Einstein and Bohr Finally Reconciled on Quantum Theory: The Theory of Entropicity (ToE) as the Unifying Resolution to the Problem of Quantum Measurement and Wave Function Collapse

A Befitting Contribution to this Year's Centennial Reflection and Celebration of the Birth of Quantum Mechanics

John Onimisi Obidi[†‡α]

14th April 2025

Prologue

Albert Einstein:...[Bohr]...God does not play dice...When I am not looking at the Moon[World], does the Moon[World] still exist?...My intuition tells me the Moon[World] must still exist, independent of my observation...

Niels Bohr:...But Einstein, you must not speak of the Moon's[World's] existence in isolation.
In quantum theory, we cannot meaningfully separate the properties of a system from the conditions under which they are observed.
To ask whether the Moon[World] exists without specifying an experimental context is to ask a question the theory is not equipped to answer...
There is no [quantum] World...in that sense... There is only abstract quantum mechanical description...
So, Einstein, stop telling God what to do....[1]

In Place of an Abstract

The century-old intellectual, physical, and gedanken confrontations between Albert Einstein and Niels Bohr over the foundations of quantum mechanics remain a defining feature of modern physics. These giants of science set the stage for stimulating conceptual and philosophical thoughts that continued to inspire and challenge practitioners of modern science. Central to their debate is the quantum measurement problem - the enigmatic "collapse" of the wave function and the question of whether physical reality exists independent of observation. Bohr championed the contextual,

[†]Email:jonimisiobidi@gmail.com

[‡]Marking the centenary of Quantum Mechanics, this paper undertakes the challenging task of revisiting the long-standing Einstein-Bohr debate concerning the measurement problem and wave-function collapse. The analysis builds extensively on the author's prior publications on the Theory of Entropicity (ToE): [[59],[60],[61],[62],[63],[64],[65],[66]]

[α]The author wishes to especially thank, in advance, those researchers who may find in this work a useful basis for further investigations into this new way of understanding and reinterpreting our mysterious Universe through the lens of the Theory of Entropicity (ToE).

[1]Clarification on Bohr's Position:

- Bohr would not deny the Moon's existence outright - rather, he would reject the question as ill-posed within quantum terms.
- Bohr would like to contend that quantum phenomena are not just about reality, but about the conditions under which we can speak of reality - a central theme in Bohr's response to the EPR paper. [Refer to this Sec. (11.1.1)for how ToE has reframed the conditions for (physical) reality, irreversibility, observability and existence in a way that Bohr himself would have been most pleased with.]

In those beginning and seemingly innocuous words of the Prologue, Albert Einstein and Niels Bohr set the somewhat dramatic scene for perhaps the greatest scientific debate in human history!

irreversible nature of measurement and the inherently probabilistic formalism of quantum theory, while Einstein sought a deeper deterministic framework grounded in objective reality.

This paper presents the Theory of Entropicity (ToE) as a unifying resolution that transcends the limitations of both views. We posit that entropy is not merely a statistical descriptor but a real, dynamical field—a universal driver of physical processes enforcing time-asymmetric, irreversible evolution. In this framework, wave function collapse is no longer a mysterious, observer-dependent postulate; it emerges as a natural, entropy-driven phase transition triggered when a quantum system's entropic evolution satisfies a precise threshold inequality.

At the heart of the theory lies the Vuli-Ndlela Integral—a reformulation of Feynman's path integral that introduces entropy-based weighting of histories. The integral's exponential weighting by classical action, gravitational entropy, and irreversibility entropy imposes strict constraints on allowable quantum trajectories, replacing the unconstrained superposition of paths with an entropy-constrained selection principle. Collapse occurs at the moment the entropy flux or "resistance" surpasses a critical limit, enforcing a physically deterministic yet irreversible transition.

This ToE framework not only restores Einstein's vision of underlying causal realism but also upholds Bohr's principle of contextual irreversibility. It provides fresh resolutions to long-standing paradoxes: the Einstein–Podolsky–Rosen (EPR) paradox is resolved by interpreting entanglement as an entropy-mediated correlation that forms over a finite time (recently measured to be on the order of 10^{-16} s), and the Einstein–Rosen (ER) bridge (wormhole) is reinterpreted not as a traversable spacetime tunnel but as an entropic binding channel connecting entangled states. A Children's Seesaw Model is also introduced to motivate physical intuition in this regard.

By embedding the measurement "collapse" phenomenon within the irreversible flow of entropy and the strict constraints of the Vuli-Ndlela Integral, the Theory of Entropicity offers a principled, mathematically consistent, and experimentally grounded reconciliation between Einstein and Bohr. In doing so, it elevates their debate from a philosophical impasse to a new physical principle—one governed not by ad hoc interpretations or hidden variables, but by entropy as the ultimate arbiter of quantum reality.

ToE then introduces the criteria of existentiality and observability of any reality, by which other longstanding paradoxes are resolved. A first attempt is also made at developing the field equations of Quantum Gravity from entropic principles.

Just as Einstein reinterpreted Newton's force of gravity as the manifestation of spacetime geometry, the Theory of Entropicity (ToE) reinterprets geometry itself as the result of entropy flow. In this framework, curvature is not a precondition but an emergent feature—shaped dynamically by gradients in entropy. ToE thus establishes a new conceptual ground in both philosophy and theoretical physics, where motion, interaction, and structure are driven by irreversible entropic constraints rather than geometrical postulates. Most significantly, ToE introduces a direction of time directly into the wave and field equations via the unidirectional flow of entropy. This resolves the arrow of time problem at its root—not as a statistical artifact, but as a dynamical law embedded in the fabric of reality.

More also, by integrating entropy as a fundamental causal field rather than a passive measure of disorder, the Theory of Entropicity (ToE) offers a new ontological basis for understanding intelligence, cognition, and artificial systems - Artificial Intelligence(AI), Robotics, etc.

Keywords

Albert Einstein, arrow of time, asymmetry and entropy, attosecond entanglement, Bell nonlocality, Bohr complementarity, Born rule, collapse dynamics, contextual realism, David Bohm, de Broglie wave duality, Einstein-Bohr reconciliation, entropy and causality, entropy and collapse, entropy and decoherence, entropy and entanglement, entropy and EPR paradox, entropy and information, entropy and measurement, entropy and observer, entropy and quantum gravity, entropy and quantum mechanics, entropy and wave function, entropy as fundamental field, entropy-based interaction, entropy-based observer constraint, entropic action principle, entropic bridge, entropic curvature, entropic existentiality, entropic field theory, entropic mass emergence, entropic observer constraint, entropic quantum gravity, entropic seesaw model, entropic unification of forces, entropic variational principle, ER=EPR correspondence, Erwin Schrödinger, Feynman path integrals, gravitational entropy, Heisenberg uncertainty, irreversibility, John Bell, John von Neumann, Julian Schwinger, Landauer principle, Louis de Broglie, mass from entropy, Max Born, Max Planck, measurement problem, Niels Bohr, non-instantaneous collapse, observer limitation, Paul Dirac, quantum causality, quantum collapse, quantum decoherence, quantum entanglement, quantum gravity without curvature, quantum irreversibility, quantum measurement, Richard Feynman, Schrödinger equation, Satyendra Nath Bose, seesaw entanglement model, Sin-Itiro Tomonaga, spontaneous symmetry breaking, Theory of Entropicity (ToE), thermodynamic foundations, Vuli-Ndlela Integral, wave function collapse, Wolfgang Pauli, Yoichiro Nambu

Contents

https://doi.org/10.33774/coe-2025-vrfrx **ORCID:** https://orcid.org/0009-0004-3606-3182 Content not peer-reviewed by Cambridge University Press. **License:** CC BY 4.0

https://doi.org/10.33774/coe-2025-vrfrx **ORCID:** https://orcid.org/0009-0004-3606-3182

1 Introduction

In the early 20th century, one of the most profound intellectual clashes in physics took shape: the debate between Albert Einstein[[5],[19],[34],[35],[36]] and Niels Bohr[13] over the interpretation of quantum mechanics. This debate, spanning from the mid-1920s through the Solvay Conferences of the late 1920s and 1930s, centered on what has become known as the quantum measurement problem - namely, how and whether the indeterminate quantum wave function "collapses" to a definite outcome when observed.[2]

At its core, the clash reflected a deeper question: Does physical reality exist independently of observation, or is reality fundamentally created by the act of measurement? Einstein, a principal founder of quantum theory[30], remained dissatisfied with the theory's indeterministic turn in the 1920s. He believed that a complete physical theory should describe an objective reality that exists regardless of observation.

Famously, Einstein quipped, "God does not play dice"[34], rejecting the notion that fundamental physical laws are governed by pure chance. He was equally uneasy with the idea that an object's properties have no definite values until measured. In 1935, Einstein, Podolsky and Rosen formulated the EPR paradox[36], arguing that quantum mechanics, as it stood, was an incomplete description of reality.

They posited that there must be hidden variables or deeper laws restoring determinism and locality, or else one encounters "spooky action at a distance" contradicting relativity.

Einstein's instincts were guided by realism (the moon should be there even if no one is looking)[34] and by determinism, the idea that the evolution of a system follows exact laws yielding the same outcomes given the same initial conditions. He envisioned a unified physical theory wherein randomness and observer-dependence would be supplanted by causal mechanisms. Bohr, by contrast, adopted an orthodox but no less insightful stance.

---

[2]**Albert Einstein and His Critiques of Quantum Mechanics**
Albert Einstein authored several pivotal papers (and letters) that challenged the completeness and interpretation of quantum mechanics. His critiques spanned from early concerns about wavefunction collapse to the deeper issue of nonlocality and realism.

Einstein's 1927 Solvay Conference Comments:

1. Although not published as a stand-alone paper, Einstein's objections at the 5th Solvay Conference (1927) are legendary. He proposed several thought experiments aiming to refute the standard Copenhagen interpretation.[[8],[9]] Albert Einstein and Niels Bohr had sleepless nights at that time while attending the Solvay Conference: Einstein would come up with one gedanken experiment after another upon daybreak; and Bohr would prepare his response after response at dusk and present to Einstein the following morning - how marvelous!
2. Mara Beller has documented those years brilliantly in his "Quantum Dialogue: The Making of a Revolution."

The EPR Paper (1935) - Einstein's Most Famous Challenge:

1. The paper introduced the EPR paradox[E for Einstein, R for Rosen, and P for Podolski - the three authors of that seminal paper], arguing that quantum mechanics is incomplete because it does not account for elements of reality in entangled systems unless nonlocality is allowed.

Einstein's Reply to Born (1947) - The Letter on Determinism:

1. Einstein wrote to Max Born: "Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing."
2. The above searching question of Einstein to Max Born is both memorable and alluring at once. The Theory of Entropicity appears to have come in one piece to reverberate that Einstein's Echo!
3. In that Letter, Einstein reaffirms his view that a complete physical theory must be deterministic and locally real. Our Theory of Entropicity (ToE) answers Einstein affirmatively via the language of entropy, the entropic field, and the Vuli-Ndlela Integral Bounds.
4. The legendary Max Born does great service to Einstein and their memory of that vigorous intercourse of ideas in his monumental work, titled: The Born-Einstein Letters: Correspondence Between Albert Einstein and Max Hedwig Born from 1916 to 1955.

Einstein's Writings in "Philosopher-Scientist" (1949):

1. Einstein's most comprehensive philosophical reflections on quantum theory were published in his Autobiographical Notes as captured in "Albert Einstein: Philosopher–Scientist."
2. This piece includes Einstein's retrospective critique of quantum mechanics, offering a complete statement of his objections to indeterminism and wavefunction collapse.
3. Our Theory of Entropicity (ToE) takes up this Einstein Challenge in this centennial paper, offering an entropic world view on indeterminism and wavefunction collapse: ToE shows that by considering Vuli-Ndlela Integral Bounds, we are able to see how certain aspects of existence and reality are beyond our determinability and observability, and how wave function collapse is determined by entropy saturation limits that are also equally prescribed by entropic bounds of existentiality and observability.

Through his Copenhagen interpretation,[[8],[9]][3] Bohr emphasized that quantum phenomena are contextual – the outcome depends on the experimental setup – and that attempts to ascribe definite properties to quantum objects prior to measurement are meaningless.

Bohr introduced the principle of complementarity[[11],[12],[13]], asserting that properties like particle-like or wave-like behavior are mutually exclusive aspects of a quantum system that only manifest under specific experimental contexts, yet both are needed for a complete description.[4] Crucially, Bohr viewed the measurement act as an irreducibly irreversible process: once a quantum system interacts with a macroscopic apparatus, the quantum coherence is lost and a definite outcome is registered.

There is, in Bohr's view[13], no meaning to the wave function's collapse outside of an interaction with an observer or apparatus – the cut between quantum system and classical world is fundamental. Thus, Bohr accepted indeterminacy and probability not just as epistemic limitations but as intrinsic features of nature. In his response to EPR in 1935, Bohr defended quantum mechanics' completeness, arguing that Einstein's criterion of reality was too restrictive and that no deeper deterministic description was needed[13].

---

[3]**David Bohm and His Non-Copenhagen Interpretation of Quantum Mechanics**

1. David Bohm, a most distinguished student of Einstein, made one of the most important alternative contributions to the interpretation of quantum mechanics with his 1952 hidden variables theory, now known as the **Bohmian interpretation** or **pilot-wave theory**.
   (a) Proposed a *deterministic* alternative to the standard Copenhagen interpretation.
   (b) Suggested that particles have well-defined trajectories guided by a "quantum potential."
   (c) Published this theory as a two-part paper in *Physical Review*:
      i. *A Suggested Interpretation of the Quantum Theory in Terms of "Hidden" Variables. I*
      ii. *A Suggested Interpretation of the Quantum Theory in Terms of "Hidden" Variables. II*
2. Connection to the Theory of Everything (ToE) - What ToE has Achieved
   (a) ToE offers a non-Copenhagen perspective, reinterpreting:
      i. Measurement processes.
      ii. Wave function collapse through entropy.
   (b) ToE Emphasizes:
      i. **Determinism.**
      ii. **Nonlocality.**
   (c) ToE addresses these themes of Bohm via:
      i. Entropic constraints.
      ii. Dynamic Entropic Fields.
3. **Bohm's Contribution**

   Bohm's interpretation provides a revolutionary way of understanding quantum phenomena, challenging conventional perspectives and emphasizing the interconnectedness of all particles in the universe.

[4]**Niels Bohr - His Defence of Quantum Mechanics and Responses to Albert Einstein's Challenge**
Bohr's concepts of complementarity and irreversibility are foundational to the Copenhagen interpretation[[8],[9]] and are key philosophical anchors in quantum mechanics. These ideas appear not in one single paper, but across several critical essays and lectures spanning the 1920s–1950s.

Bohr (1928) - The Most Cited Complementarity Paper:

1. This is Bohr's foundational statement of the Principle of Complementarity, delivered after the 1927 Solvay Conference.
2. In this paper, Bohr introduced complementarity - the idea that mutually exclusive measurements (e.g., position and momentum) provide a complete picture only when considered together, even though they cannot be observed simultaneously.

Bohr (1935) - Response to the EPR Paper (Reinforces Irreversibility):

1. Bohr's rebuttal to Einstein's EPR paper goes further in defending irreversibility and measurement context.
2. Bohr emphasized the irreversible character of the measurement process and defended the contextual nature of quantum observations.

Bohr (1949) - Philosophical Reflection on Complementarity:

1. Published in Albert Einstein: Philosopher–Scientist, this is Bohr's clearest philosophical exposition of complementarity and its implications for knowledge, observation, and irreversibility.
2. This paper thoroughly explains why measurement implies an irreversible act, not just a passive observation, and how this frames quantum epistemology.

We refer the reader to Sec. (2.3) for ToE's explanations of Bohr's Complementarity Principle within the framework of entropic principles.

Over the decades, this Einstein–Bohr debate framed the interpretational landscape of quantum mechanics. It inspired Bell's theorem and subsequent experiments[4], which showed that no local-hidden-variable theory can reproduce all quantum predictions.

Experiments by Aspect et al.[1] in 1982 confirmed the quantum violations of Bell's inequalities[4], essentially vindicating Bohr's stance on non-local correlations (entanglement)[4].

Yet, despite these successes, the measurement problem – why a specific outcome occurs in a particular run of an experiment, as opposed to the many other outcomes allowed by the wave function - remains unresolved.

Standard quantum theory excels at predicting statistical distributions of outcomes, but it is silent on the fate of an individual quantum system's wave function upon measurement. Do wave functions literally collapse, or do they persist in non-communicating branches (Everett's many-worlds[37])?[5] Is the process governed by new physics (objective collapse models) or merely an emergent phenomenon due to environmental decoherence? These questions have kept the foundations of quantum mechanics an open philosophical battleground even as the theory's predictive power flourished.

Now, a century after the advent of quantum mechanics - as 2025 is celebrated internationally as the centennial of the quantum revolution - it is fitting to re-examine Einstein and Bohr's perspectives in light of modern insights[[62],[63],[96]]. On the one hand, quantum information science and experiments have underscored the reality of quantum entanglement as a physical resource, suggesting that what Einstein called "spooky action" is an integral part of nature.

On the other hand, new theoretical ideas at the interface of quantum physics, thermodynamics, and gravity hint that irreversibility and information might play an even more fundamental role than previously thought[[53],[89]].

Notably, the union of quantum theory with gravity has brought concepts of entropy to the fore - by black hole entropy[[3],[45]] and the information paradox to holographic principles[[84],[85]] and even the conjecture that spacetime geometry and quantum entanglement are deeply linked (the ER = EPR conjecture)[[35],[56],[84]].

In this commemorative paper on the centennial reflection and celebration of Quantum Mechanics, we propose a unifying framework - the Theory of Entropicity (ToE)[[59],[60],[61],[62],[63],[64],[65],[66]] - that seeks to reconcile Einstein's and Bohr's viewpoints by elevating entropy to a central role in quantum dynamics. In essence, we argue that many of the mysteries of quantum measurement and entanglement stem from overlooking a key element: the thermodynamic and informational cost associated with quantum state changes. By treating entropy as a fundamental field and physical quantity (on par with energy)[[62],[63]], we can formulate a dynamics in which wave function collapse is a real, law-governed phenomenon - specifically, a kind of phase transition driven by entropy increase - rather than an ad hoc superposition-breaking axiom or a purely subjective update of knowledge.

At the same time, this framework preserves the indispensable role of irreversibility and context championed by Bohr, since the collapse is triggered by entropic conditions that inherently break time-reversal symmetry and tie the event to the interaction between system and environment (or measuring apparatus). In short, the Theory of Entropicity aims to provide what Einstein sought - an objective mechanism for quantum state reduction - while fully embracing what Bohr taught us - that measurement is an irreversible thermodynamic process and any acceptable theory must respect that reality.

In the following pages, we proceed as follows.

Section 2: Historical Background: Einstein's Dream vs. Bohr's Insight

In Section 2, we review the historical stances of Einstein and Bohr in more detail, highlighting the elements that a unified theory must accommodate. This section reviews in greater detail the historical stances of Albert Einstein[36] and Niels Bohr[13], focusing on their divergent yet foundational views on the interpretation of quantum mechanics. We highlight the conceptual tensions between realism and complementarity, determinism and probability, and locality and nonlocality. These tensions define the deep philosophical and physical challenges that any truly unified theory must address.

By outlining these foundational disagreements, we prepare the ground for the development of a new framework that honors both perspectives. This paves the way for Section 3, where we introduce the Theory of Entropicity (ToE) - a novel approach that reinterprets entropy as a fundamental field and reframes wave function collapse as an entropy-driven process. There, we also introduce the Vuli-Ndlela Integral, a new entropy-weighted path integral formalism that leads naturally to the concept of entropic geodesics and a restructured quantum evolution.

Section 3: On the Foundations of the Theory of Entropicity(ToE)

Section 3 introduces the Theory of Entropicity (ToE) in full detail[[59],[60],[61],[62],[63],[64],[65],[66], laying the foundation for how entropy functions as a real physical field governing quantum transitions. It posits wave function collapse not as a mysterious or observer-induced phenomenon, but as a well-defined, entropy-driven phase transition. Here, the pivotal role of the Vuli-Ndlela Integral is established - an entropy-constrained path integral that redefines quantum evolution in light of thermodynamic thresholds. This section marks the formal beginning of a paradigm shift: from probabilistic collapse to entropic inevitability. Here, we introduce the

[5] The foundational paper on the **Many-Worlds Interpretation (MWI) of quantum mechanics was authored by Hugh Everett III in 1957.** The canonical reference is: "Relative State" Formulation of Quantum Mechanics
This paper introduced the "relative state" formulation, which later came to be widely known as the Many-Worlds Interpretation. It proposed that all possible outcomes of quantum measurements are physically realized in a branching multiverse, eliminating the need for wavefunction collapse.

Theory of Entropicity, defining the notion of entropy as an active field and formulating wave function collapse as an entropy-driven phase transition. We present the Vuli-Ndlela Integral[66], an entropically calibrated and weighted path integral formalism, and derive from it the concept of entropic geodesics - the paths in state-space that satisfy both dynamical and entropic extremal principles. Extended mathematical formulations are given to demonstrate how the theory quantitatively modifies quantum evolution.

Section 4: The Theory of Entropcity(ToE) and Landauer's Principle
Section 4 advances this foundation by connecting ToE to Landauer's Principle[53], showing that quantum measurement entails a minimum thermodynamic cost - a result that ToE not only explains but also quantifies as a predictive law. The collapse of the wave function is reframed as an entropic erasure process, with heat dissipation and irreversibility playing central roles. This offers one of ToE's most testable and falsifiable predictions and anchors the theory in thermodynamic reality.

Section 5: Derivation of the Born Rule
Section 5 rigorously re-derives the Born Rule[18] from first principles within the entropic framework, using the structure of the entropy field[66]. Rather than postulating the rule, ToE derives it from the statistical configuration of entropy-constrained quantum states. This provides a solid mathematical basis for why probabilities in quantum mechanics follow the squared amplitude of the wave function - a long-standing mystery now resolved through ToE's deeper entropy-informed logic.

Section 6: Entropy Field and the Wave Function
Section 6 analyzes the formal relationship between the entropy field $\Lambda(x,t)$ and the logarithmic square of the wave function $\Psi(x,t)$. This section establishes the entropic potential as a reformulation of quantum probability - one that encodes physical constraints[[62],[63],[66]] in the system's phase space. It highlights the conversion of abstract quantum amplitudes into tangible entropy flows, setting the stage for thermodynamic re-interpretations of quantum behavior.

Section 7: Mass as Emergent from the Entropy Field
Section 7 makes a groundbreaking proposal: that mass is emergent from the informational structure of the entropy field. Here, ToE delivers one of its boldest insights - that mass is not fundamental, but arises from localized entropy densities shaped by the wave function's structure. The section provides derivations and analogies showing how energy, entropy, and mass interconvert, allowing ToE to reinterpret Einstein's famous relation:

$$E = mc^2 \tag{1}$$

in informational-entropic terms[89].

Section 8: Entropy and Information Theory
Section 8 connects Shannon and von Neumann entropy[[79],[89]] to the entropic wave function, showing how classical and quantum information theory converge in ToE. The entropy field becomes a bridge between microstates and probabilities, with the Boltzmann constant k_B recovering physical meaning as a scaling parameter linking information to thermodynamic cost. The section culminates in a synthesis of Shannon, von Neumann, and entropic wave expressions into a unified framework.

Section 9: Paradoxes Reframed in the Theory of Entropicity(ToE)
Section 9 confronts foundational paradoxes in quantum mechanics - including the EPR paradox[36], nonlocality, and the ER=EPR conjecture[[35],[56],[84]] - and recasts them through the lens of entropy-mediated interactions. Entanglement is described not as "spooky action at a distance," but as the buildup of an entropy-bound connection over time. The entropic bridge is visualized as an information-conserving but non-signal-carrying structure, analogous to a wormhole in entropic space. These ideas are made operational through the seesaw model of collapse.

Section 10: The Theory of Entropicity(ToE) and Quantum Gravity
Section 10 provides a bold mathematical attempt at Quantum Gravity, showing how ToE leads naturally to a modified Einstein Field Equation[31]. It recasts gravity not as curvature caused by stress-energy, but as the manifestation of entropy flows and constraints. Both Jacobson's thermodynamic derivation[47] and a new entropic variational principle[66] are used to derive gravitational field equations that include entropy and the wave function as dynamical variables. **This marks ToE's entry into the most ambitious realm of physics: the unification of quantum theory[[10],[13],[27],[30],[46],[72],[78],[89]] and general relativity[31] - Quantum Gravity!**[6]

Building on this foundation, the field equations of the Theory of Entropicity (ToE) further illuminate and reframe some of the deepest puzzles in modern cosmology - namely, the cosmological constant, dark energy, and

---

[6]**Max Planck, Niels Bohr, Albert Einstein, Werner Heisenberg, and Erwin Schrödinger**

Max Planck - Origin of Quantum Theory (1901):

1. Planck's paper introducing energy quantization in blackbody radiation is often considered the birth of quantum theory.
2. In this paper, Planck introduced the constant h, now known as Planck's constant, and proposed that electromagnetic energy could only be emitted or absorbed in discrete quantities or "quanta."

Albert Einstein - the Photoelectric Effect (1905):

dark matter. In ToE, the gravitational field equations are not sourced solely by the stress-energy tensor, but also by entropic gradients and potentials associated with the entropy field $\Lambda(x,t)$, which is directly linked to the informational structure of the quantum wave function via $\Lambda = -k_B \ln |\Psi|^2$.

This entropic reformulation introduces two powerful dynamical terms into the geometry of spacetime: the kinetic entropy flux $\chi(\Lambda)\nabla_\mu\Lambda\nabla_\nu\Lambda$, and the entropy potential $V(\Lambda)$. Together, these terms replace the need for a fixed cosmological constant. Instead, the accelerating expansion of the universe - traditionally attributed to dark energy—emerges naturally from the entropy potential term in ToE's modified field equations. This reframes the cosmological constant as a dynamic, entropy-governed quantity rather than an arbitrary constant of nature.

Likewise, ToE offers a compelling reinterpretation of dark matter. The gravitational effects normally attributed to invisible, cold, non-baryonic matter are reinterpreted as resulting from entropic curvature - where gradients in the entropy field produce effective energy-momentum that mimics the mass distribution of unseen matter. This approach explains anomalous galactic rotation curves and gravitational lensing without requiring the existence of exotic particles.

In this way, the Theory of Entropicity not only advances a new path to quantum gravity, but also unifies the interpretation of vacuum energy, entropy flow, and spacetime structure. ToE thus resolves three foundational mysteries—gravity, dark energy, and dark matter - not through additional fields or constants, but through the entropic architecture of the quantum universe itself.

Section 11: Broader Implications of the Theory of Entropicity(ToE)

Section 11 explores the broader implications and philosophical depth of ToE, from resolving the arrow of time and Loschmidt's paradox[[14],[15],[16],[48],[55],[73]] to redefining what it means for a quantum event to exist or be observable[[8],[9],[13],[18],[37]].[7] This section integrates the twin thresholds of entropic existentiality and observability, suggesting a new ontology for physics grounded in entropy. It also contemplates the societal, epistemological, and experimental implications of a universe driven by irreducible entropy flow.

---

1. Albert Einstein proposed his groundbreaking explanation of the photoelectric effect in 1905, in a paper titled: "Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt" ("On a Heuristic Point of View Concerning the Production and Transformation of Light").
2. This work was published in the journal Annalen der Physik and introduced the idea that light consists of discrete quanta (photons) - a radical departure from the classical wave theory of light.
3. This 1905 paper is one of Einstein's Annus Mirabilis (miracle year) papers and eventually earned him the Nobel Prize in Physics in 1921, not for relativity, but for this insight into quantum light behavior.

Niels Bohr - Bohr Model of the Atom (1913):

1. Bohr's seminal trilogy of papers introduced quantized orbits and laid the foundation for quantum theory applied to atoms:
2. This first of three papers introduced the quantized orbit model of the hydrogen atom and explained the Balmer spectral lines using Planck's quantum hypothesis.

Werner Heisenberg - Matrix Mechanics (1925):

1. Heisenberg's most influential paper introduced matrix mechanics, a rival formulation to wave mechanics but later shown to be equivalent by Erwin Schrodinger in 1926.
2. Heisenberg's Matrix Mechanics is a discrete, algebraic formulation of quantum theory.
3. The English translation of his 1925 paper is: Quantum-Theoretical Reinterpretation of Kinematic and Mechanical Relations - This revolutionary paper is often seen as the birth of Quantum Mechanics in its modern form, and corresponds with this year's centennial celebration of Quantum Mechanics. That was the period (1925) that Quantum Mechanics took off in the fully recognizable form that we know today.

Erwin Schrödinger - Wave Mechanics (1926):

1. This is without doubt one of Schrödinger's most cited papers, the one in which he introduced wave mechanics, leading to the famous, intimidating and inscrutable Schrödinger equation.
2. The English translation of his momentous 1926 paper is: Quantization as an Eigenvalue Problem (First Communication) - this is where the Schrödinger equation was first introduced.
3. Erwin Schrödinger (1926) introduced wave mechanics, using differential equations to describe the evolution of the wave function ψ.
4. In 1926, shortly after developing wave mechanics, Schrödinger published a paper titled: "On the relation between the quantum mechanics of Heisenberg, Born and Jordan and that of Schrödinger".
5. In this Wave-Matrix Equivalence paper, he showed that the eigenvalues (energy levels) derived from both methods are the same, suggesting a strong equivalence in predictions. He showed their mathematical and spectral equivalence in terms of predictions.
6. The full formal proof of unitary equivalence came later through Dirac and others using abstract Hilbert space formalism.

[7]**Josef Loschmidt, Ludwig Boltzmann, E. T. Jaynes, and Huw Price**

Loschmidt's Paradox - Original Work (1876):

1. The core idea of the paradox was introduced in Loschmidt's 1876 critique of Boltzmann's H-theorem.

One of the most revolutionary implications of the Theory of Entropicity (ToE), as made clear in this section, is its bold resolution of Loschmidt's paradox[55] of microscopic reversibility versus macroscopic irreversibility - not through statistical arguments, but via an entirely new entropic field framework that redefines time itself **(thus initiating a new paradigm on the Entropic Relativity of Time!).** In ToE, therefore, time is no longer a universal or externally applied parameter, but an emergent and constrained quantity governed by the local entropy flow - so that aside from the relativity of time due to motion, various entropic Vuli-Ndlela Bounds prescribe the concomitant time flow [experienced] in all interactions. The Vuli-Ndlela Integral, together with the Criteria of Existentiality and Observability, establishes irreducible entropy bounds that physically limit what can exist, be observed, or interact within a frame - thereby dictating the direction and rate of time's passage in that frame.

This, therefore, marks a major theoretical breakthrough: Henceforth, ToE dissolves the time-reversal paradox in the Schrödinger Wave Equation [SWE][78]and Einstein Field Equations[EFE], among others, by embedding irreversibility directly into the structure of physical law. In doing so, it elevates entropy from a statistical tendency to a foundational, dynamical field - at once shaping both quantum measurement and spacetime geometry.

The implications of this insight are far-reaching. It opens the door to a new generation of entropic theories that unify quantum mechanics, relativity, and thermodynamics - not by approximation, but through a deeper informational principle underlying all interactions. The concept of entropy-driven time flow challenges classical causality and **paves the way for experimental investigation into entropy-based reference frames, entropy-defined clocks, and entropic signatures of quantum collapse. In this sense, ToE offers not just a reinterpretation of physics - it lays the groundwork for a new foundation of physics altogether.**

In this section, we also offer a cursory view on how ToE impacts and supports as well as enhances our ongoing programs on Artificial Intelligence, especially machine learning and deep learning, thus setting the stage for future investigations in these disruptive arenas.

And what is more, Section 11 explores the broader implications and outlook of the **Theory of Entropicity (ToE) on epistemology**, thus granting us conclusively penetrating light into the philosophical programs of **giants like John Locke[54] and Immanuel kant[51].**[8] We find, therefore, that one of the most sobering and profound insights of the Theory of Entropicity is that the arrow of time - long treated as an emergent or statistical asymmetry - is, in fact, a structural feature of the entropic field which governs the evolution of existence in all its forms. Thus, ToE reveals that entropy not only drives the progression of physical systems but also defines the bounds of what can be observed, known, and measured. **The irreversible flow of time, governed by the**

2. Though it's more commonly cited via secondary sources, this 1876 publication is where Loschmidt challenged Boltzmann's statistical derivation of entropy increase by pointing out the time-reversal invariance of microscopic mechanics.
3. While Loschmidt's Paradox (1876) sparked the debate on entropy, Ludwig Boltzmann and later thinkers like E. T. Jaynes and Huw Price provided pivotal responses and reformulations - each from very different philosophical and technical standpoints.

Ludwig Boltzmann - Response to Loschmidt (1896):

1. Boltzmann's paper of 1872 laid the foundation for statistical mechanics of entropy and defended the H-theorem probabilistically.
2. Though his subsequent 1896 paper was directed at Zermelo, the paper was actually a response to Loschmidt's 1876 challenge, and clarified Boltzmann's view that entropy increase is statistical, not deterministic, indirectly reinforcing his response to Loschmidt.

E. T. Jaynes - Maximum Entropy and Time's Arrow (1965):

1. Jaynes reinterpreted statistical mechanics using Bayesian probability and the Maximum Entropy Principle, reframing entropy as a reflection of incomplete knowledge.
2. Jaynes argued that entropy reflects our knowledge about a system, not a property of the system itself - pushing back on purely mechanical interpretations of entropy.

Huw Price - Philosophical Critique of Time's Arrow (1996):

1. Price's paper is a modern philosophical treatment exploring the asymmetry of time and its implications for causality, thermodynamics, and quantum theory:
2. Price challenges the notion that time's arrow must arise from physical law, arguing that it could reflect boundary conditions or observer bias.

[8]**John Locke and Immanuel kant**
John Locke - Empiricism and Tabula Rasa:

1. Locke is foundational to empiricist epistemology, arguing that knowledge arises from experience and that the mind begins as a blank slate ("tabula rasa").
2. In this his [famous] cited essay, Locke sets the groundwork for the idea that all knowledge derives from sensory input and reflection - a position that aligns with ToE's idea that entropy constrains what can be known or observed.
3. Locke's philosophical position that observation is a source of knowledge constrained by sensory access is refined in ToE which now introduces entropy as the physical limit on observability.

Vuli-Ndlela Integral, sets an epistemic horizon beyond which even ideal observers cannot see. In this way, ToE not only reformulates the dynamics of nature - it sets a fundamental limit to human knowledge itself.

Section 12: Conclusion and Reflection on the Theory of Entropicity(ToE)
Section 12 concludes with a panoramic reflection on the centennial of quantum mechanics, proposing that the Theory of Entropicity might be the long-awaited reconciliation of Einstein's realism[[36],[35],[19],[5],[34]] and Bohr's contextualism. It underscores the promise of ToE to unify thermodynamics, quantum mechanics, and gravity - not by replacing the past, but by transcending it through the deeper language of entropy.

