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Article

The Scaling Entropy-Area Thermodynamics and the Emergence of Quantum Gravity

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Abstract - This article introduces the "Scaling Entropy-Area Thermodynamics" (SEAT), a unified framework claiming that all gravitational systems' entropy scales with their surface, rather their volume, allowing gravity to be explained as an emergent phenomenon. This approach reveals how entropy, information, spacetime geometry and quantum mechanics are intrinsically linked from notions such as von Neumann entropy, Bekenstein bound and Ryu-Takayanagi conjecture. With the help of new entropy formulations involving surface gravity, SEAT illustrates how gravitational entropy explains gravitational systems from structured information at the boundary surface. SEAT not only solves the black hole information paradox by suggesting that they evolve, as their entropy decrease, towards order, with information preserved in a progressively organized manner and emitted through the entangled Hawking radiation, but, offers by the extending of the "entropy-area" relation to all gravitational systems, to comprehend, in a unified approach, the emergent nature of gravity from how information is encoded and organized on the boundary surface.

Keywords - Quantum gravity; Emergence; Black hole information paradox; Bekenstein-Hawking entropy; Hawking radiation; Ryu-Takayanagi conjecture; Surface gravity; Gravitational fine-grained entropy.

1 Introduction

This article introduces the "Scaling Entropy-Area Thermodynamics", SEAT which shows that all gravitational systems' entropy adapts with their surface area, not volume. This general approach and its implications solve some profound challenges in modern theoretical physics such as black hole information paradox [1], the nature of gravity, and their links to quantum mechanics and thermodynamics. This approach provides a unified perspective on gravity, thermodynamics, quantum mechanics and quantum information theory, by explaining how the geometry of spacetime, entropy and information are interconnected, reconciling the laws of quantum mechanics and general relativity, by explaining gravity as not fundamental phenomenon, but rather emergent phenomenon arising from quantum entanglement, thermodynamic processes, and informational dynamics. SEAT links gravity with thermodynamics and ties quantum entanglement and thermodynamic processes to spacetime, where gravity arises from the microscopic interactions of quantum states. Additionally, surface gravity and entangled Hawking radiation illustrate how gravitational effects evolve through changes in entropy, providing a unified framework for understanding quantum gravity, showing that gravitational systems follow thermodynamic principles and that entropy changes can lead to observable gravitational effects. From entropic information theory approach [2], with the help of new black holes entropy formula and by incorporating surface gravity [3] in new formulations exploring the relationship between entropy, information, and spacetime geometry, the article offers a comprehensive theory that unifies black hole mechanics, quantum gravity, and entropy, culminating in the SEAT that explains quantum gravity as emergent phenomenon arising from more fundamental quantum and thermodynamic processes localized at the boundary surface. The inclusion of surface gravity within the broader framework supports the idea that entropy and information are fundamentally connected to the geometry of spacetime and reinforces the idea that gravity emerges from thermodynamic and quantum processes. By incorporating key concepts such as von Neumann entropy [4], Bekenstein bound [5, 6], Bekenstein-Hawking entropy [7 - 9], the Ryu-Takayanagi conjecture [10], the works of Casini and Bousso [11 - 20], and by the introduction of the gravitational fine-grained entropy, the entropic information theory approach resolves the black hole information paradox, moreover, SEAT explains the relationship between entropy, information, and the geometry of spacetime leading to a unified comprehensive framework explaining the emergence of quantum gravity, arising from more fundamental quantum and thermodynamic processes localized at the boundary surface.

2 Black Holes' Thermodynamics

Black holes thermodynamics represents a fascinating intersection between general relativity, quantum mechanics, and statistical mechanics. The concept, which emerged in the 1970s, challenges our understanding of some of the most fundamental principles in physics, particularly those related to entropy, temperature, and the nature of information. The foundations of black hole thermodynamics were laid by the analogy between the laws of black hole mechanics and the laws of thermodynamics. This analogy was first formalized by Jacob Bekenstein [21] and further developed later by Stephen Hawking [22, 23]. Bekenstein proposed that the area of a black hole's event horizon can be interpreted as a measure of its entropy, leading to the formulation of the famous Bekenstein-Hawking entropy:

$$S = \frac{kc^3 A}{4\hbar G} \tag{1}$$

where A is the area of the event horizon, k is the Boltzmann constant, $\hbar$ is the reduced Planck constant, c is the speed of light and G is the gravitational constant.

