, changing the nature of Hawking radiation, or most recently using replica wormholes. Although various claims of progress in resolving the paradox have been made over the years, all previous attempts have been criticized for issues involving inconsistencies, failures in analytic support, and mostly failures to specify required mechanisms.

The PST was developed without any mention of or purpose of resolving the information paradox. (The theory's first application was to address the inconsistencies found in the Hubble constant [76]. In a far more detailed 2021 article [72], the PST was shown also to address how clumps of spacetime explain the phenomena for which "dark matter" has been hypothesized, why magnetism is found everywhere, how very early-universe supermassive BHs got their start, and why filaments show angular momentum.) Even so, the theory explicitly offers a mechanism to resolve the paradox: phase changes in the most fundamental entity in the universe. The paradox is resolved with a simple idea: once we see spacetime as composed of energy fragments, even the incredible gravitational field that is a BH cannot destroy the information of infalling material, either to form a singularity or through BH evaporation caused by Hawking radiation.

The shortcomings of previous attempts at resolving the information paradox were not found with the PST. BH geometry was not altered (except in denying the existence of the theoretically impossible singularity at its core), so violations in such geometry do not exist. The PST explicitly avoids any violation the Bekenstein bound. The mechanisms for "saving" information are clearly stated. The theory, constructed using an integration of numerous empirical, observational, and theoretical findings [72], was even found consistent herein with something not previously considered for the PST, the Page curve for BH entropy. The underlying mechanism for the curve was also explicated. Overall, the PST appears to offer a resolution to the BH information paradox while avoiding all the types of shortcomings found in previous resolution attempts. The parsimony of the PST coupled with its explanatory power, including its ability to resolve the information paradox, suggests it deserves further exploration.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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