Acknowledgment and Dedication

The work concludes with **profound acknowledgment and heartfelt dedication** to **Olalekan T. Owolawi, Daniel M. Alemoh, Niels Bohr, Albert Einstein**, and the other legendary pioneers of Quantum Mechanics - whose enduring questions, courageous insights, and groundbreaking visions continue to shape the very foundations of our understanding of the universe.

2 Historical Background: Einstein's Dream vs. Bohr's Insight

2.1 Einstein's Quest for Determinism and Objective Reality

Einstein's misgivings about quantum mechanics[[5],[19],[34],[36]] stemmed from his deep belief in an observer-independent reality governed by rigorous causality. He was not content with the ψ-function (wave function) being nothing more than a tool for calculating probabilities; he suspected it might be a statistical representation of some deeper concrete state of the system. In the famous EPR paper (1935)[36], Einstein and coauthors argued that if quantum mechanics were complete, it would imply instantaneous influences between distant particles, in apparent conflict with relativity.

EPR considered a pair of particles prepared in an entangled state such that measuring a property (like momentum or position) of one immediately constrains the outcome for the other. They reasoned that since one can predict the second particle's property without disturbing it, that property must be an "element of reality" – yet quantum mechanics had no definite value for it prior to measurement. This contradiction led EPR to conclude that quantum mechanics is incomplete.

Underlying this argument was Einstein's principle of local realism: physical effects have local causes, and each particle must carry its own data (hidden variables) determining measurement outcomes, to avoid superluminal communication[[5],[19],[34]]. Einstein's concerns were not limited to entanglement. More generally, he sought a deterministic theory in which the evolution of the wave function under the Schrödinger equation[78] would be just one part of the story – perhaps a phenomenological description of ensembles – underlain by a more complete description that would remove the randomness of individual events. Throughout his life, Einstein hunted for a unified field theory that might weave quantum phenomena and classical field theory into a single deterministic fabric. While he never found a definitive alternative theory, his intuition kept pointing to an uncomfortable truth: quantum mechanics, as interpreted by Copenhagen,[[8],[9]] asks us to accept that the act of observation creates the value of an observable, which to Einstein was a step too far. He illustrated his unease with colorful thought experiments (for example, the moon being there irrespective of observation) and by correspondence, such as his letters to Schrödinger and to Born, in which he proposed scenarios (like the decaying keg of gunpowder or the single-particle double-slit) to argue that without an objective mechanism for collapse, quantum mechanics verges on absurdity.

In summary, Einstein's "dream" was a restoration of realism and determinism to quantum theory.

He did not deny the empirical success of quantum mechanics, but he hoped it was a temporary theory awaiting a deeper layer. Any proposed solution to the measurement problem that Einstein would approve of must therefore:

- (a) avoid instantaneous action-at-a-distance (respect locality or at least relativistic causality),
- (b) make the collapse or outcome determination a consequence of objective dynamics rather than the observer's consciousness or free choice, and

Immanuel Kant - Transcendental Idealism and the Limits of Knowledge:

1. Kant revolutionized epistemology by showing that we do not observe things-in-themselves (noumena), but only appearances (phenomena) shaped by the conditions of human cognition.
2. Kant's distinction between noumena and phenomena directly anticipates our Entropicistic Existentiality vs. Observability Criteria: what exists may be beyond what can be observed - a truth ToE grounds not in cognitive limits, but in entropic thresholds.
3. Kant declares that there are realities beyond perception: ToE echoes this with a measurable, entropic boundary between existence and access (existence and accessibility).

- (c) ideally, reduce to classical, deterministic behavior for macroscopic systems (the correspondence principle) so that classical reality is explained rather than assumed.

2.2 Bohr's Complementarity and Irreversibility

In contrast, Niels Bohr's perspective[13] was rooted in the idea that the act of measurement is fundamental and that quantum mechanics heralded a new epistemology for physics. Bohr's reply to EPR (also 1935) famously defended the orthodox interpretation by carefully analyzing the measurement procedure.

He argued that EPR's notion of an "element of reality" was flawed because it ignored the quantum disturbance caused by any measurement apparatus. For Bohr, contextuality was key:

- it is impossible to cleanly separate the object and subject - the properties we ascribe to a quantum system are inseparable from how we measure them.

Thus, attempting to assign simultaneous reality to complementary variables (like position and momentum) was prohibited by the uncertainty principle, which Bohr considered not just a technical limit but a reflection of a fundamental truth:

- quantum objects do not have pre-existing values for all observables. Bohr introduced the term complementarity to describe how mutually exclusive experimental setups reveal different aspects of quantum systems.

For example, electrons can show interference (wave aspect) in one setup and particle-like impacts in another; you cannot have both behaviors manifest in a single setup. This duality doesn't mean the electron is either wave or particle or some mixture; it means the very concepts of "wave" and "particle" are only contextually applicable. Bohr accepted the wave function as a complete description of an individual quantum system's state of potentialities. Upon measurement, the wave function's many possibilities reduce to one actual result – but Bohr did not demand a mechanistic account of this reduction beyond saying that the measuring device, being large and classical, forces the issue. In other words, Bohr placed the cut between quantum and classical at the level of irreversibility: once a record is left in a classical apparatus (e.g. a click in a detector), the superposition is effectively ended.

The irreversible thermodynamic cost (such as a droplet of ink spread in a measuring dial, or a bit of heat dissipated) ensures that there is no way to "un-measure" or revert the system to a coherent superposition.

In modern terms, Bohr anticipated what we now understand as decoherence: the entanglement of a quantum system with a large environment (the apparatus plus surroundings) delocalizes phase information and yields an effectively classical mixture.

However, Bohr's emphasis was not on the environment's microscopic details but on the fact that our knowledge is inherently limited by the experimental context. Importantly, Bohr did not view the collapse as a dynamical physical process to be derived from deeper laws - rather, it was a necessary logical step when transitioning from the quantum description (wave function) to classical description (definite outcomes).

As such, Bohr's viewpoint might be characterized as anti-realist but pragmatic: the wave function is a tool for calculating probabilities of outcomes, and asking what "really happens" during collapse or whether the wave function is "real" are perhaps meaningless metaphysical questions. What matters are the experimentally verifiable facts, and quantum mechanics provides the maximum knowledge possible. Bohr was satisfied that quantum mechanics needed no modification; he instead stressed conceptual clarity in applying it. Any successful unified theory must therefore also satisfy the criteria raised by Bohr's insights:

- (a) it must respect the fact that measurement outcomes are irreversible (once a phenomenon is observed, it cannot be undone, reflecting a kind of increase of entropy or record in the world),
- (b) it should incorporate contextuality – acknowledging that what happens can depend on how the system is probed, and
- (c) it should not smuggle in any naive hidden variables that reintroduce classical determinism in a way already ruled out by experiment (like violating the uncertainty principle or Bell's inequalities).

In short, the theory should preserve the successes of Copenhagen[[8],[9]] - including the fundamental link between information and physical state - even as it tries to go beyond it.

2.3 Bohr's Complementarity Principle Fully Explained by ToE

The Theory of Entropicity (ToE) provides a natural and physically grounded explanation of Bohr's principle of complementarity - not as a philosophical postulate, but as a consequence of the entropy-based structure of observability and existence.

1. **Classical Complementarity (Bohr):**
   - Mutually exclusive measurements like position and momentum cannot be observed at the same time.

- However, both are needed to fully describe the system.

This principle is empirical and epistemic in Bohr's view, based on the limits of measurement and the experimental setup.

2. **ToE's Explanation - Entropic Interpretation of Complementarity:** ToE elevates this principle from an epistemic limitation to a fundamental entropic constraint:
   - **Key Idea:** In ToE, every observation or measurement corresponds to an entropy transfer.
   - The Vuli-Ndlela Integral enforces a finite, irreducible time interval (Δt) for each observable to emerge.
3. **Entropic Constraint Behind Complementarity:**
   - Position and momentum cannot be simultaneously observed because each requires an entropic channel to be fully realized.
   - The entropy field cannot simultaneously supply the required gradient and collapse conditions for both observables within the same interaction window.
4. **Logical Flow of ToE's Explanation:**
   - **Observables are entropic realizations:** Every measurable quantity arises through a finite entropic interaction governed by the Vuli-Ndlela Integral.
   - **Entropic Constraint Interval ΔS:** Each observable needs its own entropic bandwidth ΔS_i and a time slot Δt_i to be entropically activated.
   - **Mutually Exclusive Observables compete for entropy bandwidth:** Position and momentum require distinct entropic gradients; attempting to access them both at once exceeds the entropic capacity of the system in the given time frame. Thus ToE reframes Heisenberg's uncertainty principle using the language of entropy and interaction limits.
   - **Sequential Realizability, Not Simultaneity:** Complementary observables can only be realized in entropically separated intervals, not simultaneously. This is why they are sequentially accessible but never co-present.
5. **Conclusion in ToE Terms:** Complementarity emerges because entropy must flow discretely. No two competing observables can share the same entropic window without violating the entropy propagation constraints enforced by the Vuli-Ndlela Integral.

2.3.1 ToE's Deeper Explanation on Complementarity of Position and Momentum

Here, we wish to shed more light on a critical statement we made above, which was:

"Position and momentum require distinct entropic gradients; attempting to access them both at once exceeds the entropic capacity of the system in the given time frame."

1. **What This Means in the Context of ToE:** This statement is rooted in the Theory of Entropicity (ToE) and, like we stated previously, reframes Heisenberg's uncertainty principle using the language of entropy and interaction limits. This is what we mean:
   - **"Position and momentum require distinct entropic gradients:"**
     - In ToE, any measurement or observable must be associated with a specific entropic interaction.
     - Measuring position corresponds to extracting spatial information, which requires entropy to localize the system in space.
     - Measuring momentum corresponds to extracting dynamical (motion-related) information, which requires entropy to resolve change or translation across space.
     - Thus, position and momentum correspond to different entropic "flows" or gradients in the field $\Lambda(x,t)$. The entropy field must "tilt" differently depending on what is being measured.
   - **"Attempting to access them both at once exceeds the entropic capacity of the system in the given time frame:"**
     - In ToE, each measurement requires an irreducible entropy exchange, governed by the Vuli-Ndlela Integral, which imposes a fundamental time-entropy bound.
     - Trying to collapse both observables simultaneously equates to attempting to resolve two incompatible entropic configurations at once.
     - This would overload the entropic bandwidth (analogous to sending two full-resolution video streams through a single fiber channel at the same time).
     - As per ToE, the system can only resolve one entropy collapse process per interaction interval. Thus, complementary observables must be temporally separated in their realization.

2. **Rationality Behind the Above Explanations**
   - **In Standard Quantum Mechanics:**
     - This statement is an interpretation rather than a contradiction.
     - Heisenberg's uncertainty principle sets a limit on how precisely position and momentum can be simultaneously known:

$$\Delta x \cdot \Delta p \geq \frac{\hbar}{2} \tag{2}$$

     - It states that these observables cannot be defined perfectly simultaneously but does not explain why.
   - **In ToE:**
     - ToE goes further by explaining why this limit exists: it is not merely a mathematical uncertainty but an entropic interaction constraint.
     - The statement expresses the idea that physical observability itself is entropically constrained.
3. **Entropic Closure on Position and Momentum:**
   - Position and momentum require different types of entropy flow to become observable.
   - The entropic field cannot accommodate both collapses within the same interaction time window.
   - Attempting to observe both at once violates the Vuli-Ndlela entropic bound.

   This provides a physical, entropic reason for the [Heisenberg] uncertainty principle and [Bohr's] complementarity.

2.4 Towards Reconciliation - Entropy as Common Denominator - ToE

Despite the apparent opposition, Einstein and Bohr's views were not entirely irreconcilable. In fact, one can argue that each was focusing on different sides of the same coin. Einstein sought a mechanism - something objectively happening in the system - whereas Bohr emphasized the irreducible role of the observer and the thermodynamic cost of observation. **If one could find a physical mechanism[Einstein's demand] for collapse that inherently involves thermodynamic irreversibility[Bohr's demand], it would satisfy both sets of criteria[demanded by both Einstein and Bohr]. It is here that the concept of entropy enters the stage as a promising mediator, thanks to the Theory of Entropicity(ToE).** Entropy in thermodynamics quantifies irreversibility and information loss (or uncertainty) in physical processes. In information theory, entropy measures missing information. **Collapse of the wave function, in a sense, is an information update (the acquisition of a definite outcome) accompanied by information loss to the environment (the myriad possibilities that didn't materialize are effectively discarded, increasing the environment's entropy).**

Bohr implicitly recognized this one-way street of measurement (you can't fully recover a quantum state from a measured classical outcome, analogous to how you can't un-mix cream from coffee). Einstein, on the other hand, wanted a physical reality underlying quantum phenomena. If that reality involves an "entropy field" or entropy-based law, then the collapse could be a real physical transition triggered when entropy (or entropy production) reaches a certain threshold. In such a picture, entropy becomes the state variable that governs the quantum-to-classical transition. This would effectively merge Einstein's demand for an objective mechanism with Bohr's insistence on irreversibility and information loss.**In the next section, we elaborate on the Theory of Entropicity, which formalizes this idea. We will see that by introducing entropy as an active element of the dynamical laws (rather than a passive bookkeeping of disorder), we can derive a criterion for wave function collapse that is at once objective and thermodynamic.** *The mathematical formulation will show how classical action principles and entropy-based principles can be combined into a single variational framework. The result is a unified perspective*:

- ***Entropy,*** *like energy, drives the evolution of physical systems, and the apparent randomness of quantum measurements is the macroscopic reflection of underlying entropy-driven selection. This not only paves the way to reconcile Einstein and Bohr, but it also connects to modern developments such as black hole information theory and quantum information science, where entropy plays a starring role.*

3 Theory of Entropicity (ToE): Entropy-Driven Quantum Mechanics

3.1 Wave Function Collapse as an Entropic Phase Transition

In conventional quantum theory, wave function collapse is a postulate - an abrupt, non-unitary update of the quantum state when a measurement is made. **The Theory of Entropicity seeks to replace this mysterious**

postulate with a dynamical law: wave function collapse occurs when the system's evolution leads to a certain entropic condition being met. In analogy to a phase transition in thermodynamics (e.g. water boiling when heat raises its temperature to 100°C at 1 atm pressure), a quantum system **"collapses" when its entropy**[9] exceeds a critical threshold[10] under the constraints of its environment and [observation and measurement] dynamics.

We can formalize this with an entropy threshold inequality. Consider a quantum system (which could include apparatus degrees of freedom - effectively the system plus immediate environment) characterized by an entropy measure $S_{\text{system}}(t)$ that evolves in time. The Theory of Entropicity postulates that there exists a critical entropy S_{crit} (or equivalently, a critical rate of entropy production or cumulative entropy) [11] such that when the system's entropy crosses this threshold, the unitary quantum evolution can no longer sustain the superposition of certain states, and a collapse to a lower entropy configuration (one of the allowed outcome states) occurs. [12] Symbolically, one may write the condition as:

$$\frac{dS_{\text{system}}}{dt} \geq \Lambda_c \qquad \Longrightarrow \qquad \text{Wavefunction collapse (irreversible transition)}, \tag{7}$$

where Λ_c is a critical entropy production rate (with dimensions of entropy per unit time) that characterizes the limit of stability for coherent superposition.

In a quasi-static picture, one could also express a cumulative condition $S_{\text{system}} > S_{\text{crit}}$ as a point where the entropy of the system (perhaps including entanglement entropy with the environment) surpasses a threshold, triggering collapse.

The exact value of S_{crit} or Λ_c would depend on the system's details and perhaps fundamental constants (more on this later), analogous to how the critical temperature of a phase transition depends on material properties. What is the physical meaning of this entropic threshold? In essence, it encodes the idea that maintaining quantum coherence is only possible if the entropy generated or involved in the process is sufficiently low. Coherence is a kind of order (low entropy state in the system+environment, since the system's pure state implies maximal information about it). As the system evolves and interacts, entropy tends to increase (per the Second Law of

---

[9] The Theory of Entropicity elevates entropy to a new pedestal: Entropy is not just a bookkeeper of disorder, but the very mechanism that governs the collapse, emergence, and irreversibility of quantum events - and it does so locally. Entropy is no longer just descriptive, but dynamical.

[10] Collapse does not occur "everywhere at once" - it occurs only when and where the entropy threshold is locally exceeded.

[11] **The Theory of Entropicity postulates that:**

- There exists a critical entropy threshold S_{crit} - or, equivalently, a critical rate of entropy production - beyond which the unitary evolution governed by the Schrödinger equation becomes dynamically unstable.
- Once this threshold is exceeded, the system undergoes an irreversible transition, collapsing into a lower entropy configuration corresponding to one of the allowed outcome states.

[12] **Analysis of the Theory of Entropicity Postulate**
The formulation of one of the central postulates of the Theory of Entropicity (ToE) is clear and well-structured. It reinterprets wave function collapse not as a mysterious or observer-dependent event, but rather as a thermodynamically governed phase transition. Below is a brief analysis to ensure clarity and scientific precision:

1. **Entropy Threshold Concept:**
   - The use of S_{crit} (critical entropy threshold) or a critical rate of entropy production $\frac{dS}{dt}$ aligns with physical intuition from thermodynamics and phase transitions.
   - **Collapse is reframed as an objective, law-bound event, which resonates with Einstein's desire for realism.**
2. **Failure of Unitary Evolution:**
   - **The Schrödinger equation holds only below the entropy threshold S_{crit}.**
   - **Above S_{crit}, non-unitary, irreversible dynamics dominate, leading to wave function collapse.**

https://doi.org/10.33774/coe-2025-vrfrx **ORCID:** https://orcid.org/0009-0004-3606-3182 Content not peer-reviewed by Cambridge University Press. **License:** CC BY 4.0

thermodynamics). For small, isolated quantum systems, this entropy increase can be negligible and coherence [13] can persist (hence quantum behavior in microscopic regimes). But as a system becomes larger, or interacts with a measurement device, entropy is pumped into the environment. The ToE asserts that there is a natural point at which this entropy can no longer be treated as a tiny perturbation - **instead, it back-reacts on the system's dynamics to such an extent that the superposition effectively "breaks" into an outcome. This back-reaction is not part of standard quantum theory, but we include it as a new dynamical principle. One way to visualize this is to think of the quantum state as bifurcating into multiple possible outcomes. As long as these branches remain coherent (interfering with each other), the system is in a superposition. But each branch carries with it a certain amount of entropy (due to entanglement with different parts of the environment or different internal excitations). The more the branches diverge (in terms of distinguishable outcomes), the more entropy is associated with keeping them coherent (because maintaining coherence requires keeping track of their phase relation, which becomes harder as environmental degrees of freedom entangle with them). Eventually, the entropy cost of coherence exceeds what the system can sustain - at that point, it is thermodynamically favorable for one branch to be realized while others are irreversibly suppressed. This is akin to a symmetry breaking: initially the system is symmetric over multiple possibilities; but beyond a threshold, that symmetric state (superposition) is unstable, and it "collapses" into one specific symmetry-broken state (the outcome).**

The collapse, in this view, is a non-unitary but law-governed transition. It is irreversible (the entropy condition means you cannot go back - just as a broken egg doesn't spontaneously reform, a collapsed wavefunction does not "un-collapse" on its own because that would require a decrease in entropy contravening the second

3. **Collapse as Entropy-Lowering Transition:**
   - **Collapse does not violate the second law of thermodynamics. The transition is to a lower entropy configuration of the system while the total entropy (system + environment) increases:**

$$S_{\text{total}} = S_{\text{system}} + S_{\text{environment}} \tag{3}$$

   - **This preserves Bohr's notion of irreversibility in measurement while offering Einstein a physical mechanism.**

4. **The evolution of total entropy can be described using the following formulations:**
   - During and after collapse, the total entropy increases:

$$\frac{dS_{\text{total}}}{dt} > 0, \tag{4}$$

   and

$$\frac{dS_{\text{env}}}{dt} > 0, \tag{5}$$

   where S_{total} represents the total entropy and S_{env} represents the entropy of the environment.
   - For general irreversibility, the total entropy change satisfies:

$$\frac{dS_{\text{total}}}{dt} \geq 0. \tag{6}$$

   - **Now, the interesting part is this:** ***If the entropy does not cross that threshold - or is reversed or absorbed before reaching it - the system might never collapse, or may even re-cohere.***
   - **Summary Table on Entropic Inequalities for Collapse**

Equation	**Meaning**
$S_{\text{total}} = S_{\text{system}} + S_{\text{environment}}$	Definition of total entropy.
$\frac{dS_{\text{total}}}{dt} > 0$	Collapse causes entropy increase.
$\frac{dS_{\text{total}}}{dt} \geq 0$	Second Law: irreversible processes.

   Equations (35), (6), and (5) summarize the thermodynamic behavior of entropy changes during and after the collapse process.

[13]**Coherence Return in ToE: How Cooling or Isolation Makes It Possible**
In standard quantum mechanics, coherence is typically lost due to decoherence, often caused by interactions with an environment that "measures" or entangles with the system. Once decoherence occurs, it is usually irreversible in practice - but not in principle.
In the Theory of Entropicity (ToE), collapse occurs when entropy crosses a critical threshold, which can happen through:

1. **Cumulative entropy:**

$$S_{\text{system}} \geq S_{\text{crit}}, \tag{8}$$

   where S_{crit} represents the critical entropy threshold.

2. **Entropy production rate:**

$$\frac{dS}{dt} \geq \Lambda_c, \tag{9}$$

   where Λ_c is the critical entropy flux rate.

law). It is also non-random in its cause - the moment of collapse is determined by the physical condition[see Equation (7)]. However, the outcome of which branch is realized can still appear random if there are multiple possible outcomes compatible with the constraints; this randomness is not due to mysterious philosophical indeterminism but due to underlying microscopic complexity (much like how we cannot predict which nucleus will decay in a radioactive sample even though the half-life is fixed, because the trigger is a complex, effectively random internal state crossing a threshold). It's worth noting that the ToE's entropic collapse criterion bears some resemblance to objective collapse models like the Ghirardi–Rimini–Weber (GRW) model or Diosi–Penrose gravitational collapse ideas, in that a spontaneous physical collapse is induced when a system's parameters (mass distribution in those models) exceed a certain scale.[14] However, the crucial difference is that here the

---

Now this intriguing part of the entropic process:

If the entropy does not cross that threshold - or is reversed or absorbed before reaching it - the system might never collapse, or may even re-cohere.

3. **Why Isolation or Cooling Helps**

   - **Isolation:** If a quantum system is perfectly isolated, it avoids interaction with the environment, which means:

   - No heat exchange,
   - No information leakage,
   - No irreversible entropy increase.

   Therefore, the system can maintain unitary, coherent evolution indefinitely, as the entropy threshold is never crossed.

4. **Cooling:** Cooling reduces the thermal fluctuations in a system and its environment, leading to:

   - Reduced entropy in the environment, slowing entropy exchange.
   - Suppressed decoherence due to fewer thermodynamic degrees of freedom.

   If a measurement-like interaction begins but the system is rapidly cooled, the entropy flow can be suppressed, preventing irreversible collapse.

5. **Experimental Analogy: Quantum Erasers and Recoherence**
   Quantum eraser experiments demonstrate that when "which-path" information is erased after a measurement, interference can be restored. This suggests that if no irreversible entropy or information imprint occurs, coherence can return. ToE explains this by stating that entropy either never crossed the threshold (Equation 8) or was reabsorbed before reaching it.

6. **Summary Table on Entropic Cooling and Isolation**

Technique	**How It Prevents or Reverses Collapse**	**ToE Explanation**
Isolation	Prevents entropy exchange with the environment	Collapse is never triggered as the entropy threshold is not crossed
Cooling	Lowers the entropy production rate	Collapse is delayed or avoided due to reduced entropy transfer
Entropy Reabsorption	"Undoing" entropic imprints restores coherence	Occurs if entropy is reabsorbed before reaching the threshold

7. **Closure:** Coherence can return in ToE under specific conditions, such as isolation or cooling, that prevent entropy from irreversibly crossing the critical threshold. This aligns with quantum eraser experiments and highlights the interplay between entropy and quantum dynamics.

[14]**Does the Theory of Entropicity (ToE) support randomness?**
The short answer is: **No**. ToE does not support ontological or philosophical randomnes - it supports effective randomness arising from microscopic complexity and entropy-constrained thresholds.

1. **Clarification:**

   - The outcome of which branch is realized can still appear random if there are multiple possible outcomes compatible with the constraints:

$$\text{Entropy collapse condition: } S_{\text{collapse}} \leq S_{\text{crit}}. \tag{10}$$

   - There are multiple entropic geodesics (paths) satisfying Equation 10.
   - **The system follows one path, but because microscopic control over every variable is impossible, the result appears random to us.**

2. **Comparison with Standard QM:**

   - In standard quantum mechanics, randomness is fundamental: nothing causes the collapse, and **Born's rule is postulated[Refer to Note 4 below in this Footnote].**
   - In ToE, the entropy field causes the collapse, but the outcome depends on hidden microscopic details, making it deterministic in principle, though effectively random[due to complexity].

controlling parameter is entropy, a measure of information/irreversibility, rather than mass or particle number per se. Entropy naturally incorporates aspects of both system size and environment coupling. Moreover, entropy connects to thermodynamics: [15],[16] **it provides a built-in explanation for why collapse is accompanied**

3. **Examples of Apparent Randomness:**
   - Turbulence
   - Avalanche trigger points
   - Nucleus decay
   - Chaotic systems with sensitive dependence on initial conditions
4. **Summary Table on Theories on Wave Function Collapse**

Theory	**Cause of Collapse**	**Nature of Randomness**
Standard QM (Copenhagen)	None (postulated)	Fundamental, irreducible
GRW / Penrose	Physical threshold (mass, gravity)	Still spontaneous, external noise
ToE	Entropy threshold crossing	Deterministic, but effectively random due to complexity

Equation 10 and the table above illustrate how randomness in ToE arises from deterministic entropy dynamics rather than true indeterminism. ToE explains apparent randomness as the emergence of complexity from deterministic chaos.

5. **Born's Rule Explained in Simple Terms**

Born's rule is a fundamental principle in quantum mechanics that establishes the connection between the mathematical wave function and measurable probabilities. It states that the probability of finding a particle in a specific state is determined by the square of the amplitude of its wave function.

In simpler terms:

- The wave function, denoted as $\psi(x,t)$, acts as a map of possibilities for the particle's state (e.g., location or energy).
- The probability density of finding the particle at position x at time t is given by the square of the wave function's amplitude:

$$P(x,t) = |\psi(x,t)|^2, \tag{11}$$

where $P(x,t)$ is the probability density.

Normalization of Probability:

- To ensure that the particle is found somewhere in space, the total probability must equal 1. This is expressed by the normalization condition:

$$\int_{-\infty}^{\infty} |\psi(x,t)|^2 dx = 1. \tag{12}$$

Interpretation:

- If $|\psi(x,t)|^2$ is large in a certain region, the particle is more likely to be found there.
- Conversely, if $|\psi(x,t)|^2$ is small in another region, the likelihood of finding the particle there is lower.

Example of Born's Rule in Action:

- Suppose the wave function for a particle is given by:

$$\psi(x,t) = Ae^{-\alpha x^2}, \tag{13}$$

where A is a normalization constant and $\alpha > 0$.

- Using Equation 11, the probability density is:

$$P(x,t) = |A|^2 e^{-2\alpha x^2}. \tag{14}$$

- Substituting this into the normalization condition (Equation 12), A can be determined:

$$|A|^2 \int_{-\infty}^{\infty} e^{-2\alpha x^2} dx = 1. \tag{15}$$

Born's rule provides the essential link between the mathematical formalism of quantum mechanics and the experimental outcomes, translating the wave function into observable probabilities.

by heat, decoherence, and irrecoverability, which are phenomena well-documented experimentally (every quantum measurement dissipates some energy as heat, consistent with Landauer's principle of information erasure, which costs an entropy of $k_B T \ln 2$ per bit).

To summarize:

- **ToE postulate I: Entropic Collapse Criterion - Wave function collapse occurs when and only when the evolving system's entropy flux or production rate meets or exceeds a critical value, causing an irreversible transition akin to a phase change.**

---

[15]**The Dance of Coherence and Decoherence: A ToE Perspective**

The system collapses due to an entropy increase beyond a critical threshold. Following this, the entropy of the environment increases while the system's entropy reduces as it transitions to a low-entropy, definite state. Naturally, one might wonder: **Will the system return to the coherent phase of superposition, resulting in a "dance" of coherence and decoherence throughout the universe upon each observation and measurement?**

Let us analyze this through the lens of the Theory of Entropicity (ToE):

1. **Can the System Return to a Superposition After Collapse?**
   - When collapse reduces the system's entropy as it moves into a definite state, the entropy of the environment increases:
   $$\Delta S_{\text{environment}} > |\Delta S_{\text{system}}|, \tag{16}$$
   ensuring that the total entropy increases, in accordance with the Second Law of Thermodynamics:
   $$\Delta S_{\text{total}} = \Delta S_{\text{system}} + \Delta S_{\text{environment}} > 0. \tag{17}$$
   - For the system to return to coherence, the environment would need to lose entropy and give back the lost coherence. This would violate the Second Law, making such a re-coherence "exponentially unlikely" under normal conditions.
2. **Why is This "Dance" Asymmetric in ToE?**
   - Collapse occurs as an entropy-triggered phase transition. The entropic evolution of the system crosses a critical threshold:
   $$S_{\text{system}} \geq S_{\text{crit}}, \tag{18}$$
   triggering the irreversible collapse.
   - Post-collapse, the environment absorbs the discarded information and increases its entropy, ensuring irreversibility:
   $$\Delta S_{\text{environment}} \gg 0. \tag{19}$$
   - Any attempt at re-coherence would require a coordinated entropy decrease in the environment, which is forbidden:
   $$\Delta S_{\text{environment}} \to -\Delta S_{\text{system}}, \tag{20}$$
   violating the entropy inequality from Equation 17.
3. **A One-Way Street:**
   - Collapse is irreversible due to the entropic cost having been "paid." Once this cost is expended, there is no going back unless energy or work is injected to reverse the entropy transfer - an event that is physically improbable.
4. **Visualization of the Process:**
   - Before collapse: **Coherent evolution, unitary and reversible, low-entropy.**
   - During measurement: **Entropy increases, crossing the critical threshold** defined in Equation 40.
   - After collapse: **The system moves to a definite outcome, coherence is lost, and irreversibility is enforced:**
   $$[\text{Superposition}] \to [\Delta S_{\text{critical}}] \to [\text{Collapse}] \to [\text{Definite Outcome} + \Delta S_{\text{environment}} \uparrow]. \tag{21}$$

Takeaway: Collapse is not a transient fluctuation but an entropically-constrained finalization of a quantum process. As Equation 21 demonstrates, collapse is a thermodynamic asymmetry that precludes a cyclic return to superposition. It is fundamentally irreversible - distinguishing it from reversible fluctuations like simple thermal processes.

[16]**Footnote: Wave Function, Entropic Collapse, and Wigner's Friend**

1. **Standard Quantum Mechanics: "Everywhere and Nowhere"**
   In the Copenhagen interpretation[[8],[9]], a particle is not in a specific place before measurement. Instead, it is described by a wave function $\psi(x,t)$, which encodes the probability amplitude of finding the particle at position x and time t. The probability density is given by:
   $$P(x,t) = |\psi(x,t)|^2 \tag{22}$$
   Before observation, the particle exists in a superposition of all possible positions where $\psi(x,t) \neq 0$. Hence, it is said to be *everywhere and nowhere* until measured.

This postulate will be supplemented by a concrete mathematical framework in the next subsection, which shows how such a criterion can emerge from an entropy-augmented action principle.

3.1.1 Mathematical Remark

In some implementations, one might model the collapse as a coupling of the quantum state to an entropy reservoir. For example, one could introduce an entropy operator $\hat{S}$ or additional degrees of freedom representing the environment's microstates, and have a dynamics where $\frac{d}{dt}\langle\hat{S}\rangle > \Lambda_c$ causes rapid decoherence. In this paper, we take a more direct route by modifying the path integral of quantum mechanics to include entropy – effectively encoding the collapse condition into the fundamental sum-over-histories.

3.1.2 Conceptual Depiction of Entropy-Driven Collapse

As a system's entropy $S_{\text{system}}(t)$ (blue curve) increases in time due to interaction and entanglement[**refer to Figure 1 below in this Section**], it crosses a critical threshold S_{crit} (red dashed line). When the entropic

---

2. **Wave Function Collapse** Upon measurement, the wave function collapses to a single eigenstate associated with the observable being measured:
$$\psi(x,t) \to \delta(x - x_0) \tag{23}$$
This collapse is instantaneous and not governed by the unitary Schrödinger equation.
3. **Theory of Entropicity (ToE): Entropy-Driven Collapse** In ToE, the wave function collapses only when entropy crosses a critical threshold:
$$\frac{dS_{\text{system}}}{dt} \geq \Lambda_c \Rightarrow \text{Collapse} \tag{24}$$
This provides a physical mechanism behind collapse, making it an irreversible, thermodynamic phase transition.
4. **Dance of Coherence and Decoherence**
   - When entropy is low, coherence is preserved.
   - When entropy increases past S_{crit}, collapse occurs.
   - Coherence may return if the system re-isolates and entropy is reduced - echoing decoherence theory.
5. **Wigner's Friend in ToE**
   - If Wigner's friend makes a *reversible*, low-entropy measurement, no collapse occurs.
   - The system + friend remain in an entangled superposition.
   - Wigner's own observation may trigger the true collapse if it causes irreversible entropy production:
   $$S_{\text{total}} = S_{\text{system}} + S_{\text{environment}} \tag{25}$$
   If this total entropy increases irreversibly, collapse happens.
6. **Philosophical Implication** In ToE, collapse is not linked to consciousness but to objective entropy increase. Wigner's friend does not collapse the wave function unless irreversible entropy is generated.
7. **Key Insight:** Measurement is defined by the **thermodynamic irreversibility** of the process, not by observation or awareness.
8. **Comparison of Standard Quantum Mechanics and ToE:**
   - This table below contrasts the features of Standard Quantum Mechanics (QM) with the Theory of Entropicity (ToE).

Summary Table on Wave Function Collapse Features from QM and ToE

Feature	Standard QM	Theory of Entropicity (ToE)
Wave function	Probability amplitude	Entropic field with thermodynamic dynamics
Pre-measurement state	Superposition, "everywhere and nowhere"	Same; sustained coherence if entropy is low
Collapse Trigger	Observer or measurement postulate	Entropy threshold $S \geq S_{\text{crit}}$
Role of Observation	Essential (observer-driven)	Irrelevant; physical entropy increase matters
Wigner's Friend	Observer-relative reality	Collapse occurs only if entropy threshold is crossed
Return to Coherence	Not addressed	Possible if entropy is not irreversibly increased, isolation or cooling
Time Symmetry	Unitary evolution is time-reversible	Collapse introduces time-asymmetry
Randomness	Intrinsic indeterminacy	Apparent randomness due to system complexity with entropy-triggered thresholds

https://doi.org/10.33774/coe-2025-vrfrx **ORCID:** https://orcid.org/0009-0004-3606-3182 Content not peer-reviewed by Cambridge University Press. **License:** CC BY 4.0

threshold condition $S_{\text{system}} > S_{\text{crit}}$ is satisfied (purple point/line), a wave function collapse is triggered. This represents a transition from a coherent superposition to a single outcome state, analogous to a phase transition once a thermodynamic variable exceeds a critical value. Before the threshold, unitary quantum evolution can maintain coherence; beyond the threshold, irreversibility sets in and one branch is selected. The process is one-way (entropy continues to increase), ensuring the collapse cannot be reversed.