This formula shows that black holes can be described using concepts such as entropy and that the entropy of a black hole is directly proportional to the area of its event horizon, rather than its volume, as would be the case for a conventional thermodynamic system. Stephen Hawking proposed that black holes are not completely black but emit radiation due to quantum effects near the event horizon. This radiation causes the black hole to lose mass and energy over time, leading to its eventual evaporation. The process of black hole evaporation is inherently a non-equilibrium phenomenon because the black hole is losing mass and energy, changing its entropy and other thermodynamic properties as it evolves. This non-equilibrium thermodynamics approach is particularly significant in addressing the black hole information paradox, which arises when considering what happens to the information that falls into a black hole as it evaporates and eventually disappears. The black hole information paradox arises from the conflict between quantum mechanics and general relativity. According to quantum mechanics, information must be preserved, while classical general relativity suggests that information could be lost in a black hole. In addition to this non-equilibrium approach of black holes' thermodynamics, there exist an equilibrium approach to black hole thermodynamics concerning with black holes in a steady state or quasi-steady state, where their properties are stable or only change slowly over time, allowing for the use of thermodynamics at equilibrium. In the equilibrium thermodynamics of black holes approach, black holes are treated as stable systems where their thermodynamic properties can be described using analogies to classical systems where the key insight is that the event horizon of a black hole behaves in many ways like the surface of a traditional thermodynamic system. A crucial component in understanding black hole equilibrium thermodynamics is the concept of surface gravity, κ, defined as a measure of the gravitational acceleration at the surface of a body and related to the force exerted by gravity on an object at that point.

In equilibrium thermodynamics, for black holes, the equilibrium temperature can be expressed using the concept of surface gravity (κ). The surface gravity of a black hole is defined as the acceleration due to gravity at the event horizon, as measured by an observer at infinity. It is related to the black hole's temperature by the formula:

$$T_H = \frac{\hbar \kappa}{2\pi k c} \tag{2}$$

This relationship illustrates how black holes, despite their classical gravitational nature, have quantum mechanical properties that can be described thermodynamically. The surface gravity's role in this equation is crucial because it connects the gravitational properties of the black hole (which are classical) with quantum mechanical properties (Hawking radiation), providing a bridge between these two realms of physics. The equilibrium thermodynamics approach to black holes treats them as static, unchanging entities, allowing for the application of classical thermodynamic principles. Conversely, the non-equilibrium approach considers black holes as dynamic systems, where deviations from equilibrium play a crucial role in their evolution. Both perspectives of Hawking temperature describe how black holes radiate energy but from different angles: one focuses on a stable, equilibrium scenario based on surface gravity, while the other looks at the dynamic process of radiation leading to a non-equilibrium state. Understanding these approaches is vital for gaining insight into the nature of black holes and their role in the broader cosmos.

3 Entropic Information Theory

Now, the black hole problematic is introduced within the entropic information theory [2] approach with the help of Hawking temperature and the surface gravity notion, concerning black holes' equilibrium and non-equilibrium thermodynamics approaches, giving fundamental insights about emergence of quantum gravity from quantum and thermodynamics underlying processes. We start this entropic information theory approach by introducing the mass of bit of information [24, 25]:

$$mass_{bit} = \frac{kTln(2)}{c^2} \tag{3}$$

into the hidden thermodynamic of Louis de Broglie [26]:

$$\frac{Action}{h} = -\frac{Entropy}{k} \tag{4}$$

About the hidden thermodynamics of isolated particles, it is an attempt to bring together the three furthest principles of physics: the principles of Fermat, Maupertuis, and Carnot. Hidden thermodynamic of Louis de Broglie which suggests that entropy, a macroscopic thermodynamic quantity, can be viewed as a manifestation of quantum mechanical action, bridging the gap between classical thermodynamics and quantum mechanics. We obtain a new value for the entropy S, with a formula based on the hidden thermodynamics of Louis de Broglie wherein the mass of bit of information has been injected [2]:

$$S = -k^2 \frac{Tln(2)t}{h} \tag{5}$$

where: S entropy, h Planck constant, k Boltzmann constant, T temperature at which the bit of information is stored, t time required to change the physical state of the information bit.

The ln 2 factor comes from defining the information as the logarithm to the base 2 of the number of quantum states [20]. The negative sign refers to a state in which the disorder or randomness of a system decreases, or the uncertainty or information content decreases, implicating a movement towards a more organized, structured, or predictable state. This equation encapsulates a profound synergy between entropy, information theory, and quantum mechanics. This approach unifies classical thermodynamic concepts (entropy and energy) with quantum mechanics by introducing information as a physical entity, represented by mass and action.