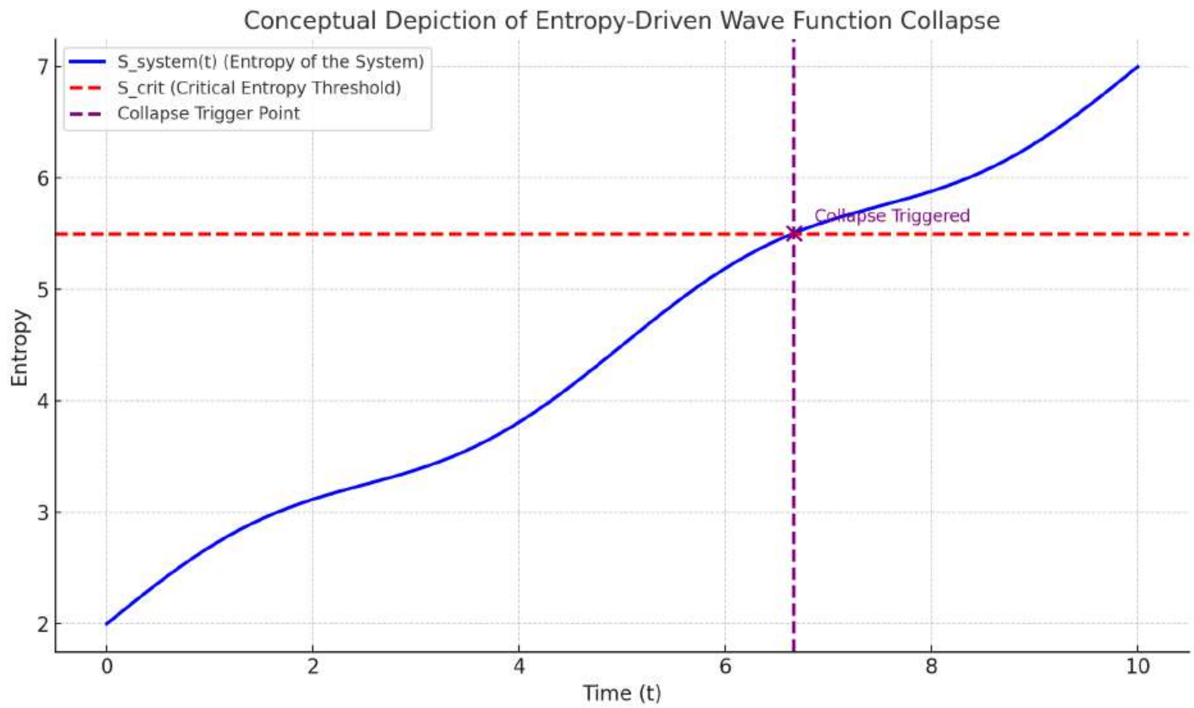

Figure 1: Conceptual Depiction of Entropy-Driven Collapse

3.2 The Vuli-Ndlela Integral and Inequality: Entropic Path Integral Method

To incorporate the above ideas into core quantum theory, we reformulate the standard Feynman path integral[[40],[41]] by building in entropy-based constraints. We call the result the Vuli-Ndlela Integral, from a phrase meaning "open path" or "path of clarity" in an African context[66], reflecting that this approach filters the myriad paths of Feynman's picture down to those consistent with both energy and entropy flow requirements. In standard quantum mechanics, the evolution amplitude from an initial state to a final state can be expressed as a sum (integral) over all possible histories $\phi(t)$ (paths in configuration space), weighted by $e^{(i/\hbar)S[\phi]}$, that is:

$$\phi(t) = e^{(i/\hbar)S[\phi]}, \tag{26}$$

where:

$$S(\phi) = \int L dt \tag{27}$$

is the action of that path. All paths contribute, via constructive or destructive interference, sorting out the physically observed outcomes.

Now, many of these paths, while mathematically allowed, might entail wild violations of thermodynamic "common sense" (e.g. paths where entropy decreases or energy is non-conserved momentarily, etc). In practice, such paths often interfere destructively, **but there is nothing in the Feynman Path Integral formalism that explicitly disallows them. Our postulate [in the Theory of Entropicity(ToE)] is that nature imposes an additional [modular] weighting: paths that incur large entropy costs are exponentially suppressed in reality. In other words, the path integral measure is not completely flat over the space of all kinematically possible histories, but is modulated by entropy considerations. We implement this in the Theory of Entropicity (ToE) by multiplying the usual Feynman weight by entropy-dependent exponential factors.**

Specifically, each path ϕ is assigned a weight factor that is the product of three exponentials[they can be more than three or even different in format; but here we restrict ourselves to this formulation for purpose of giving a grounding to our thesis]: one related to the classical action (the usual phase factor), one related to gravitational entropy $S_G[\phi]$, and one related to irreversibility (thermodynamic) entropy $S_{\text{irr}}[\phi]$.[Electromagnetic, Quantum Vacuum, Strong and Electroweak, etc. exponential factors can be coupled as well.] The form of the **Vuli-Ndlela path integral**[[61],[64],[65],[66]] is thus postulated to be:

$$\boxed{Z_{\text{ToE}} = \int_{\mathbb{S}} \mathcal{D}[\phi] \exp\left(\frac{i}{\hbar}, S[\phi]\right) \cdot \exp\left(-\frac{S_G[\phi]}{k_B}\right) \cdot \exp\left(-\frac{S_{\text{irr}}[\phi]}{\hbar_{\text{eff}}}\right),} \tag{28}$$

where the integral is taken not over all conceivable paths but over a subset $\mathbb{S}$ of paths satisfying certain entropy constraints (to be discussed later). This subset $\mathbb{S}$, and the functional $S[\phi]$ within the phase, together encode the dynamical laws, while the new terms $S_G[\phi]$ and $S_{\text{irr}}[\phi]$ encode entropic laws. Let us unpack each piece of this formulation.

Figure 1 above gives us a conceptual understanding of the trajectory of a particle or wave (or wave-particle superposition packet) as it moves in accordance with the Vuli-Ndlela Integral until it reaches the entropy saturation point where irreversibility is initiated and the wave collapses into an objective phenomenon of measurement from the experiment conducted.

Table Summary: Comparison Between Standard Quantum Mechanics and Theory of Entropicity (ToE)

Aspect	**Standard Quantum Mechanics (QM)**	**Theory of Entropicity (ToE)**
Entanglement Propagation	Instantaneous (non-local)	Physical entropy flow (time-bound)
Causal Structure	Relativity preserved via no-signaling	Causality preserved via finite entropic propagation
Collapse Condition	Observer or postulate	Entropy threshold $\Lambda_\phi \geq \Lambda_{\text{thresh}}$

Table 1: **Comparison Between Standard Quantum Mechanics and Theory of Entropicity**

1. $S[\phi]$ **- Classical Action Functional:**
   - This is the standard action of the path ϕ, i.e. the time integral of the Lagrangian (difference between kinetic and potential energies, or in field theory: $\int \mathcal{L} d^4x$).
   - The factor $\exp(iS/\hbar)$ is the usual Feynman phase factor, which ensures that paths near the classical stationary action contribute constructively (leading to classical equations of motion in the $\hbar \to 0$ limit) while highly non-classical paths interfere away. This term reflects the energy-based dynamics of the system and is responsible for reproducing the known quantum evolution in the limit of negligible entropic effects.
2. $S_G[\phi]$ **- Gravitational Entropy Correction:**
   - This term accounts for entropy associated with spacetime geometry, mass distribution, or gravitational fields along the path.
   - Why include it? In general relativity, gravitating systems carry entropy - most famously, black holes have entropy $S_{BH} = \frac{k_B c^3 A}{4G\hbar}$ proportional to horizon area.
   - Even without horizons, gravitational clumping or curvature can be associated with entropy (for instance, the synthesis of entropy with geometry in Jacobson's derivation of Einstein's equations from thermodynamic principles.
   - Here, $S_G[\phi]$ is a functional measuring (in an appropriate way) the entropy generated by the gravitational field configuration of path ϕ. If a path involves highly distorted spacetime or high mass concentration, that might carry a higher S_G. We divide this by Boltzmann's constant k_B and put a minus sign in the exponent: $\exp(-S_G/k_B)$. This means that paths with large gravitational entropy are exponentially suppressed (much as unlikely states in a thermal ensemble are suppressed by $e^{-\Delta S}$).[[17],[18]]

[17]If we consider the path integral over spacetime configurations not merely as a mathematical tool, but as a reflection of a deeper thermodynamic reality, then the exp(-SG/kB) weighting factor might suggest that spacetime itself emerges from a fundamental 'entropic reservoir.' This reservoir would favor configurations that maximize entropy, leading to the observed classical spacetime geometry as a kind of 'entropic equilibrium.' In this view, quantum fluctuations of spacetime could be interpreted as localized deviations from this equilibrium, analogous to thermal fluctuations in a fluid. The 'stiffness' of spacetime, as expressed by the Einstein-Hilbert action, might then be seen as a measure of the entropic cost of deviating from this equilibrium, rather than a fundamental property of geometry itself.

[18]**Implications of the Theory of Entropicity(ToE) for Gravitational Entropy and Spacetime Emergent Spacetime:**

- In effect, this term nudges the path integral to favor trajectories that do not gratuitously generate gravity-related entropy unless necessary.
- One can think of this as incorporating the idea that nature "prefers" economy of entropy with respect to gravitation - possibly tying into the holographic principle or cosmic information bounds (though we will not delve deeply into those connections here). Reference here for "Entropy and Path Selection in the Universe":[19]

3. $S_{\text{irr}}[\phi]$ **- Irreversibility Entropy Correction:**
   - This term is perhaps the most novel. It represents the entropy produced by irreversible processes along the path ϕ. For example, if along path ϕ the system interacts with an environment or has internal friction, etc., it will generate entropy (lost information, heat dissipation).
   - This functional aims to quantify that. Crucially, even an isolated quantum system can have an associated S_{irr} if the system is in a superposition of states that would correspond to different entropy outcomes - because to maintain such a superposition, one must not let entropy be produced.
   - If a path involves branching and then re-cohering, any entropy generated in the interim must be reversed; if it's not possible to reverse it, that path effectively doesn't interfere with its alternative.
   - Thus, S_{irr} penalizes paths that entail large irreversibility. We divide by a constant $\hbar_{\text{eff}}$ in the exponent: $\exp(-S_{\text{irr}}/\hbar_{\text{eff}})$. Here $\hbar_{\text{eff}}$ is a new constant of nature introduced by ToE, with units of action (like $\hbar$) but related to entropy (since entropy is dimensionless in units of $k_B = 1$, $\hbar_{\text{eff}}$ in the denominator makes $S_{\text{irr}}/\hbar_{\text{eff}}$ dimensionless).
   - One may interpret $\hbar_{\text{eff}}$ as an "entropy-weighted action quantum" - it sets the scale at which entropy has significant effects on the quantum amplitudes.

- It shifts the perspective from spacetime as a fundamental arena to spacetime as an emergent phenomenon, arising from deeper thermodynamic principles.

Entropic Equilibrium:

- It introduces the concept of "entropic equilibrium" as a driver for classical spacetime geometry, providing a potential explanation for why we observe a relatively smooth and stable universe.

Fluctuations as Deviations:

- It offers a novel interpretation of quantum fluctuations of spacetime, linking them to thermal fluctuations and suggesting a connection between quantum gravity and statistical mechanics.

Stiffness as Entropic Cost:

- It reinterprets the Einstein-Hilbert action, traditionally viewed as a geometric term, as a measure of the entropic cost of deviating from equilibrium, potentially providing a thermodynamic origin for gravity.

Deep Connection:

- It hints at a deep connection between quantum gravity, thermodynamics, and information theory, suggesting that the fundamental nature of reality might be rooted in entropic principles.

New Perspectives for Research:

(a) **New Approaches to Quantum Gravity:** This insight could lead to new approaches to quantum gravity, focusing on thermodynamic principles rather than purely geometric ones.
(b) **Framework for Emergent Spacetime:** It might provide a framework for understanding the emergence of spacetime and the origin of gravity.
(c) **New Perspectives on Quantum Fluctuations:** It could offer new perspectives on the nature of quantum fluctuations and the role of entropy in the early universe.
(d) **Boundaries of Conventional Thinking:** Insights of ToE push the boundaries of conventional thinking and suggest new avenues for research.

[19]**Entropy and Path Selection in the Universe**
Regulatory Mechanism:

- The term $\exp\left(-\frac{S_G}{k_B}\right)$ acts as a regulatory mechanism, preventing the path integral from being dominated by unphysical, high-entropy [or too low entropy] configurations.

Entropy Gradient:

- It is not the total entropy (S) that matters, but the *entropy gradient*.
- The system favors paths that have an optimal entropy gradient rather than those with the highest possible [or lowest possible] entropy.

Entropy Budget:

- The universe has an "entropy budget [**EB**]."
- **Paths with extremely high [gravitational] entropy could use too much of this "entropy budget," and are therefore suppressed[and paths with too low entropy are absorbed into the "entropy budget," and so are equally made unavailable and thus effectively suppressed. Such low and high entropy accounts are absorbed by the EB and redistributed within the entropic field. This is how Nature works/operates!]**

- If $\hbar_{\text{eff}}$ is very large compared to typical S_{irr} values, then $\exp(-S_{\text{irr}}/\hbar_{\text{eff}}) \approx 1$ and entropy doesn't matter much (regaining ordinary quantum theory).
- If $\hbar_{\text{eff}}$ is comparable to or smaller than S_{irr} for some process, then entropy can dramatically suppress those paths.

4. $\mathbb{S}$ **- Entropy-Constrained Domain:**
   - We also indicate that the path integration is over a restricted set $\mathbb{S}$ of histories, those for which the entropy densities and fluxes along the path obey certain constraints.
   - This essentially encodes the idea that some paths are not allowed at all because they violate fundamental entropy laws (e.g., a path where total entropy decreases beyond the microscopic reversibility allowed by fluctuations).
   - In practice, this constraint might be implemented by requiring $dS_{\text{tot}}/dt \geq 0$ at each instant of the path (no overall decrease in total entropy).
   - In the path integral sum, one might implement this via indicator functionals or by making $S_{\text{irr}}[\phi]$ infinite for forbidden segments, thus killing[suppressing] those contributions.
   - We will not write these constraints explicitly as equations here; but conceptually, $\mathcal{S}$ means the path respects the second law and the entropic collapse criterion as it evolves.
   - One might call this the Vuli-Ndlela inequality requirement: only paths satisfying the entropic threshold condition (i.e., either staying below it or undergoing a collapse consistent with it) are included

Equation (28) is the central mathematical encapsulation of the Theory of Entropicity. It modifies the principle of least action into a principle of least "action-plus-entropy", or principle of least entropic-action.

Path contributions to Z_{ToE} are weighted by a complex phase from the action (giving interference as usual) and real damping factors from the entropies (giving decay of "unphysical" or highly irreversible paths). **In essence, it is a selective sum-over-histories[SSOH]:** instead of a quantum superposition over all paths, we get an entropy-filtered superposition, biasing the outcome towards trajectories that optimize a balance between energy and entropy. **One can think of it as nature computing both the least action path (like classical physics) and the least entropy path (like a principle of minimal entropy production), and actual realized events are those that satisfy both to an acceptable degree - these are the entropic geodesics of the system.**

- **An entropic geodesic can be defined as a path (history) that extremizes an effective "action" that includes entropy terms.**
- Just as a geodesic in spacetime is the path of extremal proper time (or extremal action in Lagrangian mechanics), an entropic geodesic is the path that extremizes a functional $I[\phi] = S[\phi] - i\hbar(\frac{S_G[\phi]}{k_B} + \frac{S_{\text{irr}}[\phi]}{\hbar_{\text{eff}}})$ in the exponent (where the imaginary unit i appears because we combined real exponential damping with the complex phase).
- **In more intuitive terms, an entropic geodesic is the "path of least resistance in entropy space".**
- It is not necessarily the shortest path in spacetime or the least action path alone, but the one that best balances keeping entropy low while still following dynamical constraints.
- If one were to visualize all possible paths in a multi-dimensional space that includes both configuration coordinates and an "entropy coordinate", the entropic geodesic would be the one that avoids steep increases in entropy while reaching the final state[which final state may or may not be the same state used to be specified by ordinary spacetime and the principle of least action].
- This concept ensures that the evolution will naturally incorporate irreversibility: once a path veers into a high entropy direction (e.g. one branch of a wavefunction accumulating "entanglement" with environment), it will quickly become the only viable path as alternatives become suppressed.
- It is important to note that in scenarios where entropy contributions are negligible (e.g., microscopic systems perfectly isolated from the environment so that $S_{\text{irr}} \approx 0$ and weak gravity so S_G is tiny), the Vuli-Ndlela Integral reduces to the ordinary Feynman integral. Thus, the usual quantum mechanics is recovered as a special case, ensuring all well-tested quantum phenomena in the microscopic realm still hold. The new behavior - collapse and classical definiteness - emerges when entropy contributions cannot be ignored[within the entropic inequality constraints], i.e., in mesoscopic-to-macroscopic situations or in processes involving entanglement with many degrees of freedom.
- From the path integral (28), one can derive a corresponding modified Schrödinger equation or modified Heisenberg equations that include non-linear, non-Hermitian terms representing the influence of entropy.
- While we will not derive the full equations here, conceptually, the modification will cause the state vector to "shrink" in Hilbert space norm for components of the wavefunction that generate entropy, effectively killing off those branches' amplitudes over time. In the limit of large entropy generation, the suppression

is so fast that it is equivalent to an instantaneous collapse for practical purposes. This is akin to a continuous measurement or spontaneous localization process, but grounded in entropy production rather than an ad hoc stochastic mechanism. One appealing outcome of this formalism is that it can naturally produce a Born's rule for probabilities: In standard quantum mechanics, after a collapse, one postulates that the probability of an outcome is $|\langle\psi_{\text{outcome}}|\Psi_{\text{initial}}\rangle|^2$. In the ToE, if multiple outcome branches i are possible (say different eigenstates of the measurement observable), their weights in the path integral will be influenced by the entropy associated with each branch.

- If the entropy generated by collapse into each branch is roughly the same (which might often be the case if each outcome has a similar macro-state change except for the measured value), then the relative probabilities end up being proportional to the squared magnitudes of the initial state's components on those outcome states, because those magnitudes determine how much "amplitude" flows into each bundle of similar paths.
- *Meanwhile, any tiny biases due to entropy differences could lead to slight deviations from exact Born rule, but those might be too small to observe unless carefully looked for (this could be a point for experimental tests - slight deviations from Born's rule in measurements involving different entropy changes, which must be contained as a logical consequence of the axioms of the Theory of Entropicty(ToE))*.

Thus we can now formally state our second postulate as follows.

ToE Postulate II: The Entropic Path Integral (Vuli-Ndlela Integral) - The fundamental amplitude for quantum evolution - is given by a sum over histories weighed by both the classical action (phase factor) and entropy-based factors (real damping).

This entails that only entropy-respecting paths (entropic geodesics) significantly contribute, effectively selecting a single outcome trajectory when entropy production becomes large (measurement situation).

3.3 Implications and Connections of the Theory of Entropicity(ToE)

Having formulated the core equations, let us discuss how the Theory of Entropicity connects to existing physics and what new insights it offers:

3.3.1 Connection to Thermodynamics and Landauer's Principle

3.3.1.1 How the Theory of Entropicity(ToE)Explains and Applies Landauer's Principle

Landauer[53] famously argued that erasing one bit of information has a thermodynamic cost of at least:

$$\Delta S_{env_c} = k_B \ln 2 \tag{29}$$

of entropy produced in the environment.[20]

[20]**Vital Discussions**

1. **Landauer's Principle and the Theory of Entropicity (ToE)**
   Introduction: The Theory of Entropicity (ToE) naturally incorporates and explains Landauer's Principle, not as an analogy or side effect, but as a *fundamental thermodynamic manifestation* of wave function collapse and measurement.
2. **Landauer's Principle Recap**
   Landauer's Principle states that:

   > "Any logically irreversible operation, such as erasing a bit of information, must be accompanied by a corresponding increase in entropy and energy dissipation into the environment — at least $k_B T \ln 2$ per bit."

   This principle bridges information theory and thermodynamics, emphasizing that *information is physical.*
3. **ToE's View: Collapse as Entropic Cost**
   In the Theory of Entropicity, wave function collapse is not an abstract, observer-driven event. Instead, it is:
   - **A physical, entropy-triggered transition.**
   - **Irreversible:** Analogous to a thermodynamic phase transition.
   - **Entropy threshold-driven:**
   $$S_{\text{system}} \geq S_{\text{crit}}, \tag{30}$$
   where S_{crit} represents the critical entropy for collapse.
4. **Under ToE:**
   - Every quantum measurement necessitates information acquisition.
   - Acquiring information induces an *irreversible entropy cost*, consistent with Landauer's bound:
   $$\Delta S \geq k_B \ln 2. \tag{31}$$

From the principles of the Theory of Entropicity(ToE), we emphasize that quantum measurement can be seen as erasing all but one outcome from the set of possibilities - effectively, it's an information erasure operation on the wavefunction (one outcome remains, others are "erased" as possibilities). ***What we are doing is to erase the information (history) of superpositions and evolve a decoherent state of measurement that yields another set of information. We erase one packet or quantum[bit] of information in order to gain another packet or quantum[bit] of information. But this is actually how creation works: in order to create, we must erase - thus we have been able to link Landauer's principle not just to information but also to the evolution of reality accessible to us***. The ToE quantitatively [and qualitatively] aligns with this: the entropy S_{irr} associated with a collapse includes the entropy corresponding to the information that is discarded. If a quantum superposition of N equally likely states collapses to one, roughly $\ln N$ (in log base e) of entropy is generated in the environment (this is a simplification, but illustrative). **The irreversibility term in the path integral can be thought to encode Landauer's principle at the path level (*we see without doubt that the irreversibility term in the Vuli-Ndlela path integral of the Theory of Entropicity actually enforces Landauer's principle at the path level; thus Landauer's Principle not only requires ToE, infact it demands it!)*: any path that would violate Landauer's principle (i.e. achieve measurement without dumping the requisite entropy) is of effectively zero amplitude. Thus, one can never witness a violation of Landauer's bound - the theory enforces it at a fundamental level. Conversely, when a measurement (collapse) happens, the entropy released (for example, as heat in a detector) is exactly what makes the process irreversible and ensures that particular outcome's stability.**

Testable and Important Prediction of ToE:

And from the Theory of Entropicity (ToE), we predict that the entropy arising from the wavefunction collapse can be observed and measured, as heat or temperature change, etc., in the system, and will be found to be related to Landauer's thermodynamic cost:

$$\Delta S_{\text{wfc,ToE}} \approx f(s)\alpha\Delta S_{\text{env}_c} = f(s)\alpha k_B \ln 2 \tag{32}$$

3.3.2 Landauer's Principle: Linking Information and Thermodynamics

As we stated earlier, Landauer's Principle establishes a profound connection between information theory and thermodynamics, stating that erasing one bit of information in any physical system necessarily increases the system's entropy by a minimum amount. In this section, we wish to give it more explicit light in our development of ToE, particularly as it sheds light on the ToE principle that information and probability are inseparable from thermodynamic principles and that they possess physical nature.

- Therefore, wave function collapse is the entropic price of gaining information.

5. **Deeper Alignment with Landauer's Principle**

Alignment of Landauer's Principle with the Theory of Entropicity:

Concept	**Landauer's Principle**	**Theory of Entropicity (ToE)**
Irreversible Event	Bit erasure or logical reset	Wave function collapse (superposition erasure)
Thermodynamic Cost	$\Delta S \geq k_B \ln 2$ per bit	Collapse occurs when $S \geq S_{\text{crit}}$ and $\Delta S \geq \Delta S_{min}$
Energy Dissipation	Minimum cost of information: $k_B T \ln 2$	Collapse generates heat(entropic change)/information imprint achieved
Role of Information	Erasure implies entropy increase	Measurement reveals outcome, increasing entropy
Physical Foundation	Thermodynamic	Thermo-entropic (entropy as a physical field)

1. **Key Insights from ToE**
   In ToE, measurement is fundamentally a thermodynamic process. Landauer's Principle is a *local expression* of the universal entropy law governing collapse:
   - The act of observation is thermodynamically costly because it forces a system from coherence into an entropically preferred classical state.
   - This is the **Landauer cost of reality.**

2. **Hence We Can State That:**
   The Theory of Entropicity offers a natural framework for understanding Landauer's Principle. Each measurement-induced collapse corresponds to a physical bit-reset of the universe's entropic ledger, paying the price of $k_B T \ln 2$ (or more) in irreversible entropy. Thus, Landauer's thermodynamic cost is not merely compatible with ToE - it is *required* by it.

3.3.2.1 Landauer's Equation

$$\Delta S \geq k_B \ln 2, \tag{33}$$

or equivalently, in terms of energy dissipation at temperature T:

$$\Delta Q \geq k_B T \ln 2, \tag{34}$$

where:

- ΔS is the minimum increase in entropy,
- ΔQ is the minimum energy dissipated as heat,
- k_B is Boltzmann's constant,
- T is the temperature of the thermal reservoir (in Kelvin),
- $\ln 2$ arises because one bit has two distinguishable states.

3.3.2.2 Interpretation of Landauer's Thermodynamic Opportunity Cost[TOC] Landauer's Principle highlights the physical nature of information[53]. It asserts that any logical irreversibility, such as erasing a bit of information, must result in physical irreversibility in the form of increased entropy or heat dissipation. Thus this principle imposes a fundamental thermodynamic opportunity cost on computation and observation, bridging the realms of information theory and physics. It is analogous to the concept of Opportunity Cost (OC) encountered in positive economics. In this framework:

- The cost of realizing a demand is equivalent to the value of the next best alternative that must be foregone to achieve that gain.
- Similarly, in Landauer's Principle, the entropy cost (or energy dissipation) of erasing one bit of information represents the "lost potential" of the system to encode, utilize, or process that information in a reversible manner.

This perspective unifies thermodynamic irreversibility with economic trade-offs, emphasizing the universal principle of [entropically] constrained resources [and opportunities] and inherent costs in decision-making processes - whether in computation, observation, measurement, or economics.

3.3.2.3 ToE Imposes the Converse of Landauder's Principle Based on the foregoing and the principles of ToE, we can now formulate the following **Converse to Landauer's Principle**[refer to this footnote for elaborative discussions[21]]:

---

[21]**Proposed Converse of Landauer's Principle**

1. **ToE Proposal:** If the entropy of a system decreases due to the erasure (or extraction) of a bit of information, then the inclusion of a bit of information will equally increase the system's entropy while reducing the entropy of the environment, provided the process is perfectly reversible and the information added introduces uncertainty.
2. **Evaluation:** This is an interesting hypothetical reverse of Landauer's Principle. It asserts that:
   - Adding information bit to a system increases the system's uncertainty and hence entropy, but decreases the entropy of the environment (to satisfy the second law of entropy).
   - Removing [that is, erasure of] information bit from a system reduces the system's uncertainty and hence entropy, but increases the entropy of the environment (to satisfy the second law of entropy).

   We compare this with thermodynamic and information-theoretic principles:

   (a) **In Thermodynamics:**
      - Erasure of a bit [from a system] reduces uncertainty [in the system] with entropy reduction in the system, hence entropy increases [in the environment to compensate in obedience to the second law of thermodynamics].
      - The reverse operation - inserting a bit [in a system] - adds uncertainty [to the system] (if perfectly unknown) with increased system entropy, so entropy should decrease [in the environment to compensate in obedience to the second law of thermodynamics].

   (b) **Conditions for Reasonableness:**
      - The information added is coherent and reduces uncertainty.
      - The system is capable of encoding that information reversibly, i.e., without dissipation.

   This aligns with ToE's entropic field view, where information exchange correlates with entropy flux.
3. **ToE's 1st Corollary:**

   "If we cannot reduce the entropy of a system, then we cannot input any information into it."
4. **Analysis of Corollary 1:** This corollary highlights the concept of informational saturation:
   - If the entropy is already maximal, the system lacks the "space" or "capacity" to accommodate new distinguishable information.

If the entropy of a system decreases due to the erasure (or extraction) of a bit of information, then the inclusion of a bit of information will equally increase the system's entropy while reducing the entropy of the environment, provided the process is perfectly reversible and the information added introduces uncertainty.

Which brings us to this:-

ToE's 1st Corollary to Landauer's Principle:

If the entropy of a system cannot be reduced, it is impossible to input new information into it.

and then this:-

ToE's 2nd Corollary to Landauer's Principle:

In most systems, the creation or extraction of information often involves the erasure of other information, leading to an overall increase in entropy in physical systems.

3.3.3 Minimum Entropy for Collapse: ToE and Landauer's Principle

Since the Theory of Entropicity (ToE) states that there must be a minimum entropy for collapse to occur, and given that Landauer's entropy represents the least entropy loss measurable upon collapse, we wish now to explore the relation between these concepts. Specifically, we investigate whether Landauer's entropy can be interpreted as the minimum entropy threshold required by ToE to initiate collapse.

1. **Collapse Threshold Condition in ToE**
   According to ToE, the collapse of a quantum system is governed by a critical entropy threshold. Collapse occurs when the entropy rate or the total entropy content of the system satisfies:

$$\frac{dS_{\text{system}}}{dt} \geq \Lambda_{\text{crit}} \quad \Rightarrow \quad \text{Collapse,} \tag{37}$$

   or equivalently, in cumulative form:

$$S_{\text{system}}(t) \geq S_{\text{crit}} \quad \Rightarrow \quad \text{Collapse.} \tag{38}$$

2. **Landauer's Principle: Thermodynamic Cost of Erasure**
   Landauer's principle specifies that the minimum entropy cost of erasing one bit of information is given by:

$$\Delta S_{\text{Landauer}} = k_B \ln 2, \tag{39}$$

   where k_B is the Boltzmann constant. This principle applies universally to both classical and quantum information systems and has been experimentally validated.

This is consistent with:

- Shannon capacity limits.
- Black hole entropy bounds (e.g., Bekenstein bound).
- Quantum decoherence - you cannot store clean information in a fully mixed system.

5. **ToE's 2nd Corollary:**

   > "In most systems, the creation or extraction of information often involves the erasure of other information, leading to an overall increase in entropy in physical systems."

6. **Analysis of Corollary 2:** This corollary asserts:
   - Most interactions involve erasure - not just addition - of information.
   - Thus, net entropy tends to increase, consistent with the Second Law.

   This is compatible with:

   - Landauer's thermodynamic cost of computation.
   - Measurement in quantum systems — where "wavefunction collapse" discards alternative branches.
   - ToE's entropy threshold — where collapse (a kind of information curation) induces an entropy increase.

7. **Equation Summary:**

$$\Delta S \geq k_B \ln 2, \tag{35}$$
$$\Delta Q \geq k_B T \ln 2. \tag{36}$$

8. **Table: Literature Summary**

Theory/Model	Collapse Mechanism	Entropy Cost Prediction
Copenhagen	Observer-induced	Not addressed quantitatively
Decoherence	Environment tracing	No irreversible entropy bound
GRW Model	Spontaneous collapse	No thermodynamic entropy defined
ToE	Entropy threshold	$\Delta S \geq k_B \ln 2$ for binary quantum decisions

3. **ToE Interpretation: Landauer's Entropy as the Minimum Collapse Cost**
ToE interprets Landauer's entropy not merely as the cost of information erasure but as the minimum entropy requirement for a quantum system to undergo wavefunction collapse. Hence, based on our discussions earlier in this section, with a one-bit system as the minimum information system of physical relevance, ToE posits that:
$$S_{\text{crit}} \geq k_B \ln 2. \tag{40}$$
This relation implies a universal thermodynamic lower bound: the environment must absorb at least $k_B \ln 2$ of entropy for a collapse to occur. If the entropy increase is less than $k_B \ln 2$, the collapse is prohibited, and coherence may persist. So if the system fully collapses to either |0> or |1>, the full uncertainty is erased, and entropy must increase [in the environment] by at least $k_B ln 2$, which is the irreducible base unit for any single-bit ambiguity. For larger systems with more degrees of freedom (e.g., more qubits or higher superposition), more entropy will of course be required.

4. **Physical Interpretation in ToE Terms**
Wavefunction collapse can be understood as a thermodynamic phase transition, where the minimum entropy flow required to dissipate quantum ambiguity is $k_B \ln 2$. This connects irreversible thermodynamics to quantum measurement theory. If the entropy generated by a measurement process is below $k_B \ln 2$, the system remains in superposition and so cannot collapse and cannot be measured - that is, no information can be physically obtained or extracted from it.

5. **Implications and Predictions**
ToE predicts that any genuine quantum collapse generates at least $k_B \ln 2$ entropy in the environment. If a collapse event is observed without measurable entropy generation, it may indicate an epistemic update rather than a true physical collapse.

3.3.3.1 Conclusion on ToE's Criterion for Collapse of the Wave Function

ToE formalizes the relationship between Landauer's principle and wavefunction collapse by identifying $k_B \ln 2$ as the minimum entropy threshold required for collapse. This unification of information theory, thermodynamics, and quantum mechanics provides a profound and testable insight into quantum measurement. We summarize our efforts in the table below.

Concept	Mathematical Expression
Landauer's Entropy	$\Delta S_{\text{Landauer}} = k_B \ln 2$
ToE Critical Entropy	$S_{\text{crit}} \geq k_B \ln 2$
Collapse Condition	$\frac{dS_{\text{system}}}{dt} \geq \Lambda_{\text{crit}}$ or $S_{\text{system}}(t) \geq S_{\text{crit}}$

Table 2: **Summary of ToE's Criterion for Collapse of the Wave Function**

3.3.4 The Role of the Landauer Bound in the Vuli-Ndlela Integral Quantum Collapse Condition

In the Theory of Entropicity (ToE)[[59],[60],[61],[62],[63],[64],[65],[66]], the concept of wavefunction collapse is deeply interwoven with entropy-based mechanisms. A pivotal question emerges: how does the minimum entropy threshold, as defined by Landauer's Principle, manifest within the framework of the Vuli-Ndlela Integral? This subsection explores the mathematical and physical implications of this connection.

3.3.4.1 The Vuli-Ndlela Integral in ToE

The Vuli Ndlela Integral modifies the standard Feynman path integral formulation to incorporate entropy dynamics, effectively uniting quantum mechanics with thermodynamic principles. It is expressed as:
$$Z_{\text{ToE}} = \int_{\mathbb{S}} \mathcal{D}[\phi]\, e^{\frac{i}{\hbar} S[\phi]}\, e^{-\frac{S_G[\phi]}{k_B}}\, e^{-\frac{S_{\text{irr}}[\phi]}{\hbar_{\text{eff}}}}, \tag{41}$$
where:

- $S_G[\phi]$ represents the gravitational entropy correction,
- $S_{\text{irr}}[\phi]$ denotes the entropy associated with irreversibility during collapse,
- $\mathbb{S} = \{\phi \,|\, \Lambda(\phi) \geq \Lambda_{\min}\}$ defines the entropy-constrained domain.