3.1 Black Holes' Non-Equilibrium Thermodynamics

We inject in the previous entropy formulation (see equation (5), the Hawking Temperature represented by this formula:

$$T_H = \frac{1}{k}\frac{\hbar c^3}{8\pi GM} \tag{6}$$

We obtain the black hole entropy formula from entropic information approach, at the hawking temperature, based on the mass of bit of information, i.e., the entropy of the entangled Hawking radiation [2]:

$$S = -k\frac{c^3 ln(2) t_{evap}}{16\pi^2 GM} \tag{7}$$

The entropy formula derived in this context represents a novel way of understanding black hole thermodynamics through the lens of information theory. The equation treats the entropy of the black hole as a measure of the number of bits of information stored on the event horizon. This ties together thermodynamics and information theory, highlighting that information has a tangible physical representation. By integrating mass, energy, and information into a unified framework, this approach helps to resolve some of the outstanding problems in black hole physics, particularly the black hole information paradox. The negative sign in the entropy formula indicates a reduction in disorder or a decrease in the system's randomness. For black holes, this relates to the gradual loss of mass and energy through radiation, ultimately leading to their complete evaporation.

3.2 Black Holes' Equilibrium Thermodynamics

Now the same logic is used with the surface gravity injected in the new entropy formulation from Entropic Information Theory approach (see equation (5)) the temperature is introduced into this new entropy formulation, specifically linking it to surface gravity (κ) via the Hawking temperature relation (see equation (2)), which is pivotal as it aligns the surface gravity of the black hole with the concept of temperature in thermodynamics, allowing the use of thermodynamic principles to describe black hole systems in equilibrium. One of the key results derived is the formula for black hole entropy that incorporates these variables, demonstrating how entropy, a classical thermodynamic quantity, is directly related to gravitational properties:

$$S = -k\frac{\kappa ln(2) t}{4\pi^2 c} \tag{8}$$

This formula emphasizes the role of surface gravity and time in the informational and entropic content of a system suggesting that the entropy depends on both the gravitational intensity and the duration over which the system evolves. The ln(2) term indicates a connection to the binary nature of information, tying entropy to information content in terms of bits [20]. The involvement of (c) places the formula within the relativistic framework. The negative sign signifies that entropy decreases as the system radiates energy and mass, leading to a progressively more ordered state. As hawking radiation saturate exactly the Bekenstein bound, we can isolate the time of evaporation as [2]:

$$t_{evap} = -\frac{64\pi^3 G^2 M^3}{\hbar c^2 ln(2)} \tag{9}$$

with A, the area of the black hole horizon,$16\pi\left(\frac{GM}{c^2}\right)^2$.
The interpretation of negative time in the context of Hawking radiation is related to the mathematical description of the quantum fields near the event horizon of a black hole [2]

$$t_{evap} = -\frac{4\pi^2 M}{\hbar ln(2)} A \tag{10}$$

Injecting the value of ($t = t_{evap}$) in equation (8), we obtain:

$$S = -k\frac{\kappa MA}{\hbar c} \tag{11}$$

This yields the final form for entropy in terms of surface gravity κ and black hole properties:

$$S = -\kappa MA \tag{12}$$

in natural units where ($\hbar$ = c = k = 1).

By deriving an entropy formula that depends on surface gravity, mass, and horizon area, this reinforces the connection between gravitational properties and thermodynamic principles. This derivation shows that entropy, a thermodynamic quantity, can be directly related to gravitational properties like surface gravity and horizon area. Surface gravity (κ) is analogous to temperature in thermodynamics. This analogy allows the use of thermodynamic principles to describe gravitational systems. This equation illustrates how changes in entropy can give rise to gravitational effects, supporting the idea that gravity is not fundamental but emergent from underlying statistical mechanics. The derived relationships suggest that gravity can be understood through the behavior of microscopic degrees of freedom, consistent with the holographic principle, suggesting that the gravitational effects we observe are the result of underlying microscopic degrees of freedom, further bridging the gap between thermodynamics, gravity, and quantum mechanics. This new relation illustrates how changes in entropy can give rise to gravitational effects, supporting the idea that gravity is not fundamental but emergent from underlying statistical mechanics. This formula concerning surface gravity encapsulates a key concept in black hole thermodynamics: the relationship between entropy, mass, surface gravity, and horizon area. This shows that entropy is not only a function of its horizon area but also depends on its mass and surface gravity, reflecting a deep connection between gravitational and thermodynamic properties in the context of quantum gravity. The derived relationships suggest that gravity can be understood through the behavior of microscopic degrees of freedom, consistent with the holographic principle. This derivation reinforces the idea that gravitational systems, like black holes, can be described using thermodynamic principles. This not only illustrates the deep connection between gravity and thermodynamics but also supports the view that gravity emerges from underlying statistical mechanics rather than being a fundamental force.

4 Beyond Black holes' Equilibrium and non-Equilibrium Thermodynamics

4.1 Black holes' Fine-Grained Entropy and Black Hole Information Paradox

Concerning black holes, according to Hawking, when black holes absorb some photons in a pure state described by a wave function, they re-emit new photons in a thermal mixed state described by a density matrix. But Hawking radiation is in a pure state, this is in apparent contradiction to the fact that Hawking radiation is also said to be thermal. The apparent contradiction is solved when one realizes that in a general curved spacetime there is no unique definition of the vacuum state and therefore Hilbert space. Consequently, an observer at infinity will see a thermal bath of particles (i.e., in a mixed state) coming from the horizon even though the quantum fields are in the local vacuum state near the horizon [2].

"In fact, if we had a very complex quantum system which starts in a pure state, it will appear to thermalize and will emit radiation that is very close to thermal [27]." And if the overall system is pure, the entropy of one subsystem can be used to measure its degree of entanglement with the other subsystems. "In fact, this is precisely what happens with Hawking radiation. The radiation is entangled with the fields living in the black hole interior [28]." "In particular, in the early stages, if we computed the von Neumann entropy of the emitted radiation it would be almost exactly thermal because the radiation is entangled with the quantum system [27].” “In other words, if the black hole degrees of freedom together with the radiation are producing a pure state, then the fine-grained entropy of the black hole should be equal to that of the radiation [27].”

Where fine grained entropy is the entropy of the density matrix calculated by the standard methods of quantum field theory in curved space time. In the literature, this is often simply called the von Neumann entropy [2]. In accord with the fact that Bekenstein–Hawking entropy of three-dimensional black holes exactly saturates the Bekenstein bound [5, 6], the Bekenstein Hawking entropy [7 – 9] is equal to the Bekenstein bound, which, within the works of Casini and Bousso [11 - 20] is equal to the von Neumann entropy [4], as demonstrated by the work of Casini on relative entropy and Bekenstein bound where the difference between the von Neumann entropy of a system in an excited state and the von Neumann entropy of the same system in a vacuum state is equivalent to the Bekenstein bound. We can thus argue that the entropy of the entangled Hawking radiation, being in a pure state, is equal to the fine-grained entropy of black holes, i.e., the von Neumann entropy [4], itself equals, according to the works of Casini and Bousso [11 - 20] to the Bekenstein Bound [5, 6], which is exactly saturated by the Bekenstein–Hawking entropy of three-dimensional black holes. Thus, we obtain as corresponding equalities:

$$\begin{gathered}\text{Bekenstein-Hawking Entropy}\\ = \text{Bekenstein Bound}\\ = \text{von Neumann Entropy}\\ = \text{Fine-grained Entropy of Black Holes}\\ = \text{Entropy of Entangled Hawking Radiation (pure state)}\end{gathered}$$

We can claim that the Bekenstein Hawking entropy computes the fine-grained entropy of black holes. Moreover, as the black hole degrees of freedom together with the radiation are producing a pure state, then the fine-grained entropy of black holes is equal to that of the radiation. This radiation being entangled with the fields inside the black holes [27], permits to be able to extract information that resides from the semi-classical viewpoint, inside black holes [28]. As being in pure state, the entropy of the entangled Hawking radiation is calculated through the non-equilibrium framework and is shown to be equivalent to the fine-grained entropy of black holes giving insights concerning the black hole information paradox. As black holes emit Hawking radiation, they lose mass and energy, leading to a decrease in entropy. When entropy decreases in this system, it leads to a less chaotic or more ordered state as demonstrates by equations (7, 8, 11). This suggests that black holes, far from becoming chaotic as they age, instead progress toward an ordered, minimal state. This theory posits that the evolution of a black hole doesn’t lead to an uncontrolled, chaotic state but to a highly organized one. The black hole becomes more ”informationally rationalized,” with entropy decreasing as the system loses complexity. This connection between entropy, information, and structure suggests that black holes evolve towards order, with information preserved in a progressively organized manner as they dissipate through Hawking radiation. By the end of this process, if the black hole evaporates completely, all the information it initially contained has been radiated away in a precise, organized form. This model implies that rather than information being lost in a chaotic manner, it’s released in an orderly fashion. The SEAT framework presents several key formulas (equations 7, 8, 11) and concepts that explain the behavior of black holes emitting Hawking radiation, losing mass and energy, and evolving towards a more ordered state, with information preserved in a progressively organized manner as they dissipate through Hawking radiation, as Hawking radiation is emitted in an entangled pure state, the fine-grained entropy of the black hole comes to equal the entropy of the radiation, aligning with the Bekenstein bound and von Neumann entropy thereby resolving the black hole information paradox in an organized fashion. This progressive organization of information not only maintains the total informational content but also provides a structured release that resolves the black hole information paradox.