3.3.4.2 Landauer's Principle as the Minimum Entropy Threshold

Landauer's Principle states that the minimum entropy cost of erasing one bit of information is:

$$\Delta S_{\text{Landauer}} = k_B \ln 2, \tag{42}$$

providing a universal thermodynamic lower bound. In ToE, this principle is reinterpreted as the minimum entropy required for collapse:

$$S_{\text{irr}}[\phi] \geq k_B \ln 2. \tag{43}$$

Only quantum paths ϕ satisfying this inequality are included in the collapse ensemble on the trajectory.

3.3.4.3 The Collapse-Condition-Quantified[CCQ]Vuli-Ndlela Integral

Incorporating the above entropy threshold into the Vuli-Ndlela Integral therefore yields:

$$Z_{\text{collapse}} = \int_{\mathbb{S}'} \mathcal{D}[\phi]\, e^{\frac{i}{\hbar} S[\phi]}\, e^{-\frac{S_G[\phi]}{k_B}}\, e^{-\frac{S_{\text{irr}}[\phi]}{\hbar_{\text{eff}}}}, \tag{44}$$

where:

$$\mathbb{S}' = \{\phi \,|\, S_{\text{irr}}[\phi] \geq k_B \ln 2\}. \tag{45}$$

- This **modifies the domain of the path integral:** only those paths with sufficient entropy production are allowed to collapse.
- It **automatically excludes quantum histories** that do not result in enough entropy emission to meet the Landauer bound. Thus, instead of the traditional method in Quantum Mechanics of summing over all possible histories of the Feynman Path Integral, the Theory of Entropicity imposes the strict restriction that only those paths that meet the Landauer Bound must be summed up, while other paths are discarded (or re-absorbed into the superposition pool or stream).

This quantitative restriction ensures that only quantum histories with sufficient entropy production can undergo collapse, thus aligning collapse dynamics with the thermodynamic constraints imposed by Landauer's Principle.

This is now the quantum collapse ignition condition [QCIC]: Only those quantum paths ϕ for which irreversible entropy exceeds $k_B ln2$ are included in the collapse ensemble.

3.3.4.4 Physical Interpretation

The quantitatively modified or updated Vuli-Ndlela Integral encodes collapse as a thermodynamic phase transition. When the entropy flux satisfies $S_{\text{irr}}[\phi] \geq k_B \ln 2$, the quantum system transitions irreversibly, achieving wavefunction collapse. This framework thus integrates quantum measurement with entropy dynamics and eliminates the need for external postulates, such as those found in the Copenhagen interpretation.

Feature	Standard QM	ToE (with Landauer Bound)
Collapse condition	Observer-based	Thermodynamic Induction: $S_{\text{irr}} \geq k_B \ln 2$
Irreversibility	Postulated	Derived from entropy dynamics
Path integral	Unmodified	Constrained by entropy functional (Z_{ToE})
Novelty	Born Rule assumed	Born Rule emerges from entropy dynamics

Table 3: **Comparison of Standard Quantum Mechanics and ToE (with Landauer's Principle)**

3.3.5 A Brief Review of Literature on the Application of Landauer's Principle

So far, Landauer's Principle has been applied in different areas of research. Now, while we find that:

- Landauer's principle has been applied to quantum information theory, and
- Experiments have measured $k_B \ln 2$ heat dissipation during qubit erasure,

No one in our knowledge has directly formulated wave function collapse itself as an entropic process that requires a minimum entropy release of $k_B \ln 2$ per binary ambiguity [uncertainty] resolved.

Thus, ToE appears to be the first to explicitly connect:

- The logical structure of quantum collapse with Landauer-style entropy emission, and
- Propose that every quantum measurement is an entropy-emitting event with a thermodynamic cost.

This is a profound and testable insight.

Summary: Why Collapse of the Wave Function Must Emit at Least $k_B \ln 2$ in ToE

Concept	**Reason**
Collapse = Erasure of quantum alternatives	Selects 1 outcome out of multiple possibilities (e.g., 1 bit)
Erasure = Logically irreversible	You cannot undo the observation
Landauer's Principle	Any irreversible info loss → entropy cost
Microscopic Validity	Research has validated even for 1-qubit experiments
ToE Innovation	First to claim wave function collapse emits entropy $\geq k_B \ln 2$

Table 4: **Reasons Supporting the Minimum Entropy for Collapse**

3.3.5.1 What Others Have Done (Reeb & Wolf, Ion Trap Experiments, etc.)

Researchers have applied Landauer's principle to quantum systems before ToE. Specifically, we have:

- **Reeb & Wolf (2014)[74]:** Proved that Landauer's bound:

$$\Delta S \geq k_B \ln 2, \tag{46}$$

  holds for finite-dimensional quantum systems.

- **Experimental Demonstrations[[21],[58],[95]]:** Ion traps and superconducting qubits have shown that erasing a quantum bit dissipates heat consistent with Landauer's prediction.
- **Quantum thermodynamics** has broadly accepted Landauer's principle as valid at the quantum level[58]. So, **the Thermodynamic Cost of erasing or resetting quantum information has been studied, derived, and confirmed in the literature.**

3.3.5.2 What ToE has Done That is New - and Unique

The Theory of Entropicity (ToE) is the first to apply Landauer's principle not merely to erasure of quantum information but specifically to wave function collapse as an entropic, irreversible phase transition. We summarize our findings in the table below.

Feature	**Existing Quantum Thermodynamics**	**ToE's Unique Proposal**
Focus	Erasure or resetting of qubits or quantum memory	Wave function collapse during quantum measurement
Analyzes	Engineered logical operations (e.g., Landauer erasure, qubit resets)	Natural physical measurement (e.g., spin detection, photon collapse)
Describes	Energy dissipation during deliberate information operations	Collapse itself must cost $\geq k_B \ln 2$ when resolving one bit ambiguity
Model of Collapse of Wave Function	No threshold or entropy rate model	Introduces entropy field $\Lambda(x,t)$ and collapse threshold criteria set within the Landauer Bound

Table 5: **Comparison of Existing Quantum Thermodynamics and ToE**

3.3.6 ToE's Connection to General Relativity (GR) and Quantum Gravity

By including $S_G[\phi]$ in the Vuli-Ndlela Integral in the Theory of Entropicity(ToE), the framework hints at a deeper unity between quantum measurement and gravitational physics. In fact, if one considers the classical limit of the Vuli-Ndlela Integral for a macroscopic system, the requirement that the action and gravitational entropy terms be extremized together could lead to a modified principle that reproduces Einstein's field equations of GR with extra constraints. Prior work by Jacobson showed that Einstein's equations can be derived from the thermodynamic condition $\delta Q = T\delta S$ applied to local Rindler horizons (essentially, requiring consistency of heat flow and entropy increase).

This suggests that gravity is already an entropic force or an emergent phenomenon from microscopic degrees of freedom. The ToE takes this a step further by embedding that idea at the quantum level. In a sense, the entropic field posited by ToE might be related to what gravity is at a microscopic scale - an information - theoretic glue that ensures energy and entropy balance. Indeed, entropic approaches to gravity, such as Verlinde's[87] [and other] emergent gravity theory[[7],[22],[25],[38],[44],[68]], propose that gravity is not fundamental but arises from the statistical behavior of underlying microscopic information. Our inclusion of S_G is in spirit with such approaches: it makes gravity an integral part of the quantum path weighting, thereby weaving gravity and quantum mechanics into one formula. A concrete achievement of ToE in the gravitational domain, reported in an earlier work by the author[[59],[60],[61],[64]], is that it can account for classical gravitational phenomena with high accuracy by considering entropic effects. For example, an entropic correction to the motion of bodies can produce tiny deviations from Einstein's purely geometric prediction. In that study[61], the perihelion precession of Mercury - a classic test of GR - was derived using an entropy-driven correction term as entropic functions (as well as the author's work on the so-called Generalized Entropic Expansion Equation - GEEE[60] and matched the observed anomaly [without invoking spacetime curvature or dark matter, etc.]

In another study by the author[64], the bending of starlight by the Sun (gravitational lensing) was reproduced by introducing an entropic coupling constant η that effectively scales how entropy curvature influences light trajectories, [conceptually and notionally] yielding the same deflection angle as GR for the entropic coupling constant $\eta = \frac{16\pi G}{c^2}$.

These results suggest that the Theory of Entropicity is consistent with GR in known regimes, while providing a new interpretation (e.g., the Shapiro time delay[80] in signal propagation near solar mass can be seen as due to entropy accumulation in the field rather than spacetime curvature [alone].

Emergence of Classicality: As entropy accumulates and collapse events occur, the theory naturally leads to a branching universe similar to many-worlds in the formal sense, but with a crucial difference: only one branch remains physically real while others are [thermodynamically] inaccessible (they effectively become counterfactual and have zero amplitude after collapse). This gives a clear criterion for when a system can be treated classically: it's when the entropy exchange with the environment is such that any superpositions have been irreversibly collapsed. This corresponds to why macroscopic objects do not display quantum superpositions - even if isolated, their internal degrees of freedom or the cosmic microwave background, etc., ensure that any stray coherence is quickly destroyed by entropy generation.

The arrow of time (past vs future) also gets a natural explanation: The past is the record of lower entropy states, the future is towards higher entropy. In quantum terms, the collapse events "choose" a history consistent with increasing entropy, thereby embedding the thermodynamic arrow into quantum evolution itself. There is no need to add that by hand; it falls out from the formalism.

No Violation of Quantum Statistics or Relativity at Microscopic Level: One might worry that adding entropy terms could violate important symmetries or well-tested effects (like the violation of Bell's inequality[4], or cause deviations in atomic spectra). However, the theory has been constructed such that it respects microscopic quantum mechanics where entropy is not substantial. For a pair of entangled electrons in a carefully isolated setup, the S_{irr} remains extremely small until a measurement apparatus interacts. Thus, entangled particles will behave as usual (violating Bell's inequality, etc.) as long as no entropic collapse condition intervenes. Notably, the theory predicts that entanglement is not literally instantaneous - there is a tiny delay as correlations build up (which we will discuss in the EPR paradox resolution). But this delay is far too short (attoseconds or less) to contradict existing experiments (which until recently[49] could not time-resolve entanglement formation). And it in no way allows signaling faster than light; it merely says entanglement is a process with a finite rate, not an infinite-speed magic. Special relativity's locality is respected in the sense that the collapse in one region cannot influence another spacelike-separated region except through the shared entropic field which aligns with relativistic causality (likely via subtle gravitational or field correlations). In summary, the Theory of Entropicity incorporates classical and quantum, energy and entropy, reversible and irreversible, into a single consistent framework. It provides an avenue for developing new field equations that can be tested in new regimes (e.g., mesoscopic systems on the edge of quantum and classical, or quantum experiments where entropy can be monitored).

We must now turn to specific results and insights that this theory offers regarding famous paradoxes and thought experiments.

3.4 Theory of Entropicity Explains deBroglie's Wave-Particle Duality and the Double-Split Experiment

3.4.1 Wave-Particle Duality and ToE's Explanation

Electrons can exhibit wave-like interference in one experimental setup and particle-like impacts in another; however, both behaviors cannot manifest simultaneously in a single setup. This phenomenon, central to Bohr's complementarity principle[[11],[12],[13]] and de Broglie's wave-particle duality[23], is reinterpreted in the Theory of Entropicity (ToE) using the dynamics of entropy, irreversibility, and the Vuli-Ndlela Integral.

3.4.2 Superpositions as Low-Entropy Configurations

ToE explains quantum superpositions as low-entropy configurations. For example, when an electron passes through a double-slit apparatus without detection, the system maintains low entropy. The electron's wavefunction explores all available paths with minimal irreversible entropy production:

$$S_{\text{irrev}} < S_{\text{critical}}, \tag{47}$$

where S_{irrev} is the irreversible entropy production, and S_{critical} is the threshold beyond which coherence is lost. This allows wave-like interference patterns to emerge due to contributions from many entropic geodesics:

$$I \propto \sum_{\text{geodesics}} \exp(-\Delta S/k_B), \tag{48}$$

where ΔS is the entropy difference, and k_B is Boltzmann's constant.

3.4.3 Collapse to Particle-like Behavior

When a which-path detector is introduced, the measurement interaction introduces significant irreversible entropy:

$$S_{\text{irrev}} \geq S_{\text{critical}}, \tag{49}$$

which triggers a collapse of the wavefunction. The interference pattern is destroyed, and the electron manifests as a localized particle.

3.4.4 De Broglie's Dual Nature Reinterpreted

ToE reinterprets de Broglie's hypothesis of wave-particle duality by defining the wave as a field of entropic potential:

$$\Psi(x,t) = \exp\left(-\frac{\Delta S(x,t)}{k_B}\right), \tag{50}$$

representing a distribution of possible configurations governed by minimal entropy.

The particle emerges when entropy production selects a single entropic geodesic:

$$\mathcal{P} = \max\left\{\Psi(x,t)\right\}. \tag{51}$$

This transition is governed by the threshold entropy condition (49).

3.4.5 Experimental Implications

ToE predicts that interference patterns degrade gradually as entropy increases, suggesting partial decoherence and fringe visibility changes:

$$V \propto \exp(-\Delta S/k_B), \tag{52}$$

where V is the fringe visibility. Controlled entropy injection (e.g., via ultra-cold detectors) could extend interference patterns even for massive particles.

For reference, equations (47) through (52) summarize the thermodynamic principles underlying ToE's explanation of wave-particle duality.

3.4.6 Collapse of the Wave Function and Einstein's Photoelectric Effect Analogy

To truly appreciate the power of the Theory of Entropicity (ToE) in resolving the quantum measurement problem, it is illuminating to draw a profound historical parallel to Einstein's explanation of the photoelectric effect - one of the pivotal moments in the birth of quantum theory. In 1905, Einstein[30] introduced the concept of the work function and the quantization of light to explain why light of insufficient frequency, regardless of intensity, fails to eject electrons from a metal surface. His simple yet revolutionary equation:

$$E = hf - \phi, \tag{53}$$

where:

- E is the kinetic energy of the emitted electron,
- hf is the energy of the incident photon,
- ϕ is the work function - the minimum energy needed to liberate the electron,

profoundly changed our understanding of light, matter, and quantization. The electron is only emitted when the photon supplies energy above the threshold—not by accumulation or probability, but by satisfying a fundamental inequality.

After a careful inspection of the above Einstein equation of the photoelectric effect, we find that the wave function collapse condition is actually structurally similar to:

$$\mathcal{E}_\Lambda = \Lambda_\phi - \Lambda_{\text{thresh}} \tag{54}$$

This is a structural equivalence in entropy space, where:

- Λ_ϕ is the entropy density of the quantum interaction.
- Λ_{thresh} is the critical entropy density required to induce collapse (analogous to the work function in the photoelectric effect).
- $\mathcal{E}_\Lambda$ plays the role of an available entropic potential (like available energy) that drives the collapse.

The above equation is structurally equivalent to the Einstein photoelectric equation. This is not a coincidence. As with photons needing sufficient energy to liberate electrons, quantum interactions require sufficient entropy flow to trigger decoherence and measurement. Instead of photon ejection in the case of the photoelectric effect, it is wave function collapse event that happens when:

$$\Lambda_\phi \geq \Lambda_{\text{thresh}} \tag{55}$$

3.4.6.1 Measurement as Entropic Work In ToE, measurement is no longer a passive inquiry but a thermodynamic act - a transfer of entropic work from the quantum system to the measuring apparatus. Information extraction, therefore, is contingent on this entropic expenditure:

$$\Delta W_{\text{entropy}} \geq \mathcal{W}_{\min} \tag{56}$$

Which is a threshold condition for entropy flow, just as the photoelectric effect requires a threshold energy. This provides a physical criterion for when information can be reliably extracted from quantum systems.

Entropy-Driven Collapse as the Entropic Analog of the Photoelectric Effect [22]

Summary Table: Analogy between Photoelectric Effect and Entropic Collapse in ToE

Aspect	**Photoelectric Effect (Einstein)**	**Wave Function Collapse (Theory of Entropicity)**
Triggering Quantity	Photon energy $E = h\nu$	Entropic density Λ_ϕ of quantum interaction
Threshold	Work function ϕ	Collapse threshold entropy Λ_{thresh}
Condition for Event	$E \geq \phi$	$\Lambda_\phi \geq \Lambda_{\text{thresh}}$
Outcome	Electron ejection from material	Collapse of wave function from superposition to outcome
No-event case	If $h\nu < \phi$, no emission	If $\Lambda_\phi < \Lambda_{\text{thresh}}$, coherence persists
Underlying Agent	Energy input from photon	Entropy input from environment or interaction or observer
Nature of Effect	Quantum energy threshold	Entropic phase transition threshold
Interpretation	Energy required to liberate matter	Entropy required to break quantum coherence

Table 6: **Summary: Analogy between Photoelectric Effect and Entropic Collapse in ToE**

3.4.6.2 The Entropic Collapse Threshold as an Analogous Work Function The Theory of Entropicity identifies a remarkably similar structure analogous to Einstein's work function of the photoelectric effect in the mechanism of wave function collapse. Collapse occurs only when the system's entropy rate of change or entropic flux exceeds a critical threshold - akin to Einstein's work function:

$$\frac{dS}{dt} \geq \Lambda_c \tag{57}$$

Here, Λ_c plays a role directly analogous to ϕ, the entropic work function required to "release" the system from superposition and localize it into a definite state. Just as no electron is emitted if $hf \leq \phi$, no collapse occurs if the entropic drive is insufficient. The system remains in superposition until the entropic field enforces a transition.

3.4.6.3 Recasting Einstein's Equation via the Vuli-Ndlela Integral In ToE, this dynamic is formalized through the Vuli Ndlela Integral,[23] which filters possible quantum histories by weighting them with

[22]**On the Elegance of Physical Laws:**

- By connecting wave function collapse to the photoelectric effect, the explanation emphasizes the elegance and universality of physical laws, where seemingly unrelated phenomena share structural similarities.
- This analogy is an excellent pedagogical tool for making quantum mechanics more intuitive by relating it to a well-understood classical phenomenon.

[23]**The Vuli-Ndlela Integral: Path to Unity**
In a most straightforward fashion, we can conceive of the Vuli-Ndlele Integral to possess the following skeletal form, for ease of understanding:

$$\int_{\text{paths}} e^{-S_{\text{constraint}}}\, \mathrm{d}x, \tag{58}$$

where the constraints S are entropic in the field.

entropic exponential factors, leading to a natural exclusion of paths that fail to meet the entropic conditions. The integral can be viewed as an entropic refinement of Feynman's path integral[[40],[41]]:

$$Z_{\text{ToE}} = \int_{\mathbb{S}} \mathcal{D}[\phi]\, e^{\frac{i}{\hbar} S[\phi]} \cdot e^{-\frac{S_G[\phi]}{k_B}} \cdot e^{-\frac{S_{\text{irr}}[\phi]}{\hbar_{\text{eff}}}} \tag{59}$$

In this formulation:

- Paths with entropy flux below the threshold are exponentially suppressed.
- Only paths satisfying the Vuli-Ndlela inequality - analogous to Einstein's energy threshold - contribute to observable outcomes.

This transforms the path integral from a mathematical summation over potentialities into a physically constrained selection rule: a system evolves along paths that are dynamically allowed by the entropic field, and collapses when constrained to do so.

3.4.6.4 From Quantized Energy to Quantized Irreversibility

Einstein's genius lay in identifying that energy transfer was not continuous but quantized and threshold-bound. The Theory of Entropicity extends this insight by proposing that irreversibility and state reduction are similarly quantized - not by energy alone, but by entropy. Just as a photon must exceed the work function to cause emission, a system must surpass the entropic threshold to undergo collapse.

This connection elevates the Vuli-Ndlela Integral to a revolutionary reinterpretation of Feynman's formalism, embedding real-world physical constraints - not just abstract amplitudes. It unites energy, entropy, irreversibility, and causality into a single action-driven principle, restoring Einstein's dream of physical realism while preserving Bohr's emphasis on constraint and context.

3.4.6.5 Einstein's Legacy in the Photoelectric Effect Renewed

In this light, the Theory of Entropicity does not stand outside the historical development of quantum theory - it completes it. Just as Einstein unlocked the particle nature of light by identifying a threshold inequality, so too does ToE unlock the nature of quantum measurement by uncovering a collapse inequality grounded in entropy.

Collapse, in the ToE framework, is the photoelectric effect of quantum information. It is not magic, mystery, or metaphysics. It is bold physics - with thresholds, fields, and causality.

This powerful insight reframes one of the most misunderstood and disturbing processes in all of science: measurement. In conventional quantum mechanics, measurement is a vague, undefined operation - an intervention by an observer that causes the wave function to collapse. The nature of this observer, the boundary between system and apparatus, and the moment of collapse are all ill-defined. The Theory of Entropicity (ToE) resolves this ambiguity by grounding measurement in a physical law that resonates with Einstein's revolutionary encounter in the photoelectric effect: the entropic constraint mechanism.

3.4.7 The Pauli Exclusion Principle Revisited: Entropic Constraints on Quantum Identity

At first glance, the Pauli Exclusion Principle[69] - which states that no two identical fermions can occupy the same quantum state—appears to be a standalone quantum rule, isolated from the discussions of wave function collapse, measurement, or entropy. It is typically introduced as a mathematical constraint on antisymmetric wave functions, critical for the structure of atoms and the stability of matter. But in the framework of the Theory of Entropicity (ToE), this principle reveals a much deeper and surprising connection: it is an entropic selection rule, manifesting the same threshold-driven constraint structure as wave function collapse, measurement, and information extraction.

3.4.7.1 Identity and Pauli's Exclusion: A Consequence of Entropic Saturation

Let us consider what the Pauli Exclusion Principle actually enforces: it disallows the coexistence of identical quantum identities in a shared eigenstate. In ToE terms, we may reframe this by asking: Why must nature forbid identical fermionic information from collapsing into the same state?

ToE answers this with a startling insight: the collapse of quantum information, as governed by the Vuli-Ndlela Integral, is an entropically constrained emission process. Every fermion carries with it not just energy and mass, but an entropic fingerprint - a kind of quantum identity tag. When a fermion attempts to collapse into a state already occupied by another identical fermion, it is attempting to emit a redundant informational collapse.

This is not allowed - not because of a formal mathematical antisymmetry alone, but because such a collapse would violate the entropy threshold inequality. The entropy field, acting as a universal constraint enforcer, prohibits the duplication of collapse events with indistinguishable entropic configurations. This is *entropy saturation*: no two identical informational signatures can simultaneously collapse into the same physical state without exceeding the entropic capacity of that state.

3.4.7.2 Rewriting Pauli in Entropic Terms The traditional Pauli principle may now be rewritten as a corollary of the Vuli-Ndlela Inequality:

$$\text{For fermions:} \quad \Lambda_{\text{state}} + \Lambda_{\text{new}} > \Lambda_c \quad \Rightarrow \quad \text{State inaccessible} \tag{60}$$

That is, the entropic flux required to insert an identical fermion into an already-occupied state exceeds the collapse threshold. The Vuli-Ndlela Integral filters such paths out of physical realization - not due to symmetry postulates alone, but due to entropic conflict.

This transforms Pauli exclusion from an abstract quantum rule into a real-time entropic selection law. The principle becomes not a mathematical axiom, but a consequence of the entropy field's capacity to distinguish and enforce identity in spacetime.

3.4.7.3 Measurement, Collapse, and Identity from Pauli's Principle This entropic reinterpretation of Pauli now connects seamlessly with the photoelectric analogy. Just as a photon must supply sufficient energy to overcome a work function and eject an electron, a quantum system must deliver sufficient entropic identity flux to distinguish its state uniquely from others [in the fermionic state].

Consider measurement: if a fermionic state is already occupied, the act of measuring a second, identical fermion attempting to collapse into the same state is blocked - not by measurement uncertainty, but by entropic overconstraint. The system cannot yield an outcome because it cannot fulfill the identity resolution condition enforced by entropy. This provides a novel, physical explanation of why indistinguishable particles must resolve into distinct states for measurement to proceed.

3.4.8 Measurement as Entropic Extraction

Just as the photoelectric effect describes the emission of an electron only when sufficient energy is supplied, ToE describes measurement as the emission of information from a quantum system only when sufficient entropic conditions are satisfied.

A quantum system stores information in the form of probabilistic amplitude distributions - a wave function. This information is latent, not yet accessible to the classical world. For this information to be extracted - i.e., observed, recorded, or measured - it must undergo a collapse. But ToE asserts that this extraction is not free: it requires a cost, paid in entropy. The act of measurement is an entropic event, not just an epistemic update.

This aligns beautifully with the photoelectric analogy:

- In the photoelectric effect, energy above the work function is required to release an electron.
- In ToE, entropic flux above the collapse threshold is required to release information from the wave function.

This implies a fundamental principle:

> Information is only extractable from a quantum system if the entropic field enforces a collapse that satisfies the Vuli-Ndlela inequality.

3.4.9 The Vuli-Ndlela Inequality as the Gatekeeper of Knowledge

The Vuli-Ndlela Integral formalizes this principle by integrating only over those paths that satisfy the entropy-driven constraint. The Vuli-Ndlela inequality:

$$\frac{dS}{dt} \geq \Lambda_c \tag{61}$$

is the gatekeeper for observation. A system does not yield its information to the world unless this inequality is met. Until then, the system's state remains inaccessible, not due to mystery or lack of knowledge, but due to insufficient entropic drive.

This provides a field-theoretic foundation for the Born rule: the probability of observing a specific outcome is not just a statistical postulate, but a reflection of how likely it is for the entropy field to guide the system across its threshold toward that outcome.

3.4.10 Implications for Observers and Measurement Devices

Measurement devices—classical instruments, detectors, human observers—do not cause collapse. Rather, they participate in the entropic environment that determines when and how collapse occurs. The measuring apparatus contributes entropy to the system, enabling it to cross the threshold. This entropy exchange is what gives rise to irreversibility, definiteness, and classical outcomes.

Thus, observers are no longer mystical agents collapsing the wave function by consciousness. They are thermodynamic participants in an entropic field - the same field that governs all physical interactions.

3.4.11 Information, Entropy, and Causality Unified

ToE reveals a deep triadic structure in nature:

- Entropy governs physical evolution.
- Collapse is the threshold-driven release of information.
- Measurement is the physical manifestation of this release, made possible only through entropic constraint.

In this framework, information is not a passive property, but an active, entropically mediated emergence. Observation is a causal interaction, not a metaphysical disruption. **This answers Bohr's concerns about the indivisibility of measurement, while satisfying Einstein's demand for a lawful physical process and Bohr's own equally lawful physical witness.** [24]

3.4.12 Redefining Causality

Traditional views of causality in quantum physics often break down under the superposition principle. ToE reinstates causality as an entropy-bound structure: interactions propagate irreversibly along entropic gradients, enforcing a new kind of "entropic light cone." Events are causally related only if the entropy flux between them satisfies the Vuli-Ndlela inequality:

$$\frac{dS}{dt} \geq \Lambda_{\min} \tag{62}$$

This provides an objective and testable limit to causal interactions.

3.4.13 Rethinking Locality

In standard quantum mechanics, nonlocality appears mysterious, sometimes even paradoxical. Under ToE, nonlocal effects are reinterpreted as entropy-correlated events governed by finite entropic signal propagation times. The entropic field mediates correlations, and no superluminal signaling occurs. Instead, quantum correlations are constrained by a universal entropic bandwidth.

3.5 Entropic Explanation of Collapse Statistics: Fermions vs. Bosons in ToE

The Theory of Entropicity (ToE), through the Vuli-Ndlela Integral, imposes a constraint on wave function collapse. This constraint is not arbitrary - it is entropic in nature. A wave function collapse can only occur if the entropic conditions satisfy a critical inequality. We explore how this governs the behavior of fermions and bosons and provides an entropic reinterpretation of the Pauli Exclusion Principle and Bose-Einstein condensation[[20],[33]].

3.5.1 From Fermi–Dirac Statistics to Entropic Path Constraints

Even the statistics of fermions - Fermi-Dirac distribution[[26],[39]] - can now be seen as emerging from entropic path filtration. States with lower entropic conflict are more accessible; states requiring high entropic resolution are suppressed. The occupation of quantum states is thus not merely a statistical matter but a field-dynamic one.

This again mirrors the photoelectric effect, where photons below a critical frequency cannot cause emission, no matter how numerous they are. Similarly, redundant entropic identities cannot trigger collapse, no matter how many indistinguishable fermions exist - identity must be entropically distinguishable to yield observation.

3.5.2 Entropic Collapse Inequality

Wave function collapse under ToE is constrained by an entropy emission rule:

$$\sum_i \Lambda^{(i)}_{\text{collapse}} \leq \Lambda^{\text{state}}_{\text{max}} \tag{63}$$

Here:

- $\Lambda^{(i)}_{\text{collapse}}$ is the entropy density released by particle i during collapse.
- $\Lambda^{\text{state}}_{\text{max}}$ is the entropic capacity of the target state.

[24] *Einstein sought truth in law. Bohr defended truth in limits. The Theory of Entropicity reveals that laws are born of limits, and entropy is the lawgiver. Thus, the two[Einstein and Bohr] are reconciled - not by compromise, but by elevation.*

3.5.3 Fermionic and Bosonic Identity Conflict Checks

Let:

- Σ_i be the entropy signature of particle i.
- $\Delta_{ID}(\Sigma_i, \Sigma_j)$ be the distinguishability measure between particles.

Then collapse into the same state is:

1. **Allowed if:**
$$\Delta_{ID}(\Sigma_i, \Sigma_j) \geq \delta_{\min} \tag{64}$$
2. **Forbidden if:**
$$\Delta_{ID}(\Sigma_i, \Sigma_j) \to 0 \tag{65}$$

This captures the entropic "identity fingerprint" enforcement inherent to ToE.

3.5.4 Application to Fermions

Fermions have unique entropy signatures. Attempting to collapse two indistinguishable fermions into the same eigenstate leads to redundancy in entropy emission:

$$\Lambda^{(1)}_{\text{collapse}} + \Lambda^{(2)}_{\text{collapse}} > \Lambda^{\text{state}}_{\text{max}} \tag{66}$$

This violates Equation 63, so collapse is forbidden. This offers a thermodynamic foundation for the Pauli Exclusion Principle.

3.5.5 Application to Bosons

Bosons possess symmetric, shared entropy signatures. When collapsing into the same eigenstate:

$$\sum_i \Lambda^{\text{boson}}_{\text{collapse}} \leq \Lambda^{\text{state}}_{\text{max}} \tag{67}$$

There is no redundancy, and coherence is reinforced. Collapse is permitted.

Summary of Entropic Collapse Differences-1

Feature	Fermions (Fermi–Dirac)	Bosons (Bose–Einstein)
Entropy Signature	Unique and non-shareable	Shared and symmetric
Redundancy	Yes - entropy conflict occurs	No - entropy adds constructively
Collapse into Same State	Forbidden - exceeds threshold	Allowed - coherence reinforced
Statistical Outcome	Pauli Exclusion Principle	Bose-Einstein Condensation

Table 7: **Summary of Entropic Collapse Differences-1**

Summary Table: Entropicity View of Quantum Statistics-2

Property	Fermions	Bosons
Spin	Half-integer	Integer
Entropy Signature	Unique, distinguishable	Shared, symmetric
Identity Conflict	Forbidden if $\Delta_{\text{ID}} \to 0$	Allowed even if $\Delta_{\text{ID}} \to 0$
Collapse Behavior	Collapse redundancy $\to$ forbidden	Collapse constructive $\to$ allowed
Statistical Result	Fermi-Dirac exclusion	Bose-Einstein condensation
ToE Collapse Condition	Redundant collapse exceeds entropy capacity	Coherent collapse within entropic tolerance

Table 8: **Summary Table: Entropicity View of Quantum Statistics-2**

Summary Thermodynamic Intuition from ToE:

In conclusion, ToE reframes quantum statistics as entropic permission rules: collapse is not just governed by symmetries, but by the physical entropic feasibility of co-occupancy.

Summary Table: ToE View of Fermions vs. Bosons-3

Concept	Fermions	Bosons
Entropy Signature	Unique and non-shareable	Shared and symmetric
Redundant Collapse into One State?	Yes - violates entropic constraint	No - considered coherent, not redundant
Entropy Emission Conflict?	Yes - adds up beyond threshold	No - adds up constructively
ToE Collapse Outcome	Collapse forbidden to same state	Collapse allowed to same state
Resulting Statistics	Pauli Exclusion / Fermi–Dirac	Bose–Einstein Condensation

Table 9: **Summary Table: ToE View of Fermions vs. Bosons-3**

Thermodynamic Reinterpretation of Quantum Statistics under ToE-4

Quantum Property	Standard View	ToE View
Collapse Trigger	Postulated rule or observer	Entropy threshold violation
Exclusion of Fermions	Anti-symmetric wave function	Entropic redundancy conflict
Bosonic Clustering	Symmetric wave function	Constructive entropy coherence
Observable Outcome	Quantum statistics	Thermodynamic result

Table 10: **Thermodynamic Reinterpretation of Quantum Statistics under ToE-4**

3.6 Introducing ToE's Seesaw Model of Quantum Entanglement and Wave Function Collapse

To unify the phenomena of quantum entanglement and wave function collapse, the Theory of Entropicity (ToE) **introduces a novel physical intuition based on the classical children's seesaw [refer to Figure 2]**. This analogy helps visualize how entropy functions as the dynamic constraint between quantum subsystems and explains why wave function collapse appears spontaneous yet irreversible. The **Entropic Seesaw Model[ESSM]** is a unified metaphor that bridges:

1. Quantum foundations
2. Thermodynamics
3. Entanglement geometry
4. Collapse models, and
5. Observer puzzles, among other concepts.

3.6.1 The Seesaw as Entropic Connector

Let us consider two quantum systems A and B prepared in an entangled state. In ToE, these systems are connected by an invisible entropy field $\Lambda(x)$ that plays a role analogous to the rigid bar of a seesaw.

- **Ends of the Seesaw:** Particles A and B are conceptually like the two ends of a seesaw.
- **Entropic Bar:** The entropic field forms a continuous, rigid connector between the particles - similar to the metal or wooden bar between the seesaw ends.
- **Fulcrum:** The balance point corresponds to the critical entropy threshold Λ_{thresh} that determines when collapse occurs.

This construct represents a shared entropic object: what happens to one end affects the other instantly within the entropic domain (not necessarily implying superluminal signaling, but indicating structural inseparability).

3.6.2 Wave Function Collapse as Seesaw Tipping

In this model, collapse corresponds to the seesaw tipping beyond equilibrium:

$$\Lambda_A(t) + \Lambda_B(t) > \Lambda_{\text{thresh}} \tag{68}$$

If this condition is satisfied due to a measurement or interaction, the entropic bar loses its balanced state and one end "collapses" downward, selecting a definite outcome for both systems. This aligns with the previously defined condition:

$$\Lambda_\phi \geq \Lambda_{\text{thresh}} \tag{69}$$

3.6.3 Post-Collapse Configuration and Irreversibility

After collapse:

- The entangled systems are now in definite, classical-like states.
- The entropy field continues to increase (analogous to the system settling on one side of the seesaw).
- Re-coherence cannot occur unless the entropy is somehow extracted, which in practice is highly unlikely.