4.2 Black holes' Gravitational Fine-Grained Entropy

We have computed the fine-grained entropy of black holes, after what, we can push further the investigations to approach the gravitational fine-grained entropy of black holes by using the widely accepted Ryu-Takayanagi formula [10] providing a deep connection between quantum entanglement and the geometry of spacetime. Gravitational fine-grained entropy, in quantum gravity, represents the entropy calculated based on a complete description of the quantum states within a gravitational system. The Ryu-Takayanagi conjecture extends the developed concepts by proposing a general formula for the fine-grained entropy of quantum systems coupled to gravity, particularly in the AdS/CFT correspondence. In the context of the AdS/CFT correspondence, the Ryu-Takayanagi formula generalizes the entropy-area relationship to arbitrary regions in spacetime and suggests that entanglement plays an important role in the emergence of spacetime geometry from quantum information [10]. "According to the current understanding of the formula, which is much more general, the Ryu-Takayanagi formula requires no holography, entanglement, or anti-de Sitter spacetime, rather, it is a general formula for the fine-grained entropy of quantum systems coupled with gravity" [27], providing a powerful tool for studying the emergence of gravitational physics from quantum information theory. The Ryu–Takayanagi formula provides a way to relate the entanglement entropy of a conformal field theory to the Bekenstein-Hawking entropy of black holes in the context of Juan Martin Maldacena's holographic principle. The black hole entropy horizon law turns out to be a special case of the Ryu–Takayanagi conjecture [10] viewed as a general formula for the fine-grained entropy of quantum systems coupled to gravity.

Bekenstein-Hawking Entropy
= Bekenstein Bound
= von Neumann Entropy
= Fine-grained Entropy of Black Holes
= Entropy of Entangled Hawking Radiation (pure state)
= Ryu–Takayanagi Entropy
= Gravitational fine-grained Entropy of Black Holes

According to the widely accepted Ryu–Takayanagi conjecture [10] which is a general formula for the fine-grained entropy of quantum systems coupled with gravity [27] and which provides a way to relate the entanglement entropy of a conformal field theory to the Bekenstein-Hawking entropy of black holes, the Bekenstein Hawking entropy is interpreted as the gravitational fine-grained entropy of black holes. The Ryu–Takayanagi conjecture implies that the Bekenstein-Hawking entropy is a special case of a broader entropic framework that applies to any quantum system interacting with gravitational fields. These connections provide new insights into the nature of quantum gravity, by understanding the fundamental nature of information in the process of emergence of quantum gravity from quantum entanglement of degrees of freedom.

4.3 Gravitational Fine-Grained Entropy

Equation (8) highlights the importance of surface gravity and time in determining the informational and entropic content of a system, implying that entropy is influenced by both the intensity of gravity and the time span over which the system evolves, moreover, the entropy formula (see equation (11)), highlights that the entropy of a black hole is not only a function of its horizon area but also depends on its mass and also its surface gravity, highlighting the role of microscopic degrees of freedom in the emergence of gravitational phenomena, consistent with the holographic principle. This holographic principle, originally derived from black hole physics through the Bekenstein-Hawking formula , equation (1) — suggesting that entropy in gravitational systems is fundamentally limited by boundary conditions rather than by volume. "Scaling Entropy-Area Thermodynamics", SEAT principle is consistent with the holographic constraint, which posits that all information within a volume can be encoded on its boundary surface. In theoretical models extending beyond black holes thermodynamics, surface gravity is treated analogously to temperature in thermodynamics. Here, quantifies the gravitational pull at a given surface, correlating with gravitational entropy similarly to how temperature correlates with entropy in traditional thermodynamic systems. This analogy provides a bridge between gravity and thermodynamics: just as higher temperatures relate to higher entropy; higher values of surface gravity correspond to increased gravitational entropy. This approach offers a means to measure gravitational effects at a boundary surface without necessitating a full event horizon. Such framework broadens the explanation of gravitational systems by demonstrating how gravitational entropy can depend on surface boundaries rather than solely on the presence of an event horizon. This potentially generalizes the entropy-area relationship in gravitational systems lacking strict conformal boundaries, thereby extending the framework beyond the Anti-de Sitter/Conformal Field Theory (AdS/CFT) correspondence and making it applicable in diverse gravitational scenarios. SEAT framework quantitatively explains why entropy scales with surface area, rather than volume, across all gravitational systems by linking entropy to the information encoded on a boundary surface, aligning with the holographic principle. This framework reinforces "Scaling Entropy-Area Thermodynamics" as a universal characteristic across all gravitational systems, suggesting a unifying framework where gravitational entropy and gravity are intimately connected to processes at the boundary. An extension of the gravitational fine-grained entropy of black holes is made possible to all masses of the universe even those without event horizons, leading to the more global notion of gravitational fine-grained entropy applicable to all masses. The gravitational fine-grained entropy traditionally applied to black holes can be generalized to all masses, including those without event horizons. This insight allows the extension of the Bekenstein-Hawking entropy framework to a more universal notion of entropy. We obtain:

Bekenstein-Hawking Entropy
= Bekenstein Bound
= von Neumann Entropy
= Fine-grained Entropy of Black Holes
= Entropy of Entangled Hawking Radiation (pure state)
= Ryu–Takayanagi Entropy
= Gravitational fine-grained Entropy of Black Holes
= Gravitational fine-grained Entropy of any mass

It highlights how the calculated entropy of the entangled Hawking radiation aligns with the Bekenstein bound and the Ryu-Takayanagi conjecture, both of which are critical components of modern theories that seek to unify quantum mechanics with general relativity. Gravitational fine-grained entropy serves as a tool to explore and compute various aspects of quantum gravity. The gravitational fine-grained entropy provides a way to quantify how quantum effects, like entanglement, influence gravitational systems, which is essential for understanding how quantum mechanics and general relativity might be unified, bridging the gap between quantum mechanics and general relativity, and providing a deeper understanding of the fundamental nature of the universe. This suggests that the "entropy-area" relationship is not unique to black holes but can be applied in other quantum gravitational contexts. The generalization of the "entropy-area" relationship from black holes to other surfaces and horizons in different gravitational systems suggests that this relationship is a more fundamental feature of gravity. This generalization points to a profound connection between geometry, information, and entropy that is key to understanding the nature of quantum gravity. The key idea is that any boundary or any horizon that can be associated with an observer in a gravitational field might also have an associated entropy that scales with its area. The connection between entropy and gravity suggests that gravity may not be a fundamental force but rather an emergent phenomenon arising from the entanglement of microscopic degrees of freedom. This view is consistent with the holographic principle and other approaches in quantum gravity that describe gravity as a macroscopic effect of quantum statistical mechanics.