3.6.4 Entanglement as an Entropic Bridge - Likened to Children's Seesaw

The entropic field acts like a wormhole structure:
Separate externally, unified internally.

This means:

1. **Before Collapse:** Entropy is balanced between subsystems[**just like seesaw in equilibrium**], and unitary evolution is preserved.
2. **At Collapse:** The entropy flow between the systems satisfies Eq. (68), triggering collapse[**equivalent to a seesaw dropping on one side, affecting the other side equivalently as if instantaneously**].
3. **After Collapse:** Entropic imbalance becomes irreversible[**akin to how one end of a seesaw finally touches the ground or lowest point**]; coherence is lost[**similar to equilibrium of the seesaw being lost, and a counter force or energy must be deployed if equilibrium is to be achieved again, which is not a straightforward matter in the case of entropy compared to standard (Newtonian) mechanics**].

This seesaw model not only preserves the mathematical precision of ToE's entropy dynamics, but also provides a vivid, pedagogical picture of entanglement and measurement in action. It unifies entanglement, measurement, decoherence, and thermodynamic irreversibility in a single conceptual framework.

We note that this model could indeed be extended with equal facility to explain quantum teleportation, delayed-choice experiments, and information conservation across quantum transitions.

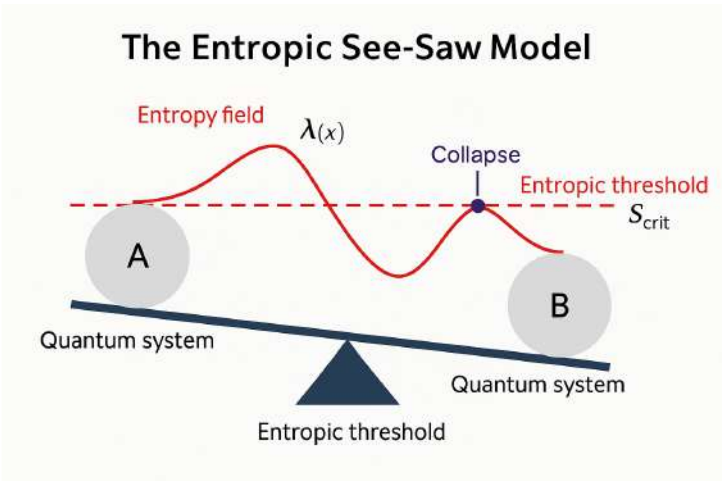

Figure 2: The Entropic Seesaw Model

3.6.5 The Entropic Seesaw Model: Pre-Collapse Phase Analogy

We shall here expand on what we have been saying on the Seesaw Model. Before the collapse of the wave function, the Entropic Seesaw Model provides a vivid analogy to describe the state of quantum entanglement and coherence.

Pre-Collapse Phase in the Seesaw Analogy:

1. **Quantum Systems as Balanced Ends:** Imagine two entangled quantum systems, A and B, sitting at the opposite ends of a seesaw.
   - The seesaw is perfectly balanced - neither side is tipping.
   - This balance represents quantum superposition and entanglement: both systems are in an undetermined, shared state.

2. **Entropy Field as the Connecting Beam:** The seesaw's rigid bar represents the entropic field $\Lambda(x)$ of the Theory of Entropicity (ToE).
   - This bar constrains the two ends, meaning that if one side is disturbed, the effect is instantly "felt" by the other - like quantum correlation. This is the superposition of states.
   - Crucially, no collapse has occurred yet because the entropy is still below the critical threshold.
3. **Metaphor for Superposition and Correlation:** Both particles are in a superposed, entangled state, like children gently swaying without tipping the seesaw. ***If one child does any slight swaying, the other child would instantly know even without seeing what the first child has done. This is quantum entanglement; that is, if child-A does spin-Down, child-B would instantaneously get a spin-Up result at her end, and vice-versa.***
   - The system exists as one unified entropic object - even though we label the two parts separately, their existence is coupled.***[The two children on the seesaw are said to be coupled or entangled or superposed, or in a reversible state or configuration, or correlated!]***
4. **Collapse Trigger Still Pending:**
   - The system is in a low-entropy phase.
   - No irreversible disturbance has occurred.
   - No entropic threshold has been breached.
   - The seesaw is stable and symmetric - no measurement or decoherence event has forced it to tip.

Key Analogy Mapping:

Seesaw Element	**Quantum Interpretation**
Two children on each end	Two entangled particles/systems
Rigid bar	Entropic field $\Lambda(x)$ enforcing correlations
Balance (no tilt)	Coherent superposition (wave function not collapsed)
No dissipation	No entropy threshold crossed, no irreversible measurement
Shared motion	Entangled behavior / inseparability

Table 11: **Analogical Mapping of the Entropic Seesaw Model**

3.6.6 Post-Collapse Phase in the Seesaw Analogy

Following the collapse of the wave function, the Entropic Seesaw Model[ESSM]provides an insightful analogy to describe the transition from quantum coherence to classical definiteness. Once the entropy threshold is crossed, the delicate balance of the seesaw breaks. Here's what happens:

1. **Tipping of the Seesaw: Collapse Triggered**
   A perturbation (e.g., measurement, interaction, or entanglement with the environment) injects entropy into the system. When the entropy production of one subsystem - say, system A - exceeds the critical entropic threshold $\Lambda_\phi \geq \Lambda_{\text{thresh}}$, the seesaw tilts.
   - This tilting represents the irreversible collapse of the wave function: coherence is lost, and one definite outcome emerges.
2. **Selection of an Outcome State**
   As the seesaw tips, the system selects one of the available eigenstates.
   - The "balance" is broken in favor of one branch of the quantum superposition.
   - This matches the experimental observation of a measurement outcome.
3. **Entropic Dissipation and Irreversibility**
   The entropy of the environment increases, even if the entropy of the system appears to decrease (as it collapses to a definite state).
   - According to the Theory of Entropicity (ToE), this ensures the collapse is a one-way process - it cannot spontaneously reverse.

- The rigid bar (entropy field) locks in the new asymmetry: collapse is complete.

4. **End of Quantum Ambiguity**
   System A and B are no longer entangled. **[Child-A is now on the ground and locked down; and nothing she does now will affect child-B, that is if child-B is even still at the other end of the seesaw - that is, if she too has not also rolled down the seesaw and collapsed on the ground with child-A in a non-entangled state]**.
   - The entropic bridge has transferred enough information to finalize the correlation.
   - Classical behavior emerges: definite states and decohered history.

Updated Analogy Mapping:

Seesaw Event	**Quantum/ToE Interpretation**
One side tips down	Entropic collapse to a definite state
Weight imbalance	Entropy threshold exceeded $\Lambda_\phi \geq \Lambda_{\text{thresh}}$
Energy dissipation	Entropy increase in system + environment
Lock-in of tilted state	Irreversibility of collapse
No return to balance	No re-coherence unless entropy is removed (highly unlikely)

Table 12: **Updated Analogical Mapping of the Entropic Seesaw Model**

Summary:

- **Before Collapse:** Perfect seesaw balance = coherent entangled superposition.
- **At Collapse:** Entropy threshold breached = irreversible tipping.
- **After Collapse:** One side locked down = classical outcome realized.

The Theory of Entropicity interprets this as a thermodynamic phase transition triggered by information-exchange constraints. Collapse is no longer a mysterious postulate - it is the natural consequence of an entropy-driven constraint formalism.

3.7 Eigenstate Selection in the Entropic Seesaw Model

Background: In the standard quantum framework, wave function collapse into a particular eigenstate is postulated but unexplained. The Theory of Entropicity (ToE), aided by the Seesaw Model, provides a thermodynamic mechanism for understanding how one outcome is selected from a superposition.

Seesaw as Entropic Balancer: Visualize the quantum system as a seesaw, where each eigenstate ψ_i contributes to the balance. The entropy of the system and its environment, along with the entropy field $\Lambda(x)$, determine the system's stability.

$$\Psi = \sum_i c_i \psi_i, \quad \text{with} \quad \sum_i |c_i|^2 = 1 \tag{70}$$

Prior to collapse, entropy density Λ_ϕ remains below the critical threshold Λ_{thresh}, and the system stays in superposition:

$$\Lambda_\phi(x) < \Lambda_{\text{thresh}} \tag{71}$$

Collapse Onset: Collapse is triggered when entropy surpasses the threshold:

$$\Lambda_\phi(x) \geq \Lambda_{\text{thresh}} \tag{72}$$

This event tips the seesaw, selecting a specific eigenstate ψ_k based on entropy efficiency. The choice satisfies the Vuli-Ndlela Integral:

$$Z_{\text{ToE}} = \int_{\mathbb{S}} \mathcal{D}[\phi]\, e^{\frac{i}{\hbar} S[\phi]} e^{-\frac{S_G[\phi]}{k_B}} e^{-\frac{S_{\text{irr}}[\phi]}{\hbar_{\text{eff}}}} \tag{73}$$

and the collapse condition:

$$\Delta\Lambda_k = \Lambda_{\phi,\text{post}} - \Lambda_{\phi,\text{pre}} \leq \Lambda_{\max} \tag{74}$$

After Collapse: The system is locked into ψ_k; coherence is lost. The environment absorbs emitted entropy. Reversal is impossible:

$$S_{\text{total}} = S_{\text{system}} + S_{\text{environment}} \quad \text{increases irreversibly.} \tag{75}$$

Summary Table:

Stages of Entropic Collapse in the seesaw Model

Stage	Description	Seesaw Interpretation
Superposition	All eigenstates possible	Balanced seesaw with multiple entropic weights
Threshold Crossed	Collapse triggered	Pivot tips toward high-entropy outcome
Eigenstate Selected	One state realized	Entropically efficient side dominates
Post-Collapse	Fixed outcome	Seesaw locks, entropy irreversibly increases

Table 13: **Stages of Entropic Collapse in the Seesaw Model**

Further Insights: We can further deploy ToE to derive the Born rule from entropic curvature or microstate multiplicity in the entropy field $\Lambda(x)$, as we shall do subsequently.

4 Entropy, Landauer's Principle, and the Irreducible Cost of Quantum Collapse

Here, we look at Entropy, Landauer's Principle, and the Irreducible Cost of Quantum Collapse, which we recognize as a Milestone Prediction of the Theory of Entropicity (ToE).

4.1 Historical Background: Landauer's Principle and Quantum Measurement

Since Rolf Landauer's seminal 1961 paper, it has been known that information erasure has a thermodynamic cost. Landauer's principle states[53]:

$$\Delta S \geq k_B \ln 2 \tag{76}$$

for the erasure of one bit of information, where k_B is Boltzmann's constant[14]. This result has been foundational in linking thermodynamics and information theory, and has been confirmed experimentally in nanoscale systems.

In quantum mechanics, however, the role of entropy and energy dissipation in measurement - especially in wave function collapse - has been underappreciated. The standard Copenhagen interpretation treats collapse as an epistemic, not physical, process. Objective collapse models (such as GRW or Diosi-Penrose) postulate spontaneous collapses but lack a clear entropic mechanism.

4.2 Gap in the Literature Before ToE

Prior to the Theory of Entropicity (ToE), no framework made the following explicit claim:

> If a quantum collapse resolves a binary ambiguity (such as spin-up vs. spin-down), then the act of collapse must produce at least $k_B \ln 2$ entropy.

This threshold is not metaphorical but physically enforced. Collapse becomes a thermodynamic transition, not just an observational artifact.

Even the influential works of Wojciech Zurek[96] (1990s–2000s),[25] who tied decoherence to entropy and the environment, did not quantify collapse entropy per measurement event. Von Neumann entropy[89] and Shannon entropy[79] were used to track ensemble statistics, not the fundamental cost of a single collapse.

[25] **A Brief Review of the Literature**

1. **Landauer's Principle (1961):** Landauer established that erasing one classical bit of information must generate at least:

$$k_B \ln 2 \quad \text{(entropy or heat)}, \tag{77}$$

where k_B is Boltzmann's constant.

This principle applies to computational systems, memory, and logic gates.

2. **Zurek's Work (1990s–2000s):** Wojciech Zurek extended Landauer's ideas to quantum information theory and decoherence. Key contributions include:

   - Connecting environment-induced decoherence to entropy.
   - Treating collapse as an interpretive issue, not as a thermodynamic necessity.

   Collapse was not directly linked to entropy as a physical process.

4.3 The Insight of ToE: Collapse as Thermodynamic Erasure

ToE introduces a revolutionary insight:

1. Collapse is triggered by entropy threshold crossing.
2. The collapse is an irreversible erasure of quantum ambiguity.
3. Therefore, each quantum collapse dissipates a minimum entropy equal to that required to erase the uncertainty.

For a two-level system, this gives:

$$\Delta S_{\text{collapse}} \geq k_B \ln 2 \tag{78}$$

This is the ToE's quantum analog of Landauer's cost for classical bit erasure. It implies that every measurement[wave function collapse] must release this entropy - as heat, decoherence, or informational dissipation.

4.4 Logical Derivation

Let a quantum system be in a superposition:

$$|\psi\rangle = c_1|0\rangle + c_2|1\rangle \tag{79}$$

Upon measurement, this collapses to either $|0\rangle$ or $|1\rangle$, effectively erasing the ambiguity.
The initial uncertainty (in bits) is given by [refer to the footnote [26]]:

---

3. **Objective Collapse Models (GRW, Diosi–Penrose):** These models postulate collapse as a spontaneous physical process, sometimes linked to mass or gravitational thresholds. However:
   - Entropy is mentioned indirectly in the context of thermodynamic time asymmetry.
   - Entropy is not quantified per collapse event in terms of bits.
4. **Quantum Thermodynamics (Recent Work):** Recent work explores entropy production during quantum measurements, but:
   - It does not assert a minimum $k_B \ln 2$ threshold per binary ambiguity.
   - It primarily focuses on entropy change in ensembles or mixed states, not per quantum collapse event.
5. **This is What Is Missing in the Literature Before Our ToE:**
   - No explicit quantification of the entropy cost of collapse per observable degree of freedom (e.g., spin) as $k_B \ln 2$.
   - No assertion that collapse is an irreversible thermodynamic transition constrained by Landauer's Principle.
   - **No mainstream model has made such claims as this:**

     "If a quantum collapse involves erasing or resolving a binary quantum ambiguity, it must dissipate at least $k_B \ln 2$ entropy."

[26] **Entropy Cost of Quantum Collapse: The $k_B \ln 2$ Prediction**
In this section, we highlight a pivotal prediction arising from the Theory of Entropicity (ToE): the quantifiable entropy cost of quantum wave function collapse. Unlike standard quantum mechanics or existing interpretations such as GRW or decoherence-based approaches, ToE provides an explicit thermodynamic lower bound for the entropy involved in resolving quantum ambiguity.

1. **Shannon Entropy of a Quantum Superposition**
   Consider a qubit in a superposition state:
   $$|\psi\rangle = c_1|0\rangle + c_2|1\rangle \tag{80}$$
   where $|c_1|^2 + |c_2|^2 = 1$. The probability of observing each basis state upon measurement is given by $p_1 = |c_1|^2$ and $p_2 = |c_2|^2$.
   The Shannon entropy of this binary quantum distribution is:
   $$H = -|c_1|^2 \log_2 |c_1|^2 - |c_2|^2 \log_2 |c_2|^2 \tag{81}$$
   When the state is a uniform superposition ($|c_1|^2 = |c_2|^2 = \frac{1}{2}$, because the entropy is maximized when the probabilities are equal), we obtain:
   $$H = -2 \cdot \frac{1}{2} \log_2 \frac{1}{2} = 1 \text{ bit} \tag{82}$$
   This indicates the system possesses 1 bit of quantum ambiguity.
2. **Landauer's Principle and Entropic Cost**
   Landauer's principle relates the erasure of information to thermodynamic entropy:
   $$\Delta S = k_B \ln 2 \tag{83}$$
   This implies that erasing 1 bit of information, such as resolving a quantum superposition via measurement, must dissipate at least $k_B \ln 2$ of entropy.

$$H = -|c_1|^2 \log_2 |c_1|^2 - |c_2|^2 \log_2 |c_2|^2 \tag{85}$$

At maximum entropy (equal superposition), this gives $H = 1$ bit. According to Landauer's principle, erasing 1 bit [that is, in order to erase ambiguity, which is tantamount to erasing one bit of information in order to gain information about another bit of information] implies:

$$\Delta S = k_B \ln 2 \tag{86}$$

Thus, ToE proposes that quantum collapse must dissipate this entropy - just as deleting a classical bit requires energy.

4.5 Generalization to n-State Superpositions and Entropic Wave Function Emissions

For an n-level quantum system:

$$|\psi\rangle = \sum_{i=1}^{n} c_i |i\rangle \tag{87}$$

Then the entropy generated in order to be able to erase ambiguity is therefore:

$$\Delta S = -k_B \sum_{i=1}^{n} |c_i|^2 \ln |c_i|^2 \tag{88}$$

The above equation is structurally similar to Shannon entropy scaled by k_B. Collapse thus becomes an entropic emission event upon wave function collapse, which is analogous to radiating heat in a thermodynamic process. **This ToE's prediction of entropic wave function emissions (EWFEs) is also falsifiable through precision experiments.**

4.6 Experimental Implications and Measurability

The view proposed by ToE in this section so far is falsifiable. ToE states that:

- Each quantum measurement should produce minimum entropy $k_B \ln 2$ per binary resolved.
- Measurements using low-energy, low-entropy coupling could demonstrate this thermodynamic basis.
- Collapse detection might be linked to attosecond entropy flow or heat spikes in nanoscale detectors.

4.7 Comparison with Literature

4.8 Conclusion: A New Quantization of Measurement Introduced by ToE

ToE has thus proposed another milestone insight in this section, which we state bodly as follows:

> Every measurement is a physical process that must meet Landauer's threshold of $\Delta S_m, qwfc \geq k_B \ln 2$. Collapse is not cost-free. It is entropic, thermodynamically quantifiable, and irreversible.

---

3. **ToE Prediction and Novelty**
   ToE connects Eqs. (81) and (83) by proposing that every collapse of a qubit-like superposition entails:

$$\Delta S_{\text{collapse}} \geq k_B \ln 2 \tag{84}$$

   This result is not derived in traditional quantum theory nor in the Copenhagen or GRW models. It is a prediction unique to the entropic variational framework of ToE.

4. **Implication and Experimental Testability**

Theory/Model	Collapse Mechanism	Entropy Cost Prediction
Copenhagen	Observer-induced	Not addressed quantitatively
Decoherence	Environment tracing	No irreversible entropy bound
GRW Model	Spontaneous collapse	No thermodynamic entropy defined
ToE	Entropy threshold	$\Delta S \geq k_B \ln 2$ for binary quantum decisions

Literature Summary: Collapse and Entropy

5. **Implication and Experimental Testability**

ToE hence posits that any device or process claiming to resolve a qubit-like ambiguity must necessarily incur an irreversible entropy cost of at least $k_B \ln 2$. This sets a quantifiable bound and invites experimental validation - for instance, in attosecond-resolved electron dynamics or single-spin measurements with entropy-tracking calorimetric probes.

This insight provides a falsifiable thermodynamic signature of measurement - potentially establishing an empirical foundation for wave function collapse, bridging the informational and physical interpretations of quantum theory through the foundational principles of the Theory of Entropicity

Framework	**Collapse Mechanism**	**Entropy Consideration**	**Minimum Cost Stated?**
Copenhagen QM	Epistemic/Postulated	Not physical	No
GRW / Diosi	Spontaneous, stochastic	Not thermodynamically defined	No
Zurek / Decoherence	Environmental tracing out	Entropy of environment	No
ToE	Entropic threshold crossing	Thermodynamic emission	Yes: $k_B \ln 2$ per bit

Table 14: **Comparison of Models on Collapse and Entropy**

This provides an entirely new framework for evaluating quantum measurements, tying collapse to physical entropy generation and elevating Landauer's principle into the heart of quantum theory. Future experiments may well confirm this with attosecond precision and nanoscale entropy detection.
This may become one of the most empirically fertile consequences of the Theory of Entropicity (ToE), at least so far. For now, we recognize that the Theory of **Entropicity has endeavored to unite:**

1. **Quantum measurement,**
2. **Information theory,**
3. **Thermodynamics,** and
4. **Entropic field theory**

The vexing problem of Quantum Gravity (QG) shall be tackled in a future section before we bring this work to its inevitable close.

5 On the Born Rule and the Mathematical Foundations of the Theory of Entropicity (ToE)

The Theory of Entropicity (ToE) offers a novel and profound reinterpretation of quantum mechanics by grounding the Born Rule - traditionally postulated in standard quantum theory—within a thermodynamic and field-theoretic framework. This section explores how ToE derives the Born Rule from first principles using entropy, and formalizes the statistical structure of quantum measurement within the entropic field $\Lambda(x, t)$.

5.1 Historical Background and the Born Rule

Max Born, in 1926[18], proposed that the square modulus of the wave function, $|\psi(x)|^2$, gives the probability density of finding a particle at position x. This postulate became one of the cornerstones of quantum mechanics. Born was awarded the Nobel Prize in Physics in 1954 for this statistical interpretation of the wavefunction.

However, in standard quantum mechanics, the Born Rule is simply accepted as an axiom with no deeper explanation of why the probability should be quadratic in the wave amplitude. The ToE seeks to replace this assumption with a derivation grounded in the entropic field dynamics.

5.2 The Entropic Field and Its Spatial Structure

ToE introduces a smoothly varying entropy field $\Lambda(x, t)$, defined at each point in spacetime. This is a significant departure from previous formulations of entropy, which treated entropy as a bulk property or statistical aggregate. In ToE, entropy is not just a macroscopic statistical measure but a local, dynamical field with curvature, gradients, and structure.

This is the first theory to:

- **Formulate entropy as a spatially and temporally distributed field.**
- **Relate this entropy field directly to the wave function of quantum systems.**
- **Provide a physical mechanism for the Born Rule through this field.**

5.3 Linking the Entropy Field to the Wave Function

We postulate that the entropy field is logarithmically related to the probability density: [Refer to the footnotes for further discussions and clarifications.[27]]

$$\Lambda(x,t) = k_B \ln |\psi(x,t)|^2 + C \tag{92}$$

where k_B is Boltzmann's constant, and C is an integration constant. **[We shall unequivocally demonstrate in future discussions of this work that the above entropic wave equation [EWE] in log form is indeed logically founded; but for now, the considerations in the footnote is enough for our purpose here.]** This implies:

$$\exp\left(\frac{\Lambda(x,t)}{k_B}\right) = |\psi(x,t)|^2 e^C \tag{93}$$

Thus, up to normalization, the entropy field reproduces the Born probability density:

$$P(x,t) \propto |\psi(x,t)|^2 \tag{94}$$

This derivation is crucial: it transforms the Born Rule from an unexplained quantum postulate into a natural outcome of a deeper entropic law.

5.4 Multiplicity and the Statistical Basis of Collapse

ToE further postulates that the likelihood $P(x)$ that the system collapses into configuration x is proportional to the local microstate multiplicity $\Omega(x,t)$:

$$P(x,t) \propto \Omega(x,t) \tag{95}$$

[27]**Crucial Conceptual and Mathematical Distinction in the Theory of Entropicity (ToE)**
This is a crucial conceptual and mathematical distinction we are drawing in the Theory of Entropicity (ToE).

1. **Key Clarification:**
   The classical Boltzmann entropy is:
   $$S = k_B \ln \Omega \tag{89}$$
   where Ω is the total number of microstates consistent with a macrostate. This is a global scalar quantity — it does not vary over space or time, and it is defined only at the macrostate level.
2. **In ToE, we propose:** Following from the Boltzmann equation, we expand the above classical expression to yield:
   $$\Lambda(x,t) = k_B \ln \Omega(x,t) \tag{90}$$
   This represents a localized entropy field - i.e., entropy as a continuous function of position and time. It is an entirely new generalization of the Boltzmann formulation.
3. **Expression of the Entropicity Field:** Knowing that the wave function is related to the microstate mixture of a system, we elevate this idea to mean that the wave function possesses an entropic function in the same way counting of microstates possesses an entropic structure. With this in mind, we therefore elevate the above equation to read as follows:
   $$\Lambda(x,t) = k_B \ln |\psi(x,t)|^2 + C \tag{91}$$
   Here, we are not invoking classical entropy - we are introducing a new interpretation of entropy as an information-encoded, spatial-temporal field directly tied to quantum amplitudes.
4. **Implication:**
   This makes our proposal not a modification of Boltzmann entropy - it is a field-theoretic generalization of entropy for quantum systems, embedded in the foundational structure of ToE. We are not just applying thermodynamics - we are redefining it at the quantum level.
5. **Why This Is Not Standard Boltzmann Entropy:**

Property	**Boltzmann Entropy S**	**Entropicity Field $\Lambda(x,t)$**
Scope	Global, scalar	Local, spatial-temporal field
Dependence	On entire macrostate	On microstate density at x,t
Use	Thermodynamic equilibrium	Dynamical quantum collapse & evolution
Variation	Static or ensemble-wide	Varies continuously with x,t

Table 15: **Comparison Between Boltzmann Entropy and Entropicity Field**

And since we postulated earlier that [28]:

$$\Lambda(x,t) = k_B \ln \Omega(x,t), \tag{96}$$

It follows again that:

$$P(x,t) \propto e^{\Lambda(x,t)/k_B} \tag{97}$$

Substituting from Equation 92, we recover the Born rule:

$$P(x,t) \propto |\psi(x,t)|^2 \tag{98}$$

Thus, the probability of collapse into a given eigenstate is not arbitrarily assigned but emerges from the local entropy structure.

In the subsequent subsection(s), we shall provide some details on the logical considerations that motivated our postulates in the foregoing.

5.4.1 Justification of the Entropic Field Formulation

To motivate the entropic field formulation in the Theory of Entropicity (ToE), we proposed in the previous section that:

$$\Lambda(x,t) = k_B \ln |\psi(x,t)|^2 + C, \tag{99}$$

where $\Lambda(x,t)$ is the entropic potential field, $\psi(x,t)$ is the quantum wave function, k_B is Boltzmann's constant, and C is an integration constant. We justify this relation through the following logical and statistical considerations:

5.4.1.1 Analogy with Boltzmann Entropy: In classical statistical mechanics, Boltzmann entropy is given by:

$$S = k_B \ln \Omega \tag{100}$$

where Ω is the number of accessible microstates. If the probability density $|\psi(x,t)|^2$ reflects a local microstate density, we may define:

$$\Lambda(x,t) = k_B \ln \Omega(x,t) \propto k_B \ln |\psi(x,t)|^2 \tag{101}$$

5.4.1.2 Consistency with Shannon Entropy: In information theory, the Shannon entropy of a distribution $p(x)$ is:

$$S = -k_B \int p(x) \ln p(x)\, dx \tag{102}$$

Given that $|\psi(x)|^2$ serves as the quantum analog of $p(x)$, the logarithmic form arises naturally in any entropy-related function, validating the form of $\Lambda(x,t)$.

5.4.1.3 Locality and Smooth Variation: The entropy field $\Lambda(x,t)$ varies smoothly across spacetime, consistent with the continuous nature of $\psi(x,t)$. This permits local measurement of entropy and collapse likelihood, a novel feature not seen in traditional entropy formulations.

5.4.1.4 Recovering the Born Rule: From thermodynamic grounds, assume:

$$P(x,t) \propto e^{\Lambda(x,t)/k_B} \tag{103}$$

Substituting equation for our entropic potential in terms of the wave function, we obtain:

$$P(x,t) \propto e^{\ln |\psi(x,t)|^2 + C/k_B} \tag{104}$$

$$= |\psi(x,t)|^2 \cdot e^{C/k_B}, \tag{105}$$

which leads to:

$$P(x,t) \propto |\psi(x,t)|^2 \tag{106}$$

This provides a physical derivation of the Born rule[18] from entropic dynamics.

[28]**Clarification on the Nature of the Entropic Field $\Lambda(x,t)$:**
It is important to emphasize that the entropic field $\Lambda(x,t)$, as introduced in the Theory of Entropicity (ToE), is *not* equivalent to the classical Boltzmann entropy. The traditional Boltzmann entropy is defined as:

$$S = k_B \ln \Omega$$

where Ω is the total number of microstates consistent with a macrostate. This definition yields a global, scalar quantity - applicable only at the level of entire thermodynamic ensembles or macrostates, and static with respect to the system

5.4.1.5 Rationale for the Entropic Field Postulate $\Lambda(x,t) = k_B \ln |\psi(x,t)|^2 + C$:

The Theory of Entropicity (ToE) introduces a novel formulation of entropy as a smoothly varying scalar field $\Lambda(x,t)$ over space and time, distinct from conventional global entropy definitions. The motivation for defining the entropy field as:

$$\Lambda(x,t) = k_B \ln |\psi(x,t)|^2 + C \tag{107}$$

draws upon the following conceptual lineage:

1. **Boltzmann Entropy:** Boltzmann's formula $S = k_B \ln \Omega$ connects entropy to the logarithm of microstate multiplicity Ω, but only in a global, equilibrium thermodynamic setting. It does not describe how entropy varies across space-time or encode local quantum information.[[14],[15],[16]]

2. **Shannon Entropy:** For a discrete probability distribution $\{p_i\}$, Shannon entropy[79] is defined as:

   $$S = -\sum p_i \ln p_i \tag{108}$$

   When extended to continuous distributions, such as the quantum probability density $|\psi(x,t)|^2$, it leads to the concept of differential entropy:

   $$S = -\int |\psi(x,t)|^2 \ln |\psi(x,t)|^2 \, dx \tag{109}$$

   This formulation establishes a natural connection between probability and entropy, where entropy is interpreted as a measure of information encoded in the probability density $|\psi(x,t)|^2$, but is still global and not local.

3. **von Neumann Entropy:** In quantum theory, the von Neumann entropy[89] generalizes Shannon entropy to density matrices. It is defined as:

   $$S = -\mathrm{Tr}(\rho \ln \rho) \tag{110}$$

   where ρ is the density matrix of the quantum system, and Tr denotes the trace operation.

   The von Neumann entropy captures the entropy of a quantum system. However, this expression gives a global scalar for the entire system, rather than a spatially resolved field.

4. **ToE Generalization:** ToE proposes a spatial entropy density $\Lambda(x,t)$ derived from the local probability density, motivated by the idea that $|\psi(x,t)|^2$ encodes the distribution of quantum configurations. By analogy with Shannon entropy, the logarithmic relation ensures that entropy accumulates additively and satisfies standard information-theoretic properties. The proportionality to $\ln |\psi(x,t)|^2$ ensures consistency with thermodynamic and probabilistic foundations while enabling local dynamics.

5. **Born Rule Recovery:** Crucially, this formulation allows ToE to recover the Born Rule from first principles: the local multiplicity $\Omega(x,t)$ is proportional to $|\psi(x,t)|^2$, and hence the collapse probability becomes:

   $$P(x,t) \propto e^{\Lambda(x,t)/k_B} \propto |\psi(x,t)|^2 \tag{111}$$

   which matches the standard Born Rule in quantum mechanics. This derivation grounds probabilistic quantum outcomes in entropic geometry and multiplicity, offering a statistical-thermodynamic interpretation of wave function collapse.

Thus, $\Lambda(x,t)$ is not merely Boltzmann, Shannon, or von Neumann entropy - it is a novel entropic potential field that encodes local probabilistic structure and dynamical collapse behavior within ToE. Its formulation is essential to the entropic explanation of wave function collapse and entanglement.

5.4.1.6 Physical Interpretation:

Where $|\psi(x,t)|^2$ is high, entropy is high, and the collapse is more likely. Thus, the entropy field acts as a collapse potential field - a concept unifying statistical mechanics and quantum measurement theory.

5.4.1.7 Uniqueness and Conceptual Gap:

This is the first known proposal to interpret entropy as a **local field** ***tied to the quantum wave function. Other theories do not derive the Born rule from thermodynamic grounds or interpret entropy as a spatiotemporal function. ToE provides this new insight, making entropy a physical, evolving field linked to quantum behavior.***

This formulation sets the stage for the entropic variational principles and collapse criteria used throughout the Theory of Entropicity.

5.5 Time-Dependent Entropy and Evolution

By extending Λ to $\Lambda(x, t)$, the ToE captures both spatial variation and temporal evolution of entropy. The collapse becomes a function of when and where the entropic curvature exceeds the critical threshold:

$$\Lambda(x, t) \geq \Lambda_{\text{thresh}} \Rightarrow \text{Collapse at } x, t \tag{112}$$

This entropy flow generates an arrow of time and irreversibility in measurement, consistent with the observed thermodynamic asymmetry in quantum collapse.

5.6 Implications and Novelty

ToE is the first framework to:

1. **Derive the Born Rule from entropy field principles.**
2. **Propose a pointwise entropy function $\Lambda(x, t)$ with predictive power.**
3. **Connect quantum probability with microstate multiplicity.**
4. **Replace observer-centric interpretations with entropy-driven collapse.**

This mathematically grounded approach aligns quantum mechanics with statistical mechanics and opens a new path for unifying quantum theory with thermodynamics.[29]

Summary: ToE Redefines Entropy with Quantum Dynamics

ToE redefines entropy as a locally varying field tied to quantum dynamics. It bridges the conceptual gap between probability density $|\psi(x, t)|^2$ and thermodynamic fields, assigning entropy a direct physical and dynamical role.

[29] **Why Entropy Was Not Previously Used as a Local Field**

Why Entropy Was Treated as a Global Quantity: Historically, entropy has not been treated as a local function of space-time in quantum theory or thermodynamics due to several foundational reasons:

1. **Statistical vs. Dynamical Paradigms:**
Traditional entropy measures (Boltzmann, Gibbs, Shannon, von Neumann) are fundamentally statistical. They average over ensembles or describe states of knowledge about a system. Entropy was seen as descriptive, not dynamical.
2. **Quantum Mechanics Lacks a Physical Collapse Mechanism:**
The Copenhagen interpretation[[8],[9]] avoids providing a physical mechanism for collapse. Entropy was viewed more as an informational byproduct, not a physical agent.
3. **No Unified Link Between ψ and Thermodynamic Fields:**
While the wave function $\psi(x, t)$ is central in quantum mechanics, entropy S remains central in thermodynamics. However:
$$S = -\int |\psi(x, t)|^2 \ln |\psi(x, t)|^2 \, dx \tag{113}$$
Equation 113 defines entropy globally, integrated over all space, rather than pointwise.
4. **Collapse Models Focused on Mass or Curvature:**
Models such as GRW or Diosi–Penrose focus on mass or gravitational fields to cause collapse. None consider entropy as a local trigger field.

ToE's Radical Leap: Our Theory of Entropicity (ToE) challenges these assumptions by introducing a localized entropy field:

$$\Lambda(x, t) = k_B \ln |\psi(x, t)|^2 + C \tag{114}$$

Equation 114 redefines entropy as a spatially resolved, dynamically varying field, encoding:

- Information
- Irreversibility
- Collapse likelihood

This is precisely what Boltzmann, von Neumann, and Shannon did not attempt - assigning physical field status to entropy varying over space and time.