4.4 Beyond Black holes' thermodynamics to Quantum Gravity

The study of black holes has extended beyond the classical framework of equilibrium thermodynamics, giving rise to novel insights into the behavior of gravitational systems. In this context, entropy, surface gravity, and horizon area is considered as fundamental quantities that connect thermodynamic principles with gravitational dynamics. These perspectives support the idea that gravity is not a fundamental force but rather an emergent phenomenon arising from underlying quantum and thermodynamic processes. As such, gravitational effects are understood as macroscopic manifestations of these microscopic dynamics. This interpretation bridges the theoretical divide between thermodynamics, quantum mechanics, and gravity. The "Scaling Entropy-Area Thermodynamics" (SEAT) posits that the "entropy-area" law is not confined to black holes alone but applies universally to a wide range of gravitational systems. SEAT extends the "entropy-area" relationship, traditionally associated with black holes, to any surface that encodes information in a gravitational field. This generalization points to the universality of the "entropy-area" principle, suggesting that quantum entanglement and spacetime geometry are intrinsically linked in all gravitational systems. The "Scaling Entropy-Area Thermodynamics" (SEAT) is a theoretical framework that links quantum information theory with the thermodynamics of black holes. It posits that gravitational systems' entropy scales with their surface area, not their volume, and helps to explain the emergence of quantum gravity. This theoretical framework supports the notion that quantum mechanical properties are central to the emergent nature of gravity. By extending the "entropy-area" relationship beyond black holes, SEAT provides critical insights into quantum gravity, which is understood as a macroscopic effect arising from microscopic quantum and thermodynamic processes. Consequently, this unified approach offers a comprehensive framework for exploring the emergent properties of gravity in a broad context. The equation (11) encapsulates the deep relationship between entropy, surface gravity, and horizon area, suggesting that gravitational effects may arise from underlying microscopic degrees of freedom, consistent with the holographic principle. This perspective supports the idea that gravity could be an emergent phenomenon rather than a fundamental force, bridging thermodynamics, gravity, and quantum mechanics. SEAT unifies concepts from quantum mechanics, thermodynamics, and information theory, that gravity is an emergent phenomenon arising from quantum entanglement and thermodynamic processes. In traditional thermodynamics, systems move toward greater entropy (disorder), but SEAT proposes that gravitational systems can have locally decreasing entropy as described in equations (7, 8, 11), creating a more ordered state. This orderly information structure on the boundary exerts an "entropic influence" on the surrounding space, causing nearby objects to follow paths that align with the entropy gradients. This orderly information structure on the boundary is a carefully organized configuration that encodes information about the object and its gravitational field, and it organizes the surrounding space's entropy in a way that naturally directs objects along paths that align with this entropic order. The entropic order refers to the level of organization in the informational structure around an object. The entropic order imposed by the object's informational boundary changes the geometry of the surrounding space. The informational organization at the boundary, driven by quantum and thermodynamic principles, creates a gradient of entropic order that affects how spacetime behaves around the object. The boundary's informational organization creates a structured configuration that influences the entropy around it, shaping the surrounding space and guiding the motion of objects within it. Thus, massive objects "curve" spacetime not because of an intrinsic gravitational force but because their informational structure imposes an entropic order on the surrounding space. In Einstein's general relativity, this behavior is described as the "curvature" of spacetime, but in SEAT, it is an entropic effect due to the structured information at the boundary. The curvature we observe—what we describe as the bending of spacetime around mass—is thus a property that arises from how information is encoded and organized on the boundary. Spacetime "curvature" in SEAT arises from the entropic structure of a massive object's boundary. This entropic framework suggests that gravity arises from organized quantum states, where quantum gravity and curvature of spacetime are manifestations of the entangled information structure on the boundary. By connecting quantum states at the boundary with macroscopic gravitational effects, SEAT frames gravity as emergent phenomenon resulting from the interactions of quantum states on the boundary. This viewpoint supports the idea that gravitational entropy, and by extension gravity itself, is deeply tied to thermodynamic and quantum informational processes occurring on a boundary surface. This perspective unifies gravity with thermodynamics and quantum mechanics, implying that gravity is product of fundamental informational and thermodynamic processes rather than intrinsic forces.

5 Testable predictions

The article presents several testable predictions that could be validated through observation or experimentation.

First, it predicts that information is conserved through Hawking radiation during black hole evaporation, meaning the black hole's entropy should equal the entropy of the emitted radiation. This could be tested through the observation or simulation of black hole evaporation processes. Using observational data or simulations focused on the later stages of black hole evaporation to analyze whether emitted radiation carries information corresponding to the black hole's initial entropy. This could involve studying the Hawking radiation patterns and spectra emitted by black holes over time to check for entropy conservation.

Second, the relationship between surface gravity and black hole entropy suggests that changes in entropy lead to observable gravitational effects, which could be verified by detailed observations of black holes, by analyzing changes in the entropy of black holes by observing gravitational waves from black hole mergers or collisions. Detailed monitoring of the emitted gravitational waves could reveal the entropy dynamics and validate the connection between surface gravity, entropy, and gravitational effects.

Third, the SEAT framework generalizes the entropy-area relationship to all gravitational systems, not just black holes. This prediction could be tested by analyzing the entropy behavior of other massive cosmic objects like neutron stars, entropic behavior in such systems, if following the SEAT predictions, could imply an area-dependent entropy rather than volume-based, supporting the model's applicability across various gravitational systems.

Fourth, the paper proposes that quantum entanglement is linked to spacetime geometry, as described by the Ryu-Takayanagi conjecture. This can be tested in the context of quantum experiments, particularly within the AdS/CFT correspondence framework, by testing quantum entanglement and spacetime geometry links by a controlled quantum experiment, simulating conditions predicted by the AdS/CFT correspondence or the Ryu-Takayanagi conjecture, both key components of SEAT. Entanglement entropy measurements between two quantum systems could offer insights about spacetime, helping test the conjecture that spacetime geometry is a function of entangled quantum information.