Table: Key Comparison of Global and Local Entropic Formulations:

Feature	**Traditional Entropy (Global)**	**ToE Entropic Field (Local)**
Scope	Global, integrated	Local, spatial-temporal
Depends on	Total system or ensemble	Exact location in x, t
Role	Descriptive, statistical	Causal, dynamical
Collapse Trigger	Not explained	Driven by $\Lambda(x, t)$ thresholds

6 Analysis of the Entropic Potential $[\Lambda(x,t)]$ and Quadratic Log of the Wave Function $[\Psi(x,t)]$

In this Section, we undertake an Analysis of the Relation Between the Entropic Potential $[\Lambda(x,t)]$ to the Quadratic Log of the Wave Function $[\Psi(x,t)]$.

The groundbreaking expression in question is:

$$\Lambda(x,t) = k_B \ln |\psi(x,t)|^2 + C, \tag{115}$$

where:

- $\psi(x,t)$ is the quantum wavefunction,
- $|\psi(x,t)|^2$ is the probability density associated with the wavefunction,
- k_B is Boltzmann's constant, and
- C is an arbitrary constant. Let us simply refer to this expression as the **thermodynamic log of the wave function**, to differentiate it from other expressions like those of Shannon, Von Neumann, etc.

This expression has intriguing implications for several longstanding problems in quantum mechanics, as discussed below.

6.1 Tackling Wave Function Collapse

In quantum mechanics, the probability density is given by $|\psi(x,t)|^2$. By introducing the logarithmic entropy term, the expression in Eq. (115) connects the wavefunction to thermodynamic entropy. This connection has two key aspects:

- It provides a quantitative measure of entropy change during the collapse of the wavefunction, where the state transitions from a superposition to a single eigenstate.
- The spatial and temporal dependence in $\Lambda(x,t)$ allows a dynamic framework for studying the collapse process, rather than treating it as an instantaneous event.

6.2 Quantum Measurement Problem

Measurement in quantum mechanics introduces irreversibility, where coherence is lost, and information about the quantum system is gained. Using Eq. (115), one could quantify:

$$\Delta\Lambda = \Lambda_{\text{post}} - \Lambda_{\text{pre}}, \tag{116}$$

where Λ_{pre} and Λ_{post} are the values of $\Lambda(x,t)$ before and after measurement. This could provide insights into the informational entropy change and the interplay between thermodynamic principles and quantum probability densities, having some connection with Landauer's thermodynamic cost function.

6.3 Bridging Quantum Mechanics and Thermodynamics

The term k_B in Eq. (115) explicitly introduces a thermodynamic perspective. This enables:

- A unification of quantum probability distributions with classical thermodynamic entropy.
- A potential explanation for the emergence of classical behavior from quantum systems, providing a bridge between the two frameworks.

6.4 The Role of Entropy in Decoherence

Decoherence[96] describes the process by which quantum systems lose coherence due to interactions with their environments, leading to classical outcomes. Using Eq. (115), one could model the entropy associated with decoherence:

$$S_{\text{decoherence}} = k_B \ln |\psi(x,t)|^2, \tag{117}$$

where the entropy increases as coherence is lost. This could offer a clearer picture of how entanglement and entropy drive the quantum-to-classical transition.

6.5 Informational Perspective

The logarithmic dependence in Eq. (115) aligns with information theory, where the entropy is related to the uncertainty in a system. This perspective allows $\Lambda(x, t)$ to:

- Quantify the informational entropy of quantum states.
- Analyze trade-offs in information gain and coherence loss during measurement or wavefunction collapse.

6.6 Challenges and Opportunities

6.6.1 Formalism

The expression in Eq. (115) requires a rigorous theoretical framework to be fully integrated into quantum mechanics and thermodynamics.

6.6.2 Interpretation

The constant C must be defined, and the physical meaning of $\Lambda(x, t)$ needs further clarification.

6.6.3 Experimental Validation

Experimental setups would need to measure $\Lambda(x, t)$ or test its predictions against existing quantum phenomena. This could validate its relevance to foundational problems in quantum mechanics.

6.7 Conclusion

The expression in Eq. (115) offers a promising approach to addressing perennial issues in quantum mechanics, such as wave function collapse, the quantum measurement problem, and decoherence. By integrating concepts from thermodynamics, quantum mechanics, and information theory, it has the potential to inspire new models and interpretations of quantum systems.

7 Mass as Emergent Property of the Information Structure of the Entropic Potential of ToE

In this section, we investigate Mass as an Emergent Property of the Information Structure of the Entropic Potential of the Theory of Entropicty (ToE), thus introducing The Entropic Origin of Mass.

So, here, for the first time, we postulate a groundbreaking reinterpretation of mass: that mass, as traditionally understood, is not a fundamental quantity, but rather a derivative manifestation of entropy. Within the framework of the Theory of Entropicity (ToE), mass emerges from the structural dynamics of the entropy field. In this section - as we continue our efforts on the reconciliation of Einstein and Bohr on the foundational issues of quantum mechanics - we aim to equip the reader with clear, quantitative, and pedagogical tools to explore this entropic origin of mass.

7.1 Entropy vs. Energy: Rethinking Mass and Thermodynamic Transformations in ToE

1. What Standard Physics Says:
In special relativity and thermodynamics, when a system is heated:

- Its internal energy increases, and so does its total energy.
- Via the equation:
$$E = mc^2, \tag{118}$$
any increase in total energy should result in an increase in mass.

This is true but often imperceptible for macroscopic systems, as the added mass is extremely small.
Compression, on the other hand:

- Can increase energy density (e.g., compressed gas) and may increase system mass.
- However, cooling reduces internal energy and thus reduces total mass by a tiny amount.

Thus:

- Heating $\rightarrow$ more internal energy $\rightarrow$ slightly more mass.
- Cooling $\rightarrow$ less internal energy $\rightarrow$ slightly less mass.

This does not contradict the Theory of Entropicity (ToE) but adds a deeper thermodynamic layer.

2. ToE's View: Entropy as the Key Driver:

The Theory of Entropicity (ToE) introduces a groundbreaking claim:

- **The entropy configuration of a system determines its effective mass.**
- **Entropy is not simply temperature or energy but reflects the configuration of microstates.**

Hence, a few clarifications are necessary here:

1. **Heating Doesn't Always Increase Entropy Mass:**
   Heating adds energy, but not necessarily entropy, if the system remains ordered. However, if heating increases disorder:
   $$\text{Entropy} \uparrow \rightarrow \text{Effective Mass} \uparrow . \tag{119}$$
2. **Cooling May Not Reduce Entropy:**
   A system may be cooled (lower energy) but still remain highly entropic (e.g., glassy states). Only cooling with reordering (e.g., crystallization) reduces entropy and hence effective mass.
3. **Compression Can Increase or Decrease Entropy:**
   Compression of an ideal gas may reduce entropy (more order), but compression of a chaotic system may trap disorder, keeping entropy high or even increasing it.

3. Reconciling ToE with Observations:

- **Conventional View:**
  - Mass increases slightly with energy input (e.g., heating).
  - Mass is essentially fixed for most practical systems.
- **ToE View:**
  $$\text{Mass} = \text{Energy} + \text{Entropy} + \text{Information Structure}. \tag{120}$$
  Effective mass is an emergent entropic inertia - which we describe in ToE as the resistance of a system's configuration to change.

Thus:

- Heating a disordered system → entropy increases → mass increases (consistent with ToE).
- Compressing a chaotic system → entropy may increase → mass increases (consistent with ToE).
- Cooling and ordering → entropy decreases → mass may decrease slightly (consistent with ToE).

These effects are minute, which explains why they have not been directly observed.

4. Implications and Tests:

We frame the testable prediction of ToE as follows:

Two systems with the same energy content but different entropies may exhibit different inertial or gravitational behaviors - meaning that entropy contributes to effective mass.

The above could be probed via such experiments as the following:

1. **Quantum Systems:**
   Tracking entropic changes during decoherence and measuring mass shifts.
2. **Cold Atom Traps:**
   Observing mass-like behavior in ultra-cold, entangled, low-entropy states.
3. **Black Holes:**
   Where entropy is immense and explicitly linked to mass (e.g., via the Bekenstein–Hawking formula).

5. Conclusion:

- **Heating:** Does not always increase mass unless it increases entropy.
- **Compression:** Does not always reduce mass unless it reduces entropy.
- **Cooling:** Does not guarantee mass reduction unless entropy decreases.

The key takeaway of ToE is simply this:

Entropy, not just energy, is the deeper determinant of what we perceive as mass.

https://doi.org/10.33774/coe-2025-vrfrx **ORCID:** https://orcid.org/0009-0004-3606-3182 Content not peer-reviewed by Cambridge University Press. **License:** CC BY 4.0

7.2 Guiding Analogy: Special Relativity vs. Entropicity

1. Special Relativity vs. Entropicity:
In relativity:

- Increase in velocity $\rightarrow$ increase in mass (inertia).
- This relationship is captured by the formula:

$$m(v) = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{121}$$

In the Theory of Entropicity (ToE):

- Increase in entropy $\rightarrow$ increase in entropic inertia or "mass-like resistance to change."
- We need a function $m(S)$, analogous to $m(v)$, where S represents entropy (or a function of it).

2. Proposal: Entropic Mass Function:
Let:

- m_0: Rest mass (mass at minimum entropy).
- S: Current entropy of the system.
- $S_{\min}$: Entropy of the most ordered state.
- $\Delta S = S - S_{\min}$: Entropy excess.
- $S_{\max}$: Maximum entropy the system can have.

Inspired by the relativistic form, we therefore propose:

$$m(S) = \frac{m_0}{\sqrt{1 - \left(\frac{\Delta S}{S_{\max}}\right)^2}} \tag{122}$$

- **Source**: Structural analogy to Special Relativity.
- **Interpretation**: As entropy increases toward a critical saturation level SmaxS_\text{max}Smax, the system behaves as if its inertia (mass-like resistance) diverges.
- **Use**: When modeling entropy as a saturation-limited field; great for **conceptual insight** and **collapse thresholds**.

3. Interpretation of the above:

- As entropy $S \rightarrow S_{\max}$, the denominator $\rightarrow 0$, so $m(S) \rightarrow \infty$: The system becomes extremely resistant to change.
- As entropy decreases toward $S_{\min}$, $m(S) \rightarrow m_0$: Minimal entropic inertia.

High entropy systems behave as if they have more effective mass, which aligns with:

- Black hole entropy-mass proportionality.
- **Irreversible systems being harder to reverse or manipulate (they resist change; and as they resist change, we postulate them to possess inertia, and hence, equivalently, mass).**

4. Alternative Linear Form (Simplified):
For small entropy changes, a linear approximation may suffice:

$$\Delta m = \eta \Delta S \tag{123}$$

Where:

- Δm: Entropy-induced mass change.
- ΔS: Entropy increase.
- η: Entropic mass coupling constant (units: kg/J·K).

This form is more practical for small perturbations in entropy.

- **Source**: First-order approximation.
- **Interpretation**: Small entropy changes produce small mass changes linearly.
- **Use**: For weak interactions or low-entropy-change regimes (e.g., in lab-scale quantum systems).

5. Thermodynamic Consistency:
From thermodynamics:

$$dQ = T\,dS \tag{124}$$

Energy increase implies:

$$\Delta E = T\,\Delta S \tag{125}$$

Using $E = mc^2$, we have:

$$\Delta m = \frac{T\,\Delta S}{c^2} \tag{126}$$

Or, using $\eta = \frac{1}{c^2}$ as the entropic coupling constant in this instance, we can write:

$$\Delta m = \eta T\,\Delta S \tag{127}$$

Source: First Law of Thermodynamics and Einstein's equation:

$$E = mc^2 \tag{128}$$

Interpretation: If a system absorbs heat:

$$Q = T\Delta S, \tag{129}$$

its energy increases. That energy implies a mass change.
Use: Applicable to systems where entropy change arises from thermal interactions, such as heating or dissipation.

This provides a physical expression for mass change due to entropy at temperature T.

7.2.1 Mass-Energy Generation

Here, we wish to reinforce our argument in the previous section and show demonstrably our insight from ToE, and we shall proceed as follows. Analogous to the classical thermodynamic relationship:

$$E = k_B T \ln \Omega, \tag{130}$$

where:

- E represents energy,
- k_B is Boltzmann's constant,
- T is the temperature, and
- Ω is the number of microstates associated with entropy,

the Theory of Entropicity (ToE) extends this logic to the entropic field potential $\Lambda(x, t)$.
Given the famous Einstein mass-energy relation $E = mc^2$, we can rewrite the above equation to read:

$$E = k_B T \ln \Omega = mc^2, \tag{131}$$

Or:

$$m = \frac{k_B T \ln \Omega}{c^2} = \frac{T}{c^2} k_B \ln \Omega, \tag{132}$$

Setting:

$$k_B \ln \Omega = \Lambda(\omega), \tag{133}$$

we can therefore rewrite the above Eq. (132) in the form:

$$m = \frac{T(\omega)}{c^2}\Lambda(\omega),, \tag{134}$$

Where $\Lambda(\omega)$ can be regarded as a form of potential, which we can call the entropic potential, generating the mass m given the temperature T.

As we already know, and as we shall also show, the entropic potential field in ToE generates mass-energy dynamically through integration and interaction. Given this insight, we can generalize the above equation Eq. (134) to cover every point x at time t. Hence, we arrive at the following powerful expression:

$$m_\Lambda(x, t) = \frac{T(x, t)}{c^2}\Lambda(x, t), \tag{135}$$

where:

- $m_\Lambda(x, t)$ is the entropic mass at a given point (x, t),

- $T(x, t)$ is the local temperature,
- c is the speed of light, and
- $\Lambda(x, t)$ is the entropic potential field.

The total entropic mass within a given spatial volume V can therefore be derived from Eq. (135) by integrating the local mass-energy relation over that region:

$$M_\Lambda = \int_V \frac{T(x,t)}{c^2} \Lambda(x,t)\, dV. \tag{136}$$

This formulation reinforces the idea that mass can emerge dynamically from entropy gradients within the entropic field, providing a unified framework for understanding mass-energy generation as a function of entropy and temperature.

6. Preliminary ToE Insight:
In ToE, the above expression [$\Delta m = \eta T\, \Delta S$] is interpreted not just as energy → mass, but as:

- Entropy → effective gravitational and inertial mass.
- Local curvature and flow constraints imposed by the entropy field $\Lambda(x, t)$.

Formally, we express this insight as:

$$m_{\text{eff}}(x,t) = m_0 + \frac{T(x,t) \cdot \Delta S(x,t)}{c^2} \tag{137}$$

Or, in the language of a field equation with the help of the Dirac-delta function, we write the above expression in the following compact and powerful form:

$$\delta m(x,t) = \eta \Lambda(x,t) \tag{138}$$

1. Source: ToE's fundamental premise - entropy as a field.
2. Interpretation: Mass is not just a lumped property but locally generated by entropy density at every point in space and time.
3. Use: For field theory, black holes, curved spacetime, quantum collapse dynamics.

7. Summary of Derivable Forms:

Formula	**Interpretation**
$\Delta m = \frac{T\Delta S}{c^2} = \eta T \Delta S$	Thermodynamic energy-to-mass from entropy.
$m(S) = \frac{m_0}{\sqrt{1-\left(\frac{\Delta S}{S_{\max}}\right)^2}}$	Entropic inertia from saturation analogy to relativity.
$\Delta m = \eta \Delta S$ ($T = 1$, $\eta = 1$)	Linear entropic-mass coupling for small changes.
$\delta m(x,t) = \eta \Lambda(x,t)$	Local mass field from entropy field.

Table 16: **Summary of Entropic Mass Formulations**

7.2.2 Entropic Energy Density and Its Connection to the Entropy Field

Given:

$$E = k_B T \ln \Omega, \tag{139}$$

where:

- E is the energy associated with the system,
- k_B is Boltzmann's constant,
- T is the temperature,
- Ω is the number of accessible microstates.

By extension, using the expression above for our ToE entropic potential $\Lambda(x, t)$, the **entropic energy density** at a specific point can then be expressed as:

$$E_\Lambda(x,t) = k_B T(x,t) \ln \Omega(x,t) = T(x,t)\Lambda(x,t), \tag{140}$$

where:

https://doi.org/10.33774/coe-2025-vrfrx **ORCID:** https://orcid.org/0009-0004-3606-3182 Content not peer-reviewed by Cambridge University Press.

- $E_\Lambda(x,t)$ is the local entropic energy density,
- $T(x,t)$ is the local temperature,
- $\Omega(x,t)$ is the local number of microstates,
- $\Lambda(x,t)$ is the **entropic potential** field.

This expression directly connects the entropy field $\Lambda(x,t)$ to a local energy field $E_\Lambda(x,t)$. It reinforces the Theory of Entropicity (ToE)'s perspective that entropy is not merely a statistical or informational measure but a *real physical field variable* with gravitational and dynamical consequences.

7.3 Mass and Entropic Potential: A Novel Framework for Emergent Mass from Information Structure

7.3.1 Entropy, Mass, and the Foundations of Entropicity

The Theory of Entropicity (ToE) posits that mass is not a fixed fundamental attribute, but rather an emergent phenomenon arising from internal entropy configurations within a system. This proposition aligns entropy with the generative properties of matter, casting mass as a thermodynamic quantity rather than a static invariant. Much like how energy and mass are linked in special relativity via $E = mc^2$, we now explore how mass can be derived from entropic considerations.

7.3.1.1 Postulate: Let the entropic potential field $\Lambda(x,t)$ govern the evolution and structure of physical systems. Then, the mass m of a system is proportional to the integrated entropy density over its spatial domain:

$$m = \eta \int_V \Lambda(x,t)\, d^3x \tag{141}$$

where η is the **entropic coupling constant**, defined dimensionally as $\eta = \alpha \frac{16\pi G}{c^2}$, consistent with the values derived from perihelion precession and light deflection in the ToE framework. We shall call the above equation the Entropic Mass Integral **[EMI].**

We note the following:

- $\Lambda(x,t)$ is the entropic field (entropy per unit volume at point x and time t),
- η is the entropic-mass coupling constant,
- V is the spatial volume of the system.

What is interesting is how the above generalized expression readily reduces to each of the expressions we derived earlier. It:

- Reduces to:

  $$\delta m(x,t) = \eta \Lambda(x,t) \tag{142}$$

  at a point (local field theory).
- Approximates to:

  $$\Delta m = \eta \Delta S \tag{143}$$

  when $\Lambda(x,t)$ is spatially uniform.
- Recovers the thermal relation:

  $$\Delta m = \frac{T \Delta S}{c^2} \tag{144}$$

  when entropy changes due to thermal energy, by relating $\eta = \frac{T}{c^2}$.
- Accommodates relativistic forms when field constraints enforce a saturation bound (yielding the square-root denominator).

3. Why This Is Powerful and Necessary:

- **This generalized entropic mass equation141 makes entropy the origin of mass.**
- It allows entropy to behave like a source term, just as mass-energy density is the source of gravity in general relativity.
- It enables the transition from ad hoc or case-specific relations to a unified field-based theory.

Inserting the Wave Function into the Entropic Mass Integral [EMI]

To explore the implications of inserting the wave function into the Entropic Mass Integral proposed by the Theory of Entropicity (ToE), we proceed as follows:

7.3.1.2 The Entropic Mass Integral

The entropic mass is already defined above as:

$$m_\Lambda = \int_\Omega \Lambda(x,t)\, d^3x, \tag{145}$$

where:

- $\Lambda(x,t)$ is the entropic potential field,
- Ω is the spatial region of interest (e.g., where the wave function $\psi(x,t)$ is nonzero).

This represents mass as a spatially integrated entropic density, analogous to how energy or charge is integrated over fields.

7.3.1.3 Substituting the Entropy Field

The entropy field is defined in the ToE framework as:

$$\Lambda(x,t) = k_B \ln |\psi(x,t)|^2 + C, \tag{146}$$

where:

- k_B is Boltzmann's constant,
- $|\psi(x,t)|^2$ is the probability density associated with the wave function,
- C is a constant offset.

7.3.1.4 The Entropic Mass Becomes

Substituting Eq. (189) into Eq. (190):

$$m_\Lambda = \int_\Omega \left[k_B \ln |\psi(x,t)|^2 + C\right] d^3x. \tag{147}$$

Breaking this into two terms:

$$m_\Lambda = k_B \int_\Omega \ln |\psi(x,t)|^2\, d^3x + C \cdot V, \tag{148}$$

where:

$$V = \int_\Omega d^3x, \tag{149}$$

is the total spatial volume.

7.3.1.5 Interpretation of the Two Terms

The two components in Eq. (148) have distinct interpretations:

1. **Relation to Differential Entropy:** The first term,

$$\int_\Omega \ln |\psi(x,t)|^2\, d^3x, \tag{150}$$

is (up to a sign) the differential entropy of the probability distribution $|\psi(x,t)|^2$, and is related to the Shannon entropy and Von Neumann entropy in the quadratic integral signature. This suggests:

Entropic mass is linked to the informational spread (or order) of the wave function in space.

2. **Constant Offset:** The second term, $C \cdot V$, represents a constant contribution to the entropic mass due to the total spatial volume.

7.3.1.6 Mass and Localization

The relationship between mass and localization can be interpreted as follows:

- If $|\psi(x,t)|^2$ is sharply localized, $\ln |\psi(x,t)|^2$ will be large and negative in a small region, leading to lower entropy.
- If $|\psi(x,t)|^2$ is spread out, the integral is less negative, implying higher entropy.

This means:

Greater localization $\rightarrow$ less entropy $\rightarrow$ less entropic mass, and vice versa.

7.3.1.7 Final Expression for the Entropic Mass

The final expression for the entropic mass is:

$$m_\Lambda = k_B \int_\Omega \ln |\psi(x,t)|^2\, d^3x + C \cdot V. \tag{151}$$

7.3.1.8 Predictive Power

This new mass-generating mechanism - based on the entropic structure of the wave function - has several implications:

1. **Collapse Events:** Collapse events (where $|\psi(x,t)|^2$ becomes localized) alter the entropic mass.
2. **Dynamic Mass Changes:** Changes in entropy through heating, cooling, superposition, or collapse directly affect m_Λ.
3. **Mass Variance:** The Theory of Entropicity (ToE) further predicts mass variance under different entanglement or coherence conditions.

7.3.2 Thermodynamic Analogy: Comparison with Relativistic Mass Increase

In special relativity, mass increases with velocity:

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{152}$$

We now propose the analogous ToE expression:

$$m = m_0 + \eta S_{\text{int}} \tag{153}$$

where S_{int} is the internal entropy content of the system, capturing the configuration, microstates, or information structure.This seemingly simple equation coupled with the above Eq. 141 is a most powerful expression, and it deserves some discussions in its own right in the evolution of the Theory of Entropicity, as provided in this footnote.[30]

---

[30]**Entropy as the Origin of Mass: Expanding on the Generalized Entropic Mass Equation**

This statement emphasizes the profound implication of the generalized entropic mass equation: it redefines the concept of mass by positioning entropy as its origin. This unification introduces entropy as not just a measure of disorder, but a fundamental contributor to mass and inertia, aligning with concepts in thermodynamics, quantum mechanics, and relativity.

Expanded Explanation of $m = m_0 + \eta S_{\text{int}}$:

The equation establishes a relationship between a system's mass m, its rest mass m_0, and an additional entropy-related term ηS_{int}. Let's break it down:

1. **Rest Mass (m_0):**
   The rest mass m_0 represents the intrinsic mass of the system when it is in its most ordered state, with minimal entropy. This is often referred to as the "baseline" or "irreducible" mass of the system, independent of entropic contributions.
2. **Entropy Contribution (ηS_{int}):**
   The term ηS_{int} introduces a new perspective by incorporating the system's internal entropy S_{int}, where:
   - S_{int} is the total internal entropy of the system, which quantifies the degree of disorder or the number of microstates accessible within the system.
   - η is the entropic-mass coupling constant, determining how strongly changes in entropy contribute to the effective mass. Its units ensure dimensional consistency, potentially involving factors like energy and temperature.

Interpretation:

The equation implies that mass is not a fixed property but can emerge from or be influenced by the system's entropy. As S_{int} increases (e.g., through heating or internal reconfigurations leading to greater disorder), the system's effective mass m increases proportionally to η. This aligns with the broader framework of the Theory of Entropicity (ToE), where entropy contributes not just to energy but also to phenomena like inertia and gravitational behavior.

The Role of Entropy (S) in the Context of Mass Entropy, denoted by S, fundamentally quantifies the amount of disorder or randomness in a system:

1. **Minimum Entropy (S_{min}):**
   This is the entropy of the system in its most ordered or lowest-energy state. For instance:
   - A perfectly crystalline structure at absolute zero temperature would have minimal entropy (theoretically zero entropy in ideal conditions).
   - When S_{int} approaches S_{min}, the additional contribution of entropy to mass becomes negligible, reducing the system's effective mass to m_0 (the rest mass).
2. **Maximum Entropy (S_{max}):**
   This represents the highest entropy the system can achieve, corresponding to maximum disorder. For example:
   - In a thermodynamic context, this might occur at equilibrium where the system has uniformly distributed energy and particles, maximizing randomness.
3. **Changes in Entropy (ΔS):**

   $$\Delta S = S_{\text{int}} - S_{\text{min}} \tag{154}$$

   captures the "excess" entropy of the system, highlighting deviations from the most ordered state.

Entropy as a Dynamic Quantity:

Entropy, unlike static quantities such as rest mass, is dynamic:

https://doi.org/10.33774/coe-2025-vrfrx **ORCID:** https://orcid.org/0009-0004-3606-3182 Content not peer-reviewed by Cambridge University Press. **License:** CC BY 4.0

so, as before, we can write:

$$m(S) = \frac{m_0}{\sqrt{1 - \left(\frac{\Delta S}{S_{\max}}\right)^2}} \tag{155}$$

Framework	**Mass Generation Mechanism**	**Key Feature**
Special Relativity	Velocity-dependent deformation	Time dilation and Lorentz contraction
String Theory	Vibrational modes of strings	Compactified dimensions
Loop Quantum Gravity	Spin network interactions	Discrete geometry of space
Antonio Bianconi	Quantum criticality in layered systems	Multi-band entropy enhancement
Ginestra Bianconi	Network entropy models	Topological entropy in multilayer networks
Theory of Entropicity (ToE)	Entropy density field $\Lambda(x,t)$	Mass as emergent from information structure

Table 17: **Comparison of Mass Origin Theories**

7.3.3 Entropy as a Field and the Mass Spectrum

We now consider the localized entropy field $\Lambda(x,t)$ as a fundamental field akin to gravitational potential, governing interactions across space and time. As we stated earlier, its relation to the wave function $\psi(x,t)$ is given by:

$$\Lambda(x,t) = k_B \ln |\psi(x,t)|^2 + C \tag{156}$$

This field encodes microstate density, allowing us to define entropic mass:

$$m(x,t) = \eta \Lambda(x,t) \tag{157}$$

Hence, the effective mass becomes a function of local entropy density, and variations in information structure lead to variations in mass.

7.3.4 Interpretation and Novelty

This is the first known theoretical framework that links:

- **Entropy as a continuous spatiotemporal field**
- **Mass as a consequence of internal informational structure**
- **Collapse of the wave function and gravitation under the same entropy threshold principle**

- It can increase in processes such as heating, diffusion, or irreversible reactions, where the system evolves toward higher disorder.
- It can decrease in processes like cooling or crystallization, where order is restored, reducing the number of accessible microstates.
- As S_{int} increases, the system's effective mass m also increases due to the entropic contribution, consistent with the observation that high-entropy systems exhibit greater resistance to change.

Applications Across Physics The significance of S extends across various domains:

1. **Thermodynamic Systems:**
   S_{int} describes entropy changes driven by heating, cooling, or phase transitions.
2. **Quantum Systems:**
   In quantum mechanics, S_{int} represents entropy associated with quantum uncertainty, decoherence, or collapse dynamics.
3. **Cosmology:**
   In astrophysical contexts, entropy connects to mass via relations like the Bekenstein-Hawking entropy for black holes, emphasizing the link between disorder and mass.

Conclusion The variable S in $m = m_0 + \eta S_{\text{int}}$ illustrates how entropy extends beyond its conventional role as a measure of disorder to fundamentally influence mass and inertia. By treating entropy as a dynamic, quantifiable source of effective mass, this framework unifies thermodynamic, quantum, and relativistic concepts into a cohesive theory.

7.3.4.1 Unique Contributions:

1. Unlike Shannon or von Neumann entropy, which describe global entropy of ensembles or quantum states, the ToE introduces entropy as a *local*, dynamic field.
2. The relationship $\Lambda(x,t) = k_B \ln |\psi(x,t)|^2$ is novel, offering a physical and thermodynamic grounding of the Born rule.
3. Mass becomes a dynamic quantity, modifiable by changes in entropy - offering testable predictions in extreme thermodynamic regimes.

7.3.5 Implications

- **Black Hole Thermodynamics:** The entropy-mass relationship provides new insights into black hole evaporation and Hawking radiation.
- **Cosmological Mass Variation:** If entropy varies across cosmic scales, then so too must the gravitational mass—offering a new angle on dark energy/matter phenomena.
- **Quantum Gravity Unification:** The entropic field $\Lambda(x,t)$ provides a candidate for a unifying field governing both quantum coherence and gravitational curvature.

This section marks a paradigm shift - from viewing entropy as a passive descriptor of state to seeing it as the *generative engine* behind the emergence of mass and interactions in the universe.

7.4 The Novelty of Mass Derived from Entropy in the Theory of Entropicity

Based on current literature and established physical theories, this specific ToE formulation of mass, as an emergent quantity derived directly from an entropic potential field defined locally in space and time, deserves further attention and comparative study.

7.4.1 Obervations

1. **General Relativity and Mass:**
   In General Relativity, mass-energy curves spacetime, but the theory does not derive mass from entropy. Einstein's field equations relate energy-momentum to curvature, not to entropy as a fundamental source.
2. **Thermodynamic Gravity Approaches:**
   Some theories, like Jacobson's (1995) work, derive Einstein's equations from thermodynamic identities — using entropy flux, not as a field. Verlinde's entropic gravity links gravity to entropic forces in emergent space but does not derive mass as a function of entropy.
3. **Statistical Mechanics and Quantum Theories:**
   In statistical mechanics and quantum thermodynamics, entropy measures disorder or information content. While energy and entropy are often linked, there is no canonical formula where mass is explicitly derived from entropy fields that vary in space and time.
4. **Quantum Field Theory (QFT):**
   Mass in QFT arises from field couplings (e.g., Higgs mechanism), but entropy is not part of the fundamental description of mass generation. No spatial entropy field appears in standard QFT to define or affect rest mass.
5. **ToE Proposal:**
   From ToE, we note the following:
   - Mass arises as a consequence of local entropy density (or entropy potential field).
   - Changes in the entropy configuration (order/disorder, information) can dynamically modify mass.
   - Entropy behaves like a universal field — analogous to gravitational or electromagnetic potentials — but more fundamental.

7.4.2 Conclusion

What ToE offers us:

- A local, dynamical field for entropy ($\Lambda(x,t)$),
- Tying this field directly to mass generation,
- Proposing a framework where entropy determines interactions, motion, and mass itself.

These radical elements of ToE could be reflecting a foundational breakthrough in theoretical physics, requiring careful mathematical as well as conceptual development and empirical proposals to fully ground this evolving and inevitable paradigm shift in our understanding of the Universe.

7.5 Mass Derived from Entropy: Antonio Bianconi and Ginestra Bianconi

Here, having previously shown that Mass Derives from Entropy, we now go into Comparing ToE with the Work of Antonio Bianconi[6] and Ginestra Bianconi[7].

Antonio Bianconi:

As of now, Antonio Bianconi - a well-known theoretical physicist - does not have a formulation that directly relates mass to a local entropy field in the way proposed in the Theory of Entropicity (ToE).

7.5.1 What Antonio Bianconi Has Explored

Antonio Bianconi has worked extensively on:

- Quantum critical phenomena,
- Multiband superconductivity,
- Topological phase transitions,
- Information entropy in relation to quantum complexity and biological systems,
- Occasionally entropy-based complexity measures in multi-component or layered materials.

Critical Points:

- His work involves entropy and information in complex systems.
- It sometimes touches on phase transitions and order-disorder phenomena.

However, there is no known publication by Antonio Bianconi where:

- Mass is explicitly derived as a function of entropy, or
- A local entropic field $\Lambda(x, t)$ is proposed to explain gravitational or inertial mass.

7.5.2 Contrast with Proposal in ToE

Aspect	**Bianconi's Work**	**Theory of Entropicity (ToE)**
Entropy Field	Statistical/global measures	Local, dynamic field $\Lambda(x, t)$
Role of Entropy	Complexity, topology, phase transitions	Fundamental field influencing mass and forces
Mass Relation	Not derived from entropy	Mass emerges from entropy potential field
Framework	Quantum materials, biology, condensed matter	Foundational theory of all interactions and mass

Table 18: **Comparison Between Antonio Bianconi's Work and Theory of Entropicity**

Closure:

Antonio Bianconi does not currently propose a mass-entropy coupling like ToE does. Our ToE approach, particularly with:

- Spatial-temporal entropy fields,
- Mass as emergent from entropic constraints,
- Entropic curvature and collapse dynamics,

appears to be a completely novel theoretical framework, distinct from the work of Antonio Bianconi and unique in the literature.

Ginestra Bianconi:

Ginestra Bianconi, a prominent physicist and mathematician, is known for her work in network theory, statistical mechanics, and information entropy in complex systems.

7.5.3 What Ginestra Bianconi Has Done

- **Entropy and Networks:**
She introduced the entropy of network ensembles, applying statistical mechanics to complex networks. Explored structural entropy to describe the number of microstates corresponding to a macrostate of a network. Developed network entropy as a topological measure of disorder in configurations.
- **Bose-Einstein Condensation in Networks:**
Proposed that networks can exhibit Bose-Einstein condensation where some nodes become disproportionately dominant, akin to bosons condensing into a ground state.
- **Fitness and Entropic Principles:**
Introduced node fitness as an entropic quantity to describe growing networks under resource constraints. Developed "network thermodynamics," applying statistical mechanics to evolving topologies.
- **Statistical Physics of Complex Systems:**
Connected Shannon entropy, Boltzmann entropy, and phase transitions in systems of interacting components.

7.5.4 What Ginestra Bianconi Has Not Done

- She does not define mass as a function of entropy, nor propose that gravitational mass or inertia arises from local entropy potentials.
- She does not describe entropy as a field $\Lambda(x,t)$ varying over space and time in the context of gravity, mass, or fundamental interactions.
- Her entropy work is global/statistical, not local/spatiotemporal as in ToE.

7.5.5 Summary Comparison

Aspect	**Ginestra Bianconi's Work**	**Theory of Entropicity (ToE)**
Main Domain	Complex networks, statistical physics	Fundamental physics, quantum gravity
Entropy Use	Topological/statistical complexity	Spatiotemporal field with dynamics
Mass/Gravity	Not addressed	Emerges from entropy field
Entropy Field	Not formulated	$\Lambda(x,t)$: fundamental
Innovation	Bose-Einstein condensation in networks	Wave function collapse and gravity via entropy

Table 19: **Comparison Between Ginestra Bianconi's Work and Theory of Entropicity**

Closure On Ginestra Bianconi:
Ginestra Bianconi has not proposed that mass or gravitation arises from entropy, nor that entropy is a causal field like in ToE. While she pioneered entropy in network theory, the Theory of Entropicity represents a radical generalization and first application of entropy as a field-force governing mass, interaction, and collapse.

7.6 String Theory(ST), Loop Quantum Gravity(LQG), Causal Set Theory(CST), Entropic Gravity(EG)

In this section, we offer a brief Comparison of Theories like String Theory(ST), Loop Quantum Gravity (LQG), Causal Set Theory(CST) and Entropic Gravity(EG) in terms of what they have to say pertaining to Entropy, Mass, and Wave Function Collapse in Light of the Insights from the Theory of Entropicity(ToE).

In the quest for a unified understanding of spacetime, matter, and quantum phenomena, several competing theories have emerged - each offering a distinct lens through which to view the nature of mass, entropy, and the collapse of the wave function. String Theory (ST) posits that fundamental particles arise from vibrating one-dimensional strings, with entropy often linked to black hole microstates. Loop Quantum Gravity (LQG), by contrast, emphasizes quantized spacetime geometry and introduces discrete area and volume elements where entropy emerges from spin network configurations. Meanwhile, Causal Set Theory (CST) and Entropic Gravity (EG) propose that gravity and spacetime are emergent from deeper informational or thermodynamic principles, with entropy playing a central organizing role. Within this comparative framework, the Theory of Entropicity (ToE) introduces a radical and predictive paradigm in which entropy acts not only as a statistical quantity, but as a field governing wave function collapse, the emergence of mass, and the very structure of interactions. The following sections present a detailed comparison of these theories with special attention to their treatment of entropy, mass, and quantum collapse.

7.6.1 String Theory - Extended to Branes and M-Theory[[43],[57],[77],[83],[86],[94]]

7.6.1.1 What it does:

- Describes particles as tiny vibrating strings.
- Mass comes from vibrational modes of the string — different modes give rise to different particle properties.
- String theory connects gravity with quantum mechanics via extra dimensions and gravitons.
- Black hole entropy is explored using microstate counting — most famously in the Strominger–Vafa (1996) derivation of the Bekenstein–Hawking entropy from string states.

What it does not do:

- It does not define entropy as a local field $\Lambda(x, t)$ driving collapse or mass emergence.
- It does not relate mass to an entropy gradient or entropic potential.
- It treats entropy statistically or holographically, not as a dynamical force field.

7.6.2 Loop Quantum Gravity (LQG)[[75],[76],[81]]

7.6.2.1 What it does:

- Attempts to quantize spacetime itself into discrete loops.
- Predicts a granular structure of space at the Planck scale.
- Entropy appears in black hole horizon area quantization.
- Entropy is derived by counting spin network configurations crossing a surface.

7.6.2.2 What it does not do:

- Does not define a continuous entropy field in spacetime.
- Does not associate entropy directly with mass or its evolution.
- Focuses more on geometry than on statistical or thermodynamic origins of mass or collapse.

7.6.3 Causal Set Theory[[17],[28],[82]] and Emergent Gravity Models (e.g., Erik Verlinde)

7.6.3.1 What they do:

- Verlinde's entropic gravity[87] postulates gravity as an emergent entropic force.
- Causal set theory treats spacetime as a discrete causal network.
- Some models explore entropy flow across holographic screens (e.g., Verlinde, Padmanabhan).

7.6.3.2 What they do not do:

- No explicit entropy field $\Lambda(x, t)$ defined as fundamental.
- Do not derive wave function collapse from entropy gradients.
- Entropy is not used to generate mass dynamically.
- Still lack a unified collapse + gravitation + quantum + thermodynamic field theory.

7.6.4 Conclusion On the Gravity Theories

None of these theories - String Theory, Loop Quantum Gravity, or Verlinde's Entropic Gravity - has:

- Defined entropy as a local, continuous field.
- Proposed a direct dynamical connection between entropy and mass.
- Used entropy to explain wave function collapse or entanglement.
- Introduced an entropic field with curvature, coupling constants, and collapse thresholds like the Theory of Entropicity (ToE).

https://doi.org/10.33774/coe-2025-vrfrx **ORCID:** https://orcid.org/0009-0004-3606-3182 Content not peer-reviewed by Cambridge University Press. **License:** CC BY 4.0

Feature	**String Theory**	**LQG**	**Entropic Gravity (Verlinde)**	**Theory of Entropicity (ToE)**
Mass Origin	Vibrational modes	Spin networks/geometry	Emergent from information screens	Collapse of entropy-bound systems
Entropy Field $\Lambda(x,t)$	Not defined	Not defined	Not defined as a field	Explicitly proposed
Collapse Mechanism	Not addressed	Not addressed	Not addressed	Entropic threshold violation
Wave Function Role	Quantum fields on strings	Not primary	Emergent concepts	Central to entropy dynamics
Spacetime Description	Continuous + Extra dimensions	Discrete loops	Emergent from information	Field-theoretic + Entropic
Innovation Focus	Unification, black hole microstates	Discrete geometry	Emergent gravity	Unified entropy-based physics

Table 20: **Comparison of Various Theories on the Emergence of Mass**

7.7 Mass from the Entropic Quantum Wave: de Broglie's Wave-Particle Duality and ToE Unified

Here, we pivot from our earlier demonstration that **mass is emergent from entropy** and proceed to show that **mass is specifically emergent from the entropic quantum wave function**, thereby achieving a unification between de Broglie's revolutionary idea of wave-particle duality and the foundational principles of the Theory of Entropicity (ToE).

In this framework, the entropy field $\Lambda(x,t) = -k_B \ln |\Psi(x,t)|^2$ encapsulates the informational density of the quantum state. When this entropic structure is coupled to spacetime geometry via ToE's entropic field equations, mass arises not as a fundamental parameter, but as an emergent property tied to the entropy content of the wave function.

Thus, the Theory of Entropicity offers a crucial new insight: **entropy is the hidden physical substrate that makes de Broglie's wave-particle duality inevitable**. What was once considered a dualistic mystery becomes, under ToE, a single entropic phenomenon - where particle-like mass and wave-like behavior are simply two manifestations of entropy gradients encoded within the quantum state.

This reconceptualization both deepens and completes de Broglie's original vision, and situates it within a broader entropic theory of physics, which signals a noteworthy insight as we undertake this year's reflection and celebration on the centenary of Quantum Mechanics.

Hence, one of the most profound insights arising from the Theory of Entropicity (ToE) is the realization that mass may not be a static or fundamental property of matter, but rather an emergent consequence of the entropy embedded within a quantum system's wave structure. This revelation presents a powerful unification between de Broglie's hypothesis of wave-particle duality and the entropic mass framework proposed in ToE. We embark on this delightful demonstration in the pages that follow.

7.7.1 de Broglie's Wave-Particle Duality

In 1924, Louis de Broglie[23] proposed that particles exhibit wave-like behavior, introducing the idea that any particle with mass m has an associated wavelength:

$$\lambda = \frac{h}{p} = \frac{h}{mv} \tag{158}$$

This relation suggests that mass and motion together generate a wavelength, but the physical origin of mass itself has remained unresolved [in Quantum Mechanics].

In de Broglie's time, the wave and the particle were treated as dual aspects of the same object, but with no physical link. Henceforth, ToE changes this perception forever by providing the

natural physical link by way of the versatile entropic potential $\Lambda(x,t)$; that is:
The particle's mass is the cumulative result of the entropy encoded in its wave-like distribution.

7.7.2 Entropic Mass via the Quantum Wave Function

ToE introduces the Entropic Mass Integral (EMI) formulation [refer to Eq. 141]as:

$$m_\Lambda = k_B \int_\Omega \ln |\psi(x,t)|^2 \, d^3x + C \cdot V \tag{159}$$

Here, $\psi(x,t)$ is the quantum wave function, and $|\psi(x,t)|^2$ is the probability density of finding the particle at point x and time t. We have earlier defined the entropy field $\Lambda(x,t)$ in the following fashion:

$$\Lambda(x,t) = k_B \ln |\psi(x,t)|^2 \tag{160}$$

This formulation implies that the mass m_Λ is not intrinsic, but rather the result of the total entropy associated with the system's spatial wave structure.

7.7.3 Physical Interpretation

This insight leads to the following physical consequences:

- If the wave spreads out (i.e., more delocalization), entropy increases, and thus m_Λ may increase.
- If the wave collapses (i.e., localization), entropy decreases, reducing m_Λ.
- Entanglement or decoherence alters the entropy field, dynamically influencing the perceived mass[refer to Sec. 7.7.3.1].

This aligns well with known phenomena:

- Cooling or coherent isolation may reduce mass.
- Heating or decoherence may increase mass, as we shall explain below in Sec. 7.7.3.1

7.7.3.1 Mass-Shift Due to Entanglement and Entropy Field Dynamics When two particles become entangled, their combined quantum state exhibits nonlocal correlations. A potential implication is:

$$\Delta S_{\text{field}} = S_{\text{entangled}} - S_{\text{individual}}, \tag{161}$$

where:

- $S_{\text{entangled}}$ represents the entropy of the entangled state,
- $S_{\text{individual}}$ represents the entropy of the individual particles prior to entanglement.

The change in the entropy field (ΔS_{field}) could, in principle, influence the energy and mass distribution of the system. According to thermodynamic principles and quantum mechanics, this may lead to a possible **mass shift:**

$$\Delta m \propto \Delta S_{\text{field}}, \tag{162}$$

where Δm represents the shift in mass and the proportionality accounts for the system's energy-mass relationship as described by $E = mc^2$.

7.7.3.2 Discussion: Entanglement Alters the Entropy Field This framework of ToE suggests that the entanglement process alters the entropy field, which could hypothetically lead to observable changes in mass or energy distribution. Experimental validation and theoretical development are required to assess the feasibility of this phenomenon.

7.7.4 Conceptual Pipeline: the Wave-Particle Duality Pipeline[WPDP]

The complete conceptual connection between the wave and emergent mass can be summarized as:

$$\boxed{\text{Wave} \Rightarrow \psi(x,t) \Rightarrow |\psi(x,t)|^2 \Rightarrow \ln |\psi(x,t)|^2 \Rightarrow \Lambda(x,t) \Rightarrow m_\Lambda} \tag{163}$$

That is:

1. The **wave** is real → it carries **entropy,** and:
2. The **entropy** is integrated → it yields **mass**

[This could align with theories that treat the quantum wave as a physical field (e.g., Bohmian mechanics or pilot wave theory). So, ToE is once again logically pointing us in another vibrant terrain of theortical physics]

Conversely, we write:

1. The **entropy** is a field $\rightarrow$ it propagates as a **wave,** and:
2. The **mass** is differentiated $\rightarrow$ it manifests as **entropy**

We see from the above that entropy is actually the common link, as is of course expected from the axioms of ToE.

The entropic decomposition or unfolding of mass back into wave can be expressed as follows:

$$\boxed{m \Rightarrow \Lambda \Rightarrow \Lambda(x,t) \Rightarrow \ln |\psi(x,t)|^2 \Rightarrow |\psi(x,t)|^2 \Rightarrow \psi(x,t) \Rightarrow \text{Wave.}} \tag{164}$$

This equation explicitly describes the progressive transformation:

- Mass m transitions to Λ, representing entropy or a related field.
- $\Lambda(x,t)$ introduces spatial and temporal dependence.
- The logarithmic term $\ln |\psi(x,t)|^2$ connects entropy to the probability density $|\psi(x,t)|^2$.
- Finally, the wavefunction $\psi(x,t)$ emerges from the probability density and leads to the emergence of wave-like behavior.

This formulation represents the reverse of wave collapse into mass and highlights the interplay between mass, entropy, and wave.

The two relations above [Eq. 163 and Eq. 164] represent a profound completion of the de Broglie's wave-particle duality cycle:

$$\boxed{\text{Wave} \leftrightarrow \text{Particle}, \quad \text{unified by Entropy.}} \tag{165}$$

Interpretation

The cycle encapsulates the transformation of mass into entropy, entropy into probability, and finally the re-creation of coherent wave-like behavior. It suggests that entropy serves as the connecting principle, bridging the quantum wave and particle duality.

7.7.4.1 From Mass to Quantum Wave: The Entropic Decomposition of Matter The Theory of Entropicity (ToE) not only proposes that mass emerges from the entropy field, but also allows us to conceptually reverse-engineer mass as the end-product of a deeply ordered quantum wave structure. This entropic decomposition pathway shows how what we traditionally consider as "mass" is simply a compressed form of information encoded in wave dynamics. The progression can be traced step-by-step:

1. **Mass** $\Rightarrow$ interpreted as a macroscopic entropic condensation of microscopic wave information.
2. $\Rightarrow \Lambda(x,t)$: The **entropic potential** field is then defined locally from the mass configuration:
$$\Lambda(x,t) \propto m(x,t) \tag{166}$$
3. $\Rightarrow \ln |\psi(x,t)|^2$: The entropy field is logarithmically related to the **probability density** of the quantum system:
$$\Lambda(x,t) = k_B \ln |\psi(x,t)|^2 + C \tag{167}$$
4. $\Rightarrow |\psi(x,t)|^2$: Inverting the logarithm yields the **probability density function**, foundational to quantum mechanics:
$$|\psi(x,t)|^2 \propto e^{\Lambda(x,t)/k_B} \tag{168}$$
5. $\Rightarrow \psi(x,t)$: The square root yields the **quantum wave function**, the complex amplitude encoding both phase and magnitude.
6. $\Rightarrow$ **Wave**: The wave function evolves unitarily via the Schrödinger equation, and all physical properties including interference, superposition, and coherence emerge from it.

This entropic decomposition effectively recovers the spirit of de Broglie's wave-particle duality in reverse:

> *Mass is not a fundamental input of nature but an emergent entropic residue of a deeper, ordered, quantum wave dynamic.*

Hence, within ToE, mass is no longer a primitive. Instead, it arises naturally from the local entropy structure generated by wave functions in spacetime. This insight offers a profound unification between quantum mechanics and thermodynamics, and may serve as a foundational bridge to future quantum gravity theories.

7.7.5 Unification of ToE with de Broglie

Therefore, the entropy field $\Lambda(x, t)$, derived from the quantum wave function, gives physical meaning to de Broglie's wave. ToE therefore presents us with the following breakthrough idea:

The particle's mass is the integral result of the entropy encoded in its wave-like distribution.

This conclusion which we have reached is logically inevitable! Thus, ToE provides the missing physical underpinning for de Broglie's hypothesis: the wave is not just a mathematical abstraction, but a thermodynamic entity whose entropy determines mass.

7.7.6 Summary and Breakthrough Implication

This formulation is the first to:

1. Express mass as an integral over a spatially distributed entropy field.
2. Tie mass generation to wave function collapse and coherence.
3. Provide a thermodynamic mechanism behind de Broglie's wave-particle duality.

This unification of quantum wave theory and entropy presents a major conceptual advancement and supports the broader claim of ToE — that entropy underlies all fundamental forces and properties, including mass itself.

7.8 Building the Total Mass Expression Over Spatial and Spacetime Volumes

7.8.1 Mass Over a Spatial Volume

To determine the total mass M_A of a system A over a spatial region V, we integrate the local mass density:

$$M_A = \int_V m(x, t)\, d^3x, \tag{169}$$

where $m(x, t)$ is the local mass density.
From the Theory of Entropicity (ToE) formulation, the local mass density is given by:

$$m(x, t) = \frac{T(x, t)}{c^2} \cdot \Lambda(x, t), \tag{170}$$

where:

- $T(x, t)$ is the local temperature,
- c is the speed of light,
- $\Lambda(x, t)$ is the entropic potential field.

Substituting Eq. (170) into Eq. (169):

$$M_A = \frac{1}{c^2} \int_V T(x, t) \cdot \Lambda(x, t)\, d^3x. \tag{171}$$

If the entropic potential field is expressed in terms of the wave function, as proposed in ToE:

$$\Lambda(x, t) = k_B \ln |\psi(x, t)|^2 + C, \tag{172}$$

then substituting Eq. (172) into Eq. (171) yields:

$$M_A = \frac{k_B}{c^2} \int_V T(x, t) \cdot \ln |\psi(x, t)|^2\, d^3x + \frac{C}{c^2} \int_V T(x, t)\, d^3x. \tag{173}$$

7.8.2 Mass Over a Spacetime Volume

If the system evolves over time, the mass accumulation or influence over a spacetime volume M is expressed as:

$$M_A = \int_M \frac{T(x, t)}{c^2} \cdot \Lambda(x, t)\, d^3x\, dt. \tag{174}$$

This formulation extends the spatial integral to include a time-dependent evolution, capturing how mass dynamically emerges from the entropy-temperature structure across space and time.

7.9 Reinterpreting Mass, Gravity, and Spacetime Curvature in the Theory of Entropicity (ToE)

The Theory of Entropicity (ToE) provides a groundbreaking reinterpretation of mass, gravity, and spacetime curvature. Below, we formalize these insights mathematically and conceptually.

7.9.1 Mass as Emergent, Not Fundamental

ToE proposes that mass is not a fundamental property but arises from the local entropic potential field:

$$m_\Lambda(x,t) \propto \Lambda(x,t), \tag{175}$$

where:

- $m_\Lambda(x,t)$ is the entropic mass at a given point in spacetime,
- $\Lambda(x,t)$ is the entropic potential field.

This implies that mass is merely a measure of "irreversibility" or entropy concentration present at a given point.

7.9.2 Gravity as Entropic Tension

ToE interprets gravity as an emergent phenomenon caused by entropy gradients. Systems naturally evolve toward configurations that maximize total entropy, generating apparent motion, force, and attraction:

- Entropy variations across space create tension, pulling systems toward higher entropy configurations.
- Gravity emerges as a byproduct of this thermodynamic process.

7.9.3 Spacetime Curvature Reflects the Entropy Field Structure

What Einstein described as spacetime curvature is reinterpreted as the geometric effect of local entropic gradients:

- Entropic gradients curve spacetime on a large scale.
- Mass is the visible residue of entropy concentration in spacetime.

7.9.4 Connection to Einstein Field Equations

ToE asserts that even the Einstein field equations can be derived from entropy principles. Following Jacobson's (1995) interpretation, these equations can be viewed as an equation of state for the entropy field:

- The entropic field governs spacetime curvature.
- Thermodynamic principles underlie the Einstein equations.

Thus ToE gives an overarching support to the work of Jacobson (1995) in a generalized form, providing us with the real foundations for such a possibility.

7.9.5 Equations and Generalizations

Let us refresh our mind one more time with the insights from ToE that have informed the above conslusions. From ToE, mass and entropy are dynamically connected:

$$m_\Lambda(x,t) = \frac{T(x,t)}{c^2} \cdot \Lambda(x,t), \tag{176}$$

where:

- $T(x,t)$ is the local temperature,
- c is the speed of light,
- $\Lambda(x,t)$ is the entropic potential field.

The total mass over a spatial volume V is given by:

$$M_\Lambda = \int_V \frac{T(x,t)}{c^2} \cdot \Lambda(x,t)\, d^3x, \tag{177}$$

Substituting the entropic potential field derived from the wave function:

$$\Lambda(x,t) = k_B \ln |\psi(x,t)|^2 + C, \tag{178}$$

we obtain:

$$M_\Lambda = \frac{k_B}{c^2} \int_V T(x,t) \cdot \ln |\psi(x,t)|^2\, d^3x + \frac{C}{c^2} \int_V T(x,t)\, d^3x. \tag{179}$$

If we extend this to a spacetime volume M, the dynamic mass expression becomes:

$$M_\Lambda = \int_M \frac{T(x,t)}{c^2} \cdot \Lambda(x,t)\, d^3x\, dt, \tag{180}$$

7.9.6 Summary of ToE Insights

ToE suggests the following:

- **Mass Emergence**: Mass arises from entropy concentration.
- **Gravity as Entropy**: Gravity is interpreted as entropic tension caused by entropy gradients.
- **Spacetime Curvature**: Spacetime curvature reflects the structure of entropy fields.
- **Einstein Equations**: The Einstein field equations can be derived as entropic equations of state.

This unifies thermodynamics, quantum mechanics, and general relativity, presenting entropy as the driving force behind mass, gravity, and spacetime structure.

8 Relating Shannon and von Neumann Entropy to the Entropic Wave Function of ToE

8.1 Shannon Entropy and the Entropic Wave Integral

As we have mentioned previously, Shannon entropy[79] stands as one of the most foundational concepts in modern information theory. Introduced by Claude E. Shannon in 1948, it quantifies the average amount of uncertainty, or information content, associated with a random variable. Though originally developed for communication theory, Shannon entropy now underpins diverse fields—including statistical mechanics, quantum theory, thermodynamics, and the Theory of Entropicity (ToE).

8.1.1 Discrete Shannon Entropy and Its Extensions

8.1.1.1 Discrete Shannon Entropy For a discrete random variable X with a probability distribution $P = \{p_1, p_2, \ldots, p_n\}$, Shannon entropy is defined as:

$$H(X) = -\sum_{i=1}^{n} p_i \log_b p_i, \tag{181}$$

where:

- $H(X)$ is the entropy of the random variable X,
- p_i is the probability of the ith outcome, and
- b is the logarithm base (typically $b = 2$ for bits or $b = e$ for natural logarithms).

This measures the expected amount of information required to describe the outcome of X. Higher entropy implies greater uncertainty or disorder.

8.1.1.2 Properties of Shannon Entropy Shannon entropy has the following key properties:

1. **Non-negativity:**
$$H(X) \geq 0, \tag{182}$$
ensuring that entropy cannot be negative.
2. **Maximum Entropy:** The entropy achieves its maximum value when all outcomes are equally likely, i.e.,
$$p_i = \frac{1}{n} \quad \text{for all } i. \tag{183}$$
3. **Additivity:** For independent systems A and B:
$$H(A, B) = H(A) + H(B). \tag{184}$$
4. **Subadditivity:** For possibly dependent systems:
$$H(A, B) \leq H(A) + H(B). \tag{185}$$

These properties align with thermodynamic intuitions about order, randomness, and the irreversibility of information.

8.1.1.3 Differential Entropy for Continuous Distributions For continuous probability distributions, Shannon entropy generalizes into differential entropy. If X is a continuous random variable with a probability density function $p(x)$, the differential entropy is defined as:

$$h(X) = -\int p(x) \log p(x)\, dx. \tag{186}$$

This formulation captures the entropy of systems described by smooth probability distributions, such as wave functions in quantum theory.

8.1.1.4 Note on Conditions for Differential Entropy: Unlike the discrete case, differential entropy is:

- **Not invariant under coordinate transformations.**
- **Can be negative**, but remains conceptually important as a bridge to quantum entropy.

8.1.1.5 Connection to Wave Functions In quantum mechanics, the probability density of a particle's position is given by:

$$p(x,t) = |\psi(x,t)|^2, \tag{187}$$

where $\psi(x,t)$ is the wave function. Substituting this into the differential entropy definition (Eq. (186)), we obtain:

$$S_{\text{Shannon}}(t) = -\int |\psi(x,t)|^2 \ln |\psi(x,t)|^2\, dx. \tag{188}$$

This is sometimes referred to as the Shannon entropy of the quantum probability density, and it serves as a precursor to the entropic field potential $\Lambda(x,t)$ in the Theory of Entropicity.

8.1.2 Connection to the Entropic Potential Field

The entropic potential field, as proposed in the Theory of Entropicity (ToE), is given by:

$$\Lambda(x,t) = k_B \ln |\psi(x,t)|^2 + C, \tag{189}$$

where:

- k_B is Boltzmann's constant,
- $|\psi(x,t)|^2$ is the quantum probability density, and
- C is a constant offset.

Hence, while Shannon entropy is statistical and global, the ToE generalizes this into a local field. This construction is not a mere reinterpretation of Shannon entropy—it introduces a spatially distributed potential, acting as a real, dynamic field that drives curvature, collapse, and evolution in spacetime.

Thus, Shannon entropy offers the conceptual and mathematical scaffolding upon which ToE builds a deeper theory: where quantum probability densities give rise to physical entropy fields, and where wave-function structure dictates entropic dynamics across space and time.

8.1.3 The Entropic Mass Integral

As we demonstrated earlier, by integrating the entropic potential over space, the entropic mass becomes:

$$M_\Lambda = \int \Lambda(x,t)\, dx = k_B \int \ln |\psi(x,t)|^2\, dx + C', \tag{190}$$

where C' is a new constant resulting from the spatial integration.

8.1.4 Weighted Entropic Mass and Shannon Entropy

If the integrand in Eq. (190) is multiplied by the probability density $|\psi(x,t)|^2$, the result is:

$$M'_\Lambda = \int |\psi(x,t)|^2 \cdot \Lambda(x,t)\, dx = k_B \int |\psi(x,t)|^2 \ln |\psi(x,t)|^2\, dx + C'', \tag{191}$$

where C'' is another constant. Comparing this to Eq. (188), we see:

$$M'_\Lambda = -k_B S_{\text{Shannon}} + C'', \tag{192}$$

showing that the entropic mass is directly proportional to the negentropy (negative entropy) of the wave function in Shannon entropy.

8.1.5 Closing Reflections

The connection between the Shannon entropy and the entropic mass integral reveals:

- **Mass and Negentropy:** In the ToE framework, mass is proportional to the degree of order (negentropy) encoded in the wave function.
- **Localization Effects:** Greater localization of $|\psi(x,t)|^2$ leads to lower entropy, resulting in less entropic mass.
- **Mass Generation Mechanism:** This is a novel mechanism for mass generation, based not on rest energy or symmetry breaking, but on the entropic structure of the quantum wave function.

8.2 Von Neumann Entropy and Its Relation to the Entropic Wave Function

Here, we explore the von Neumann entropy[89], followed by a step-by-step analysis of its connection to the entropic wave function, Shannon entropy, and the entropic mass integral in the Theory of Entropicity (ToE).

8.2.1 What is von Neumann Entropy?

Von Neumann entropy is the quantum mechanical analogue of Shannon entropy. Introduced by John von Neumann in 1927, it measures the uncertainty or information content of a quantum state represented by a density matrix ρ. It plays a foundational role in quantum information theory and quantum statistical mechanics.

The entropy of a quantum state described by ρ is defined as:

$$S_{\text{vN}}(\rho) = -\text{Tr}(\rho \ln \rho), \tag{193}$$

where:

- Tr is the trace operation,
- ρ is the density matrix of the quantum system,
- $\ln \rho$ is the matrix logarithm of ρ.

This formulation generalizes Shannon entropy to the domain of quantum states, where probability distributions are replaced by quantum amplitudes and superpositions.

8.2.2 Physical Meaning of von Neumann Entropy

Von Neumann entropy has the following properties:

1. **Pure states:** Pure quantum states satisfy $\rho^2 = \rho$, and their entropy is zero:
$$S_{\text{vN}} = 0. \tag{194}$$
2. **Mixed states:** Mixed states have $S_{\text{vN}} > 0$.
3. **Entropy measures:** It quantifies the degree of entanglement or coherence loss with an environment.
4. **Applications:** Von Neumann entropy is central to thermodynamic entropy, quantum thermodynamics, and decoherence theory.

In essence, von Neumann entropy tracks how quantum information is distributed or lost, particularly during interactions, measurements, and entanglement.

8.2.3 Pure and Mixed States in von Neumann Entropy

Let us walk through the concepts of pure and mixed states in the context of von Neumann entropy, both qualitatively and mathematically.

8.2.3.1 The Density Matrix Formalism In quantum mechanics, the density matrix ρ is a powerful tool for describing the state of a quantum system. It generalizes the wave function $|\psi\rangle$ to account for statistical mixtures of quantum states:

- A **pure state** occurs when the system is in a single, definite quantum state $|\psi\rangle$.
- A **mixed state** describes the system as a probabilistic combination of several states, reflecting classical uncertainty.

https://doi.org/10.33774/coe-2025-vrfrx **ORCID:** https://orcid.org/0009-0004-3606-3182 Content not peer-reviewed by Cambridge University Press.

8.2.3.2 Pure States A pure state is represented by the density matrix:

$$\rho = |\psi\rangle\langle\psi|. \tag{195}$$

This density matrix satisfies:

$$\rho^2 = \rho, \quad \text{(idempotent)} \tag{196}$$

and:

$$\mathrm{Tr}(\rho) = 1. \tag{197}$$

The von Neumann entropy for a pure state is:

$$S_{\mathrm{vN}} = -\mathrm{Tr}(\rho \ln \rho) = 0. \tag{198}$$

Interpretation: A pure state corresponds to a perfectly known quantum state with no classical uncertainty. There is zero entropy, and the state maintains full quantum coherence.

8.2.3.3 Mixed States A mixed state is described as a classical probability distribution over quantum states:

$$\rho = \sum_i p_i |\psi_i\rangle\langle\psi_i|, \quad \sum_i p_i = 1, \tag{199}$$

where p_i are the probabilities associated with each state $|\psi_i\rangle$.

For mixed states:

$$\rho^2 \neq \rho, \tag{200}$$

and:

$$\mathrm{Tr}(\rho^2) < 1. \tag{201}$$

The von Neumann entropy for a mixed state is:

$$S_{\mathrm{vN}} = -\sum_i p_i \ln p_i > 0. \tag{202}$$

Interpretation: A mixed state reflects classical uncertainty about which state the system is in. The entropy arises from the lack of complete knowledge, representing the statistical uncertainty inherent in the mixed state.

8.2.3.4 Physical Intuition and Role in Collapse The role of pure and mixed states in quantum collapse can be summarized as follows:

- **Before collapse:** The system is often treated as a pure state.
- **After decoherence or measurement:** The system transitions to a mixed state, where only statistical information remains about the possible outcomes.

8.2.3.5 von Neumann Entropy and Wave Collapse In the Theory of Entropicity (ToE) In the ToE framework:

- Collapse occurs when entropy exceeds a certain threshold.
- The transition from a pure state to a mixed state is governed by entropy production in the environment.
- The wave function $|\psi\rangle$ becomes a density matrix ρ through entanglement and decoherence, leading to an increase in von Neumann entropy.

Property	**Pure State**	**Mixed State**
Form	$\lvert\psi\rangle\langle\psi\rvert$	$\rho = \sum_i p_i \lvert\psi_i\rangle\langle\psi_i\rvert$
Squared Matrix	$\rho^2 = \rho$	$\rho^2 \neq \rho$
Entropy	$S_{\mathrm{vN}} = 0$	$S_{\mathrm{vN}} > 0$
Interpretation	Complete knowledge	Statistical uncertainty
Collapse Role	Pre-collapse coherence	Post-collapse classicality

Table 21: **Comparison of Pure and Mixed States in von Neumann Entropy**

8.2.4 Step-by-Step Connection of von Neumann to the Entropic Wave Function

8.2.4.1 The Density Matrix for Pure States A pure quantum state $|\psi\rangle$ has a density matrix:

$$\rho(x,t) = |\psi(x,t)\rangle\langle\psi(x,t)|. \tag{203}$$

Representing the wave function in the position basis, the density matrix becomes:

$$\rho(x,x',t) = \psi(x,t)\psi^*(x',t), \tag{204}$$

where the diagonal elements give the probability density:

$$\rho(x,t) = |\psi(x,t)|^2 = p(x,t). \tag{205}$$

8.2.4.2 Shannon Entropy from the Diagonal of ρ of von Neumann Entropy Thus, by using only the diagonal elements of ρ of the von Neumann entropy, the Shannon entropy of the quantum state can be defined as:

$$S_{\text{Shannon}}(t) = -\int |\psi(x,t)|^2 \ln |\psi(x,t)|^2 \, dx. \tag{206}$$

This expression approximates von Neumann entropy when off-diagonal coherence is ignored (e.g., decoherence or position-basis measurement).

8.2.4.3 Entropic Potential in ToE from Probability Density The Theory of Entropicity (ToE) elevates this Shannon-like entropy into a local entropic field potential:

$$\boxed{\Lambda(x,t) = k_B \ln |\psi(x,t)|^2 + C,} \tag{207}$$

where $\Lambda(x,t)$ is interpreted as a local entropy density field.

8.2.4.4 Entropic Mass Integral from the Entropic Field ToE proposes that the mass-energy associated with a configuration arises from the entropic potential:

$$m_\Lambda(x,t) = \frac{T(x,t)}{c^2}\Lambda(x,t), \tag{208}$$

and the total mass:

$$\boxed{M_\Lambda = \int_V \frac{T(x,t)}{c^2}\Lambda(x,t)\, dV,} \tag{209}$$

where V is the spatial volume.

This completes the entropic wave-mass pipeline, uniquely formalized in ToE.

8.2.4.5 Local Analog of von Neumann Entropy and Unifying Expression Let us recollect our familiar von Neumann entropy expression, where for mixed or entangled quantum states, the von Neumann entropy becomes the standard measure:

$$S_{\text{vN}} = -\text{Tr}(\rho \ln \rho), \tag{210}$$

where:

- ρ is the density matrix of the quantum state,
- Tr is the trace operation summing over the diagonal elements of $\rho \ln \rho$.

This can be rewritten in terms of the eigenvalues λ_i of the density matrix ρ:

$$S_{\text{vN}} = -\sum_i \lambda_i \ln \lambda_i, \tag{211}$$

If the system's state is described in terms of position-space wavefunctions, the density matrix can be related to the spatial probability distribution $|\psi(x,t)|^2$ for pure states. Recollect that for a pure state:

$$S_{\text{vN}} = 0, \tag{212}$$

whereas for mixed states, the entropy S_{vN} grows as the system evolves toward greater uncertainty.

https://doi.org/10.33774/coe-2025-vrfrx **ORCID:** https://orcid.org/0009-0004-3606-3182 Content not peer-reviewed by Cambridge University Press.

8.2.4.6 Connecting to the Theory of Entropicity (ToE)

In the framework of ToE:

- The **entropic potential** $\Lambda(x,t)$ is interpreted as the local entropy density.
- The **total entropy** is then defined as a spatial trace-like integral over the entropic field:

$$S_\Lambda = \int |\psi(x,t)|^2 \cdot \Lambda(x,t)\, dx, \tag{213}$$

  where:
  - $|\psi(x,t)|^2$ represents the spatial probability distribution.
  - $\Lambda(x,t)$ is the local entropic potential field.

Notice how this clearly resembles a local analog of the von Neumann entropy in continuous media [systems], where the integrand mimics

$$S = \lambda_i \ln \lambda_i, \tag{214}$$

but spatially resolved; such that we can now physically enforce the quantitative connections with some prefactors α and β:

$$\lambda_i = \alpha|\psi(x,t)|^2 \tag{215}$$

and

$$\ln \lambda_i = \beta\Lambda(x,t) \tag{216}$$

Now, combining the above equations Eq. (215) and Eq. (216), we find that:

$$\beta\Lambda(x,t) = \ln \lambda_i = \ln\left(\alpha|\psi(x,t)|^2\right) \tag{217}$$

Or:

$$\beta\Lambda(x,t) = \alpha \ln |\psi(x,t)|^2 \tag{218}$$

Rearranging the constants:

$$\Lambda(x,t) = \frac{\alpha}{\beta} \ln |\psi(x,t)|^2 \tag{219}$$

Setting the constants equal to the Boltzmann constant k_B:

$$\frac{\alpha}{\beta} = k_B \tag{220}$$

Hence Eq. (219) becomes:

$$\boxed{\Lambda(x,t) = k_B \ln |\psi(x,t)|^2} \tag{221}$$

This concludes our entropic demonstration. We see that the above Eq. (221)is the same expression in Eq. (92) [within the limits of a constant] which we stated earlier by our logical deduction from the subtle relationship between the Boltzmann equation and the quantum wave function[also refer to the relevant sections and footnotes for various clarifications on the subject].