6 Conclusion

Both, the resolution of the black hole information paradox by the organized information emitted by the entangled Hawking radiation, and the gravitational fine-grained entropy notion led to the central argument of the article, this being that gravity is not fundamental force or entity, as traditionally conceived in physics, but rather an emergent phenomenon. The SEAT model, wherein the key idea is that any boundary or any horizon that can be associated with an observer in a gravitational field also have an associated entropy that scales with its area, posits that gravity and curvature of spacetime arise from more basic quantum mechanical and thermodynamic processes localized at the boundary surface. Essentially, gravity and curvature of spacetime are macroscopic effects of the microscopic quantum states. This approach builds on previous theories, such as Jacob Bekenstein's and Stephen Hawking's insights into black hole mechanics, which suggested that the entropy of a black hole is proportional to its event horizon area rather than its volume. SEAT generalizes this idea: the "entropy-area" relationship applies not only to black holes but to all gravitational systems. By extending this relationship, the theory offers a universal framework for understanding gravitational entropy. Traditionally, gravity and thermodynamics were viewed as separate realms of physics, but SEAT demonstrates that changes in entropy directly lead to observable gravitational effects. This is a significant development because it ties the behavior of gravitational systems to quantum entanglement and thermodynamic processes. The connection between entropy and information is pivotal. The SEAT framework shows that as quantum systems evolve, the entropy of these systems can be understood in terms of the information they encode. This includes not only black holes but also more general gravitational systems, which leads to the broader conclusion that spacetime and gravity emerge from quantum information and the thermodynamics of these systems. In this sense, gravity is described as an effect of statistical mechanics rather than a fundamental force. SEAT offers a resolution to the black hole information paradox, one of the most challenging problems in theoretical physics, asking how information that falls into a black hole is conserved as the black hole evaporates through Hawking radiation. Classical general relativity suggested that this information could be lost, contradicting the principles of quantum mechanics, which assert that information must be conserved, this paradox finds its resolution by proposing that information is conserved in an organized fashion and emitted through entangled Hawking radiation. The framework suggests that the radiation emitted during black hole evaporation carries the information previously contained within the black hole. The entanglement between the radiation and the quantum fields inside the black hole ensures that no information is lost, thus preserving the principles of quantum mechanics. SEAT is the generalization of the "entropy-area" relationship beyond black holes. Traditional black hole thermodynamics established that black holes exhibit thermodynamic properties, with their entropy scaling with the area of their event horizon. SEAT takes this concept and extends it to all masses in the universe, suggesting that any gravitational system—whether or not it has an event horizon—exhibits an entropy that scales with its surface area. This has profound implications for the broader understanding of quantum gravity, as it implies that gravitational systems in the universe follow the same fundamental principles that govern black holes. The article also incorporates the Ryu-Takayanagi conjecture [10], which connects the concept of quantum entanglement with spacetime geometry. The conjecture states that the entanglement entropy of a region in a conformal field theory corresponds to the Bekenstein-Hawking entropy of a black hole in an associated anti-de Sitter space. The SEAT framework builds on this idea, suggesting that quantum entanglement plays a key role in the emergence of spacetime geometry from more fundamental quantum and thermodynamic processes. By applying the Ryu-Takayanagi conjecture more generally by the use of the surface gravity formula, the article argues that the fine-grained entropy of black holes equivalent to the von Neumann entropy provides a deeper understanding of how gravity emerges from quantum entanglement at the boundary surface. This connection between entropy, information, and geometry is one of the central innovations of SEAT, as it bridges the divide between quantum mechanics and general relativity. SEAT presents several testable predictions concerning its theoretical claims. This article presents SEAT, a framework that unifies quantum information theory with black hole thermodynamics, revealing how entropy adapts to surface area rather than volume, thereby solving the black hole information paradox by proposing that black holes evolve toward order as they emit entangled Hawking radiation, preserving all initial information in a structured and organized manner and offering a comprehensive explanation for the emergence of quantum gravity through the integration of entropy, information, spacetime geometry, and quantum mechanics, all while extending the "entropy-area" relationship to all gravitational systems. Ultimately, SEAT offers a unified perspective that connects quantum mechanics, thermodynamics, and gravity. After having resolved the black hole information paradox by extending the "entropy-area" relationship and integrating the concepts of quantum entanglement, black hole thermodynamics, and gravitational systems, the article provides a comprehensive framework for understanding the emergence of quantum gravity, suggesting that gravity emerges from how information is encoded and organized on the boundary surface, leading to new ways of thinking about the fundamental nature of the universe.

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