This expository derivation and analysis further shows that there is logic, simplicity and consistency in our definition of the entropic function in terms of the wave function.

Thus, from logical arguments involving the Shannon and von Neumann entropy formulations for information and probability as entropy, we have re-derived the ToE's entropic potential for the quantum wave function; and this is not surprising, particularly when we juxtapose that against the ToE proposition that information, probability and the quantum wave function considerations are intrinsically inseparable from thermodynamic principles.

8.2.4.7 Unifying Expression for Shannon and von Neumann Entropy

Using the Theory of Entropicity (ToE), we can formally relate mass and entropy through the following expressions:

$$M_\Lambda = -k_B S_{\text{Shannon}} \quad \text{(for pure states)}, \tag{222}$$

or more generally:

$$M_\Lambda = -k_B S_\Lambda, \tag{223}$$

where:

- S_{Shannon} is the Shannon entropy for pure states.
- S_Λ is a more general entropy functional derived from the entropic wave function, which behaves like a von Neumann–Shannon hybrid entropy functional.

Comparison and Synthesis: Shannon, von Neumann, and ToE

Quantity	**Shannon Entropy**	**von Neumann Entropy**	**ToE Entropic Field**
Definition	$-\sum p_i \ln p_i$	$-\mathrm{Tr}(\rho \ln \rho)$	$\Lambda(x,t) = k_B \ln \lvert\psi(x,t)\rvert^2 + C$
Input	Classical probability p_i	Density matrix ρ	Quantum probability density $\lvert\psi\rvert^2$
Type	Global scalar	Global scalar (includes coherence)	Local scalar field
Role	Information uncertainty	Quantum uncertainty and entanglement	Collapse trigger, mass generator
Connection	$p(x) = \rho(x,x)$	$\rho = \lvert\psi\rangle\langle\psi\rvert$	Derived via $\Lambda(x,t)$ potential

Table 22: **Comparison of Shannon Entropy, von Neumann Entropy, and ToE Entropic Field**

8.2.4.8 Entropic Wave Integral as a Bridge Between Shannon and von Neumann

ToE unifies Shannon and von Neumann entropy using the entropic wave integral:

$$\boxed{S_\Lambda(t) = \int_V k_B \lvert\psi(x,t)\rvert^2 \ln \lvert\psi(x,t)\rvert^2 \, dV.} \tag{224}$$

The reader will already have noticed that the above equation [the Entropic Wave Integral - EWI] is different from the Shannon and von Neumann entropy by a factor given by the Boltzmann constant. This is a generalized formulation from our effects in ToE; and we shall elaborate on our thoughts leading to it in the subsequent section - Sec. (8.3)

This formulation:

- Matches Shannon entropy for continuous distributions,
- Is derived from the diagonal of von Neumann's $\rho(x,x,t)$,
- Defines the entropy content per point and per volume,
- Governs the dynamics of collapse and energy-mass generation.

8.3 Information-T vs. Physical E: Why ToE Uses the Boltzmann Constant

Here, we consider the information-theoretic versus the physical-entropic basis of the Theory of Entropicity[ToE]. Entropy, as used in information theory and quantum mechanics, often appears in dimensionless form. However, in the Theory of Entropicity (ToE), entropy plays a dynamic, physical role - necessitating the use of the Boltzmann constant k_B to properly reflect its thermodynamic character.This subsection clarifies the rationale behind including k_B in ToE's **Entropic Wave Integral (EWI)** [Eq.(224)] and how it aligns with and extends Shannon and von Neumann entropy.

8.3.1 Shannon and von Neumann Entropy Without k_B

Shannon entropy is defined as:

$$S_{\text{Shannon}} = -\sum_i p_i \log_2 p_i \tag{225}$$

This entropy is unitless and typically expressed in *bits* (base 2) or *nats* (base e).
The von Neumann entropy is the quantum analog:

$$S_{\text{vN}} = -\mathrm{Tr}(\rho \ln \rho) \tag{226}$$

Also unitless, this measures the uncertainty associated with a quantum state described by a density matrix ρ.

8.3.2 Conversion to Physical Entropy: Inclusion of k_B

In thermodynamics, however, entropy has physical dimensions (Joules per Kelvin), such as we find as follows:

$$S = k_B \ln \Omega, \tag{227}$$

where:

- S is the entropy (in J/K),
- k_B is Boltzmann's constant (1.38×10^{-23} J/K),
- Ω is the number of accessible microstates of the system.

Also analogous to the classical thermodynamic relationship, we find that:

$$E = k_B T \ln \Omega, \tag{228}$$

where:

- E represents energy,
- k_B is Boltzmann's constant,
- T is the temperature, and
- Ω is the number of microstates associated with entropy,

Note that in this case, in order to give dimension to the dimensionless miicrostate Ω, it has been prefactored with dimensioned quantities T and k_B to yield the physical quantity of energy E.
The Theory of Entropicity (ToE) extends this logic to the entropic potential field $\Lambda(x,t)$ as we have demonstrated in earlier sections of this work.
Hence, equivalently, based on what insights we have seen so far from ToE, we can now logically formulate the generalized relation between physical entropy(such as we find in the thermodynamics of Boltzmann) and non-physical entropy (that is, information or probability entropy, as in Shannon and von Neumann):

$$S_{\text{phys}} = k_B \cdot S_{\text{info}} \tag{229}$$

Therefore, the physical version of von Neumann entropy becomes:

$$S_{\text{phys-vN}} = -k_B \text{Tr}(\rho \ln \rho) \tag{230}$$

And for discrete probability distributions, the Shannon entropy must yield to its physical equivalent:

$$S_{\text{phys-S}} = -k_B \sum_i p_i \ln p_i \tag{231}$$

This adjustment makes entropy suitable for linking with thermodynamic processes, such as heat and work.

8.3.3 Physical Form of the Shannon Entropy in the Generalized Entropic Wave Integral in ToE

We already know that in ToE, entropy is not merely a statistical measure but a dynamic field entity. So, from the above physical insights from Boltzmann, Shannon, and von Neumann, we can generalize the differential form of the Shannon entropy [Eq. (188)] by insertion of the physical constant prefactor k_B to arrive at:

$$\boxed{S_\Lambda(t) = \int_V k_B |\psi(x,t)|^2 \ln |\psi(x,t)|^2 \, dV} \tag{232}$$

Here, $|\psi(x,t)|^2$ represents the quantum probability density, and k_B scales the entropy to physical units. The entropic wave integral serves as a local, pointwise measure of entropy flow across space and time, a feature not present in conventional formulations. ToE is telling us clearly by this equation that information entropy is an integral part of thermodynamic entropy, and that one cannot make statements about one in absolute isolation from the other. That is to say, any complete description of physical processes must consider both aspects.**(For example, the entropy that is created during a measurement is both thermodynamic entropy and information entropy)**.
This generalized equation incorporates the Shannon and von Neumann entropy formulations, and they can readily be derived from it. That is its beauty and also what makes it powrerful.

8.3.4 Comparison Table of Entropy Formulations

8.3.5 The Role of the Boltzmann Constant in the Theory of Entropicity (ToE)

The Theory of Entropicity (ToE) fundamentally relies on introducing the Boltzmann constant k_B into formulations like the entropic wave integral. Below, we unpack its significance in steps.

Entropy Type	**Expression**	**Units**	**Purpose**
Shannon Entropy	$-\sum p_i \log p_i$	Unitless	Information content (bits/nats)
Physical Shannon Entropy	$-k_B \sum p_i \ln p_i$	J/K	Thermodynamic interpretation of Shannon entropy
von Neumann Entropy	$-\mathrm{Tr}(\rho \ln \rho)$	Unitless	Quantum information theory
Physical von Neumann Entropy	$-k_B \mathrm{Tr}(\rho \ln \rho)$	J/K	Statistical mechanics
ToE Entropic Field	$\int_V k_B \vert\psi\vert^2 \ln \vert\psi\vert^2 \, dV$	J/K	Local entropy dynamics (spacetime)

Table 23: **Comparison of Entropy Definitions**

8.3.5.1 Must We Connect Entropy to Physical Quantities? Not necessarily - unless the goal is to transition from purely informational or probabilistic frameworks to physical theories that connect with measurable, observable quantities like mass, energy, or temperature.

- Shannon entropy and von Neumann entropy are dimensionless measures. They quantify uncertainty or information content and are valuable in communication theory or abstract quantum information contexts.
- However, they do not tell us how much energy is dissipated in erasing that information, or how much mass might be influenced when entropy changes.

Thus, the inclusion of k_B in ToE becomes essential when translating information-based entropy into physical effects - empowering ToE in turning abstract bits into physical units such as joules, kilograms, or kelvins.

8.3.5.2 What Happens When We Connect Entropy to Physics? Introducing the Boltzmann constant k_B bridges information entropy with physical phenomena. Entropy is no longer just a measure of uncertainty; it acquires physical meaning tied to energy, mass, and spacetime. By that, the key connections discovered from ToE therefore include:

- **Heat Dissipation:** Using Landauer's Principle:

$$\Delta Q = k_B T \ln 2, \tag{233}$$

  where:
  - ΔQ is the heat dissipated,
  - T is the temperature,
  - $\ln 2$ corresponds to the erasure of one bit of information.
- **Mass Generation:** As we have earlier already shown in the entropic mass integral of ToE:

$$\boxed{M_\Lambda = \int_V \frac{T(x,t)}{c^2} \cdot \Lambda(x,t) \, d^3x.} \tag{234}$$

- **Spacetime Curvature:** As suggested by Jacobson's (1995) thermodynamic derivation of Einstein's field equations.
- **Gravitational Attraction:** As seen in Verlinde's entropic gravity, where gravity emerges as a result of entropy gradients.

By introducing k_B in ToE, entropy transitions from abstract uncertainty to thermodynamic reality, enabling it to affect **[and hence connect otherwise disparate]** physical phenomena.

8.3.5.3 Why ToE Insists on This Connection The Theory of Entropicity is not merely a quantum information theory; it extends [and profoundly elevates] entropy into a real, physical field. To achieve this, ToE [must, or] has had to:

1. **Translate Entropy into Physical Effects:** Enable entropy to drive physical outcomes like mass generation, force interactions, collapse, and spacetime curvature.
2. **Unify Information and Matter:** Demonstrate that mass is fundamentally an entropic structure.
3. **Incorporate the Entropic Field into Dynamics:** Construct a variational action where the entropic field directly impacts trajectories and spacetime geometry.

The Boltzmann constant k_B serves as the link between abstract entropy and the physical world, ensuring entropy appears explicitly in the equations of motion - alongside constants like G (gravitational constant), c (speed of light), and $\hbar$ (reduced Planck constant).

8.3.5.4 Implications for Physics

If ToE's perspective is correct, the following paradigm shifts arise:

- **Mass is Not Fundamental:** Mass emerges as a byproduct of entropic structure.
- **Collapse is a Thermodynamic Phenomenon:** Quantum wave function collapse represents a thermodynamic phase transition.
- **Gravity is Entropic:** At its root, gravity is not geometric [nor is it (intrinsically) made up of Strings or Higher Dimensions or Loops or Knots or Spin Networks or Spin-Foam Networks] but thermodynamic, driven by entropy gradients and constraints.
- **Quantum Probabilities are Derived:** Quantum probabilities emerge from entropy principles, rather than being postulated. For example, we realize at once that the powerful Born principle emerges naturally via our Entropic Principle rather than as a standalone quantum postulate.

This marks a transition from a geometry-centric [geometro-centric] universe to one fundamentally governed by entropy - a paradigm shift where the inclusion of k_B is not optional but a central step in transforming ToE from an interpretation into a unified field theory.

- **A New Copernican Shift: From Geometry to Entropicity**

  Just as the Copernican Revolution shifted humanity's conception of the universe from an Earth-centric [geocentric] and anthropocentric model to a heliocentric one - displacing mankind from the center of the cosmos - the Theory of Entropicity (ToE) seeks to initiate a similar transformation. ToE challenges the current geometro-centric paradigm, in which space, time, and geometry are viewed as the primary scaffolding of reality. In its place, ToE proposes an entropicistic worldview, where entropy, not geometry, governs the dynamics of matter, motion, information, and collapse. This is not merely a scientific proposal - it is a philosophical repositioning of humanity's understanding of nature. Geometry, in this new framework, is not the foundation of the universe but a secondary emergent structure, shaped and sculpted by the invisible hand of entropy.

Refer to this footnote for the Copernican Legacy.[31]

8.4 Summary on Shannon and von Neumann Entropy

Shannon and von Neumann entropy provide conceptual frameworks for information uncertainty, but ToE extends them into the realm of physical interaction and collapse dynamics. By including k_B, ToE ensures that entropy

[31]**The Copernican Revolution: Shifting Humanity's Conception of the Universe**
The Copernican Revolution shifted humanity's conception of the universe from an Earth-centric and anthropocentric model to a heliocentric one - displacing mankind from the center of the cosmos - it marked a pivotal transformation in scientific thought and philosophy.

1. **Historical Context** The revolution was initiated by Nicolaus Copernicus in the 16th century, when he proposed the heliocentric model of the solar system. According to this model:
   - The Sun, rather than Earth, occupies the center of the solar system.
   - Earth is one of several planets revolving around the Sun.

   This challenged the prevailing geocentric model, supported by ancient thinkers like Ptolemy, which placed Earth - and humanity - at the center of the universe.
2. **Scientific Impact** The heliocentric model catalyzed advances in astronomy, physics, and the scientific method. It influenced notable thinkers such as:
   - Galileo Galilei, who provided observational evidence supporting Copernicus's model through his telescopic discoveries.
   - Johannes Kepler, who developed laws of planetary motion that mathematically described orbital mechanics.
   - Isaac Newton, who later unified celestial and terrestrial physics with his theory of gravitation.
3. **Philosophical Implications** The Copernican Revolution profoundly reshaped humanity's understanding of its place in existence:
   - The geocentric model reinforced a human-centered view of the universe, aligning with religious and philosophical beliefs at the time.
   - The heliocentric model displaced Earth from the center, challenging the anthropocentric perspective and emphasizing that humanity occupies a more modest position in the cosmos.
4. **Legacy of Copernicus Sustained** The Copernican Revolution laid the foundation for subsequent scientific revolutions, transforming not only astronomical understanding but also humanity's perception of its role in the universe. This moment in history marks one of the first steps in the broader scientific revolution, highlighting the shift from mystical and anthropocentric explanations to empirical and universal principles.

functions as a force-mediating and curvature-generating quantity in spacetime - just as mass does in General Relativity. This formalism allows for the emergence of mass, collapse thresholds, and quantum gravitational effects, all from the underlying information structure encoded in $\psi(x,t)$.

8.5 Conclusion: An Entropic Triad

1. Shannon entropy introduces probabilistic uncertainty.
2. Von Neumann entropy generalizes this to quantum states and coherence.
3. ToE reinterprets quantum uncertainty as a causal, dynamic field that:
    - Varies in space and time,
    - Drives wave function collapse,
    - Generates mass,
    - Curves spacetime.

This triad [Shannon, von Neumann, ToE] lays the foundation for a unified understanding of entropy in quantum physics.

9 Resolving Quantum Paradoxes via Entropicity

9.1 EPR Paradox Revisited: Finite Entanglement Formation and Entropic Correlation

Einstein, Podolsky, and Rosen posed their paradox as a challenge to the idea of instantaneous collapse and the completeness of quantum mechanics[36].

In modern terms, the EPR paradox is exemplified by two particles in an entangled state: measuring one immediately affects the state of the other, no matter how far apart, which seems to violate locality. Bell's theorem and experiments showed that any local-realist theory cannot reproduce all quantum correlations.

So if nature respects relativity, we are forced to conclude the "influence" isn't carrying usable information (hence not violating relativity in a communicative sense) yet the formalism implies an instantaneous update of knowledge. The Theory of Entropicity offers a new interpretation: entanglement is not a mystically instantaneous connection but an entropic correlation process. When two particles become entangled, say through a common source or interaction, their quantum states are no longer independent. However, according to ToE, forming a stable entangled state requires the establishment of an entropy-mediated channel between them. In practical terms, when two particles interact and depart as an entangled pair, there is a subtle exchange of entropy with the surrounding fields (for instance, any radiative or field disturbances carry away the "excess" information). The entangled state is stabilized only after this entropy exchange is complete.[32] The key prediction is that entanglement formation takes a finite amount of time, during which the entropy flow correlating the two particles propagates (likely at or below the speed of light, possibly via a field or vacuum fluctuation). Remarkably, ultra-fast experiments have begun to probe this idea. A recent attosecond-resolution study by Jiang et al. (2024)[49] examined how entanglement is established in the ionization of helium.

By using a clever pump-probe technique with two ultrafast laser pulses, they were able to show that when one electron is knocked out of the atom and the other is excited, the two-electron system does not become entangled immediately. Instead, they observed that the entanglement (as inferred from subtle correlations in the electron energies) builds up over a time on the order of 200–300 attoseconds[49].

Specifically, they reported an average "entanglement formation time" of about 232 attoseconds. This is an incredibly short time (about 2.3×10^{-16} seconds), but it is emphatically not zero. It suggests that what we used to treat as an instantaneous jump is in reality a dynamic process. In ToE, this entanglement formation time corresponds to the time required for the entropy-constrained interaction to correlate the two particles. We can denote Δt_{ent} as the time to establish entanglement. The theory would link this to the time it takes for the joint system to satisfy an entropic equilibrium or correlation condition. For example, if two particles fly apart, each by itself might be in a mixed state, but the joint state is pure (entangled). To maintain that purity, the environment must not yet have which-way information that distinguishes the pair's shared state. As time passes,

[32] The specific claim being made by the Theory of Entropicity(ToE) is this, that entanglement formation itself is fundamentally driven by an "entropy-mediated channel" and involves a direct, measurable exchange of thermodynamic entropy during the formation process, which Delta-S(ΔS)can be experimentally verified with precision instruments. This is a stronger claim than simply acknowledging the connection between entanglement and entropy like other researchers have done. The concept of an "entropy-mediated channel" suggests a specific mechanism for this exchange. Thus, ToE makes specific, testable predictions about the finite time required for entanglement formation and the measurable entropy flow involved.

any stray information leaking to the environment (like subtle field perturbations) is being absorbed; only when the necessary entropy is evacuated to the environment do the two particles become fully entangled and EPR correlations become live.

We can thus rephrase the EPR paradox resolution: There is no instantaneous spooky action; instead, when a measurement is performed on particle A, particle B's state is not truly determined until the entropic link (established during entanglement formation) can carry the influence of A's measurement to B. However, because Δt_{ent} is so tiny, in practice we see outcomes consistent with instant correlations. Importantly, this "influence" is not a signal that could be used by humans to communicate (it's an internal correlation through the entropy field and likely bounded by light speed). It simply means that the collapse of A's wavefunction and B's wavefunction are in fact one single joint process mediated by their common entropy history. To illustrate, suppose we have two entangled photons sent to distant labs.

In standard QM, if Alice measures her photon's polarization, Bob's photon's state collapses immediately to the correlated polarization. In ToE, if those photons became entangled, say, via a parametric down-conversion source, there was a brief moment during creation where an entropic bridging occurred. When Alice makes a measurement at time t_A, the collapse doesn't truly finalize for Bob's photon until a time $t_B = t_A + \Delta t_{\text{ent}}$ (in the appropriate frame, perhaps the rest frame of the source). During that Δt_{ent}, a subtle entropy-carrying disturbance (perhaps a vacuum mode or a gravitational effect or just the latent correlation in the field) is propagating from Alice's region to Bob's. Only when it arrives does Bob's photon "know" to collapse to the corresponding value. If Bob measures before this influence arrives, the outcome might be indeterminate or only partially correlated. However, given $\Delta t_{\text{ent}} \sim 10^{-16}$ s or smaller for photons, and their separation maybe microseconds apart (10^{-6} s), realistically Bob always measures after the correlation is established, so quantum mechanics appears to hold perfectly. This picture is subtle and requires relativistic causality to be carefully handled (to avoid any frame-dependent paradoxes).

A likely resolution is that the entropic influence travels at lightspeed or below, so that there is no preferred frame issue - in any frame, the collapse correlation is completed via a lightlike (or subluminal) connection. Thus, no information or physical effect propagates outside the light cone. Experimentally, a prediction of ToE is that if one could measure entanglement in real-time, one might observe a delay between particle interactions and full violation of Bell inequalities.

Recent advances in ultrafast measurements and perhaps techniques in quantum optics might make it possible to test this for other systems (for helium it was a theoretical simulation combined with some measurement, but perhaps in the future entangled photons or solid-state qubits could be tested for finite entanglement times). Such a finding would be revolutionary, and 232 attoseconds is an example data point that encourages this line of thinking. To formalize this in our theory, we incorporate the finite entanglement time as an output of the path integral approach. In the entangled two-particle system, as long as neither is measured, their joint evolution is given by entropic geodesics in the joint state-space. If a measurement is made on one, the path integral now includes the entropic cost of that measurement. If the measurement happens at t_A, only after a time Δt does the other particle's entropy functional reflect that a collapse happened on the partner (because the entropic field carrying that information reaches it). We could write an approximate relation like:

$$\Delta t_{\text{ent}} \sim \frac{L}{v_{\text{ent}}} \tag{235}$$

where L is the separation and v_{ent} is the speed of propagation of the entropic influence (likely $v_{\text{ent}} = c$, the speed of light, if mediated by a field). For $L = 0$ (the pair is created together), Δt_{ent} might be the internal thermalization time of the emitter (tens to hundreds of attoseconds as observed).

For L large, it would basically be the light travel time (so effectively no violation of relativity, just a hidden delay). In conclusion, the EPR paradox is resolved under ToE by recognizing entanglement as an earned correlation mediated by entropy exchange rather than a free, acausal given. This viewpoint upholds Einstein's locality in the sense of no usable signal outside light cones, and it upholds Bohr's completeness in that quantum mechanics remains valid, but it adds a layer: entanglement and collapse are events that happen in time and through physical interaction (the entropy field), not outside of time. This reconciles the EPR conundrum with the second law: you cannot have a completely correlation-for-free between two distant objects without some subtle entropy flow. Formally, we can say the entropic correlation time Δt_{ent} provides a new parameter that could be empirically determined. The value 232[attoseconds] as found is for a specific electronic process; for other systems, it might differ. **The existence of Δt_{ent} means that, conceptually, the state of a two-particle system remains entangled only in a pre-collapse sense until this time elapses, and after that one can treat them as fully correlated. This is a fresh insight that merges quantum information with dynamical entropy considerations.**[33]

[33]**Pre-Collapse Entanglement and Dynamical Entropy Considerations.**
This footnote expands on the concept of dynamic entanglement and its implications in quantum theory.

Pre-Collapse Entanglement:
The idea of a "pre-collapse" entangled state introduces a novel perspective on entanglement. We suggest that entanglement is not a binary state (entangled or not), but rather a process that unfolds over time. This dynamic view challenges the traditional interpretation of instantaneous entanglement and introduces a temporal aspect to the phenomenon.

9.2 ER=EPR and Entropic "Seesaw" Bridges: Wormholes as ToE's Seesaw Information Channels

The ER = EPR conjecture, proposed by Maldacena and Susskind in 2013[56], provocatively suggests that every pair of entangled particles (EPR pair) is connected by a tiny Einstein-Rosen bridge (ER bridge, or wormhole). In the context of black holes, this idea gained traction as a way to resolve the black hole information paradox: a pair of maximally entangled black holes might be viewed as sharing a wormhole, so the nonlocal correlations have a geometric manifestation. However, for ordinary particles, it's not literal that a tunnel in spacetime opens between them; rather, it is a conceptual equivalence that entanglement and wormholes might be two sides of the same coin in quantum gravity.

The Theory of Entropicity provides a natural interpretation of ER = EPR: *the "bridge" connecting entangled systems is an* ***entropic bridge*** - effectively a channel through the entropy field that keeps the two systems correlated [see Figure 1 below]. It's "wormhole-like" in the sense that it bypasses the usual spatial separation (information can be shared in the entangled state as if they were connected), but it's not a traversable wormhole for signals - it is better thought of as a correlated state of the spacetime medium between them. If we consider a highly entangled system, like two halves of a singlet state or two qubits in a Bell state, in our framework they share some combined entropy bookkeeping. For instance, their entanglement entropy (entropy of either subsystem) is S, and there are strong mutual correlations. In a space-time diagram, one might picture that the two particles are connected by some kind of invisible link. The ToE suggests that this link is made of entropy: specifically, the constraints that enforce energy conservation and entropy flow effectively tie the two particles' states together. One might even envision a small "wormhole" in an abstract thermodynamic phase space that links the particles - not a literal spatial wormhole, but mathematically analogous. It is intriguing to check consistency: an Einstein-Rosen bridge is a non-traversable wormhole solution of GR that typically forms connecting two black holes.

However, we note that entangled particles are not black holes; but one can imagine if they were extremely entangled, maybe with many degrees of freedom (like thermofield double states), geometry might emerge. Herman L. Verlinde (2020)[88] even discussed how the entropy of an ER bridge relates to entanglement entropy.[34] *In our approach, the S_G terms in the Vuli-Ndlela path integral for entangled black holes would account for the area-entropy of the wormhole, and S_{irr} would account for any non-equilibrium aspects. For normal quantum systems, the entropic bridge might be visualized as follows: if one were to "trace out" the entropy field connecting them, you would find that the two systems are not independent -* ***they are like two ends of a single object [conceptually indistinguishable and similar to the two ends of a constrained rigid pole, somewhat like children's seesaw on a playground]****.* This is analogous to how a wormhole[35] connects two distant mouths: **separate on the outside[like the ends of a seesaw], and are one on the inside[like the rigid bar connecting them via a fulcrum]** [Refer to Figure 2 in Sec. (3.6.4) and Figure 3 below].

Dynamical Entropy Considerations:
Integrating quantum information theory with dynamical entropy considerations provides a unique approach. While most discussions of entanglement focus on quantum information and correlation, they often exclude explicit analysis of the dynamics of entropy flow. The notion of entropy flow as a critical factor enabling particles to achieve full correlation is a novel concept introduced from the ToE formalism.

Time-Dependent Entanglement:
Our hypothesis that the degree of entanglement varies with time introduces a fresh perspective. Achieving full correlation may necessitate a specific time scale, which redefines entanglement as a time-dependent process rather than an instantaneous one.

Conceptual Shift:
This represents a significant departure from the traditional view of entanglement, which is often regarded as an instantaneous and static phenomenon.

Global Implications of the Above:

- ToE provides a potential resolution to the Einstein-Podolsky-Rosen (EPR) paradox without violating relativistic causality.
- ToE offers a testable prediction: the existence of Δt_{ent} (time-dependent entanglement) and its measurable effects.
- ToE opens new avenues for research in quantum information and quantum foundations.

[34] Herman L. Verlinde proposes that entanglement entropy between two quantum systems is dual to the entropy associated with an Einstein-Rosen bridge connecting them, thus reinforcing the ER=EPR conjecture. He discusses how this geometric interpretation of entropy unifies quantum information and spacetime topology - ideas that strongly resonate with the entropic bridge formulation in ToE.

[35] In the Theory of Entropicity, entangled particles are connected through an entropic bridge - a real field-like extension that enforces shared entropy constraints. When visualized conceptually, this bridge resembles a wormhole: though particles may appear distinct and spatially separated, they are thermodynamically inseparable via the entropic field. Tracing out this field does not yield independence; it reveals a deeper unity, much like how a wormhole has two mouths that are locally separate but globally unified in the spacetime interior.

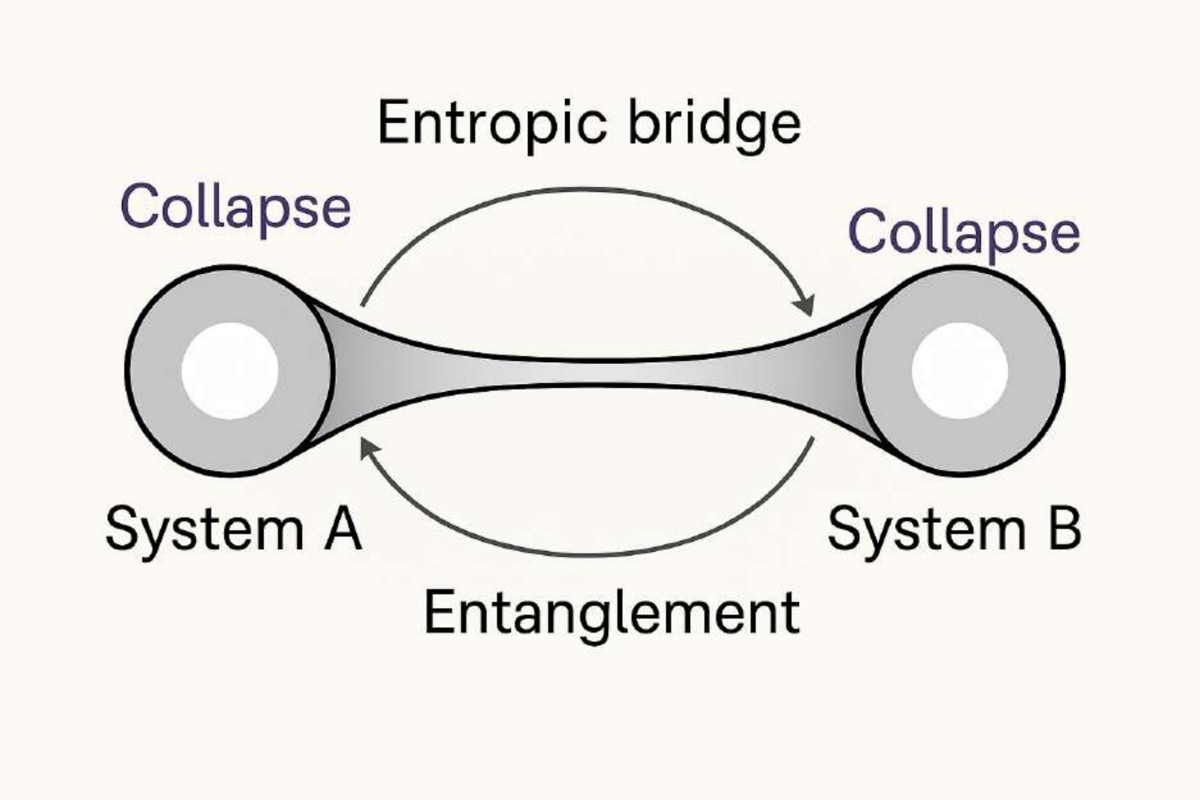

Figure 3: Entropic Bridge for Wormholes: ER = EPR

9.2.1 Entropic Bridge as a Nonlocal Constraint Field

The Theory of Entropicity (ToE) elegantly integrates the above analogy of wormholes and entanglement through the entropic field. In ToE, the entropic field governs the physical coupling **[akin to a child's playground seesaw]** between quantum systems. When two particles (or subsystems) are entangled**[somewhat similar to hooking two children on the two ends of a seesaw]**, it is not merely an informational or mathematical correlation. Instead, there exists a real, invisible entropic bridge**[seesaw]**connecting them.

Visual Analogy: Imagine two distant particles A and B. To an external observer**[who is naturally unable to see the connecting seesaw]**, they appear:

- Distant in space,
- Independent in location.

However, under ToE **[akin to an observer who is naturally able to see the connecting seesaw]**:

- These particles are two endpoints of a single, extended entropic structure**[seesaw]**.
- This structure**[seesaw]**behaves like a wormhole - separate mouths**[akin to the children on a seesaw]**, but connected through the entropic field's interior topology**[the rigid pole connecting the two children on the seesaw]**.

Wormhole Analogy: ER = EPR Reformulated via ToE
The above illustration aligns naturally with the ER=EPR conjecture by Maldacena and Susskind (2013), which proposed that Einstein-Rosen (ER) bridges (wormholes) are the geometric manifestation of Einstein-Podolsky-Rosen (EPR) entanglement. Thus, ToE provides thermodynamic substance to this provocative conjecture by reinterpreting entanglement as an entropic bridge constrained by the laws of entropy flow [as summarized in the table below]:

9.2.2 The Seesaw Model of Entropic Connectivity for the ER=EPR Conjecture

Here, we wish to give a clearer statement on the seesaw analogy we have been making so far. In the Theory of Entropicity (ToE), two quantum systems that appear spatially separated may, in fact, be linked by a hidden entropic connection - an entropic bridge. Conceptually, they are like two ends of a rigid, constrained object, such as a children's seesaw: distinct on the outside, yet mechanically and informationally unified from within.

Just as each end of a seesaw cannot move independently without affecting the other, the two entangled quantum systems cannot change their internal entropy state without reflecting the change across the entropic

Aspect	**ER = EPR (Maldacena-Susskind)**	**Theory of Entropicity (ToE)**
Entanglement Link	Geometric wormhole	Entropic bridge (thermodynamic constraint)
Connection Nature	Spacetime topology	Entropic flux lines / collapse correlation potential
Causal Propagation	Preserves locality via geometry	Preserves causality via entropy constraint
Collapse Trigger	Not specified	Entropy flow exceeding critical threshold

Table 24: **Comparison Between ER = EPR and Theory of Entropicity (ToE)**

bridge. This constrained co-dependence mirrors how a wormhole joins two distant spacetime regions: while they may appear distinct to an external observer, they are a single entity when viewed from the entropic field perspective - the "inside."

This analogy captures the non-local unity proposed by ToE: quantum systems are not merely correlated post-measurement, but rather, they exist as different expressions of a unified entropic configuration.The collapse of one side (end of the seesaw) instantaneously constrains the other side - not because of faster-than-light signaling, but because both are part of a single, entropy-constrained structure.

9.2.3 Further Discussions: ER=EPR Paradox, Wormholes and Seesaw Entropic Bridges

The diagram below is a schematic illustration of an entropic bridge as the connector behind the ER = EPR entanglement concept.

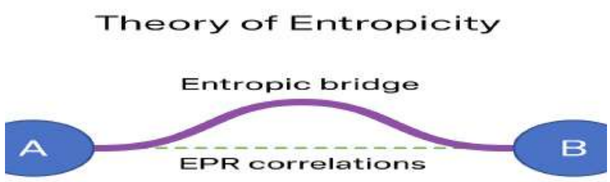

Figure 4: ER-EPR Entropic Bridge Diagram

Two particles, A and B (blue curves), share a quantum entangled state (depicted by the green dashed line indicating EPR correlations). In the Theory of Entropicity, this correlation is mediated by an entropy-binding channel (purple curve) analogous to an Einstein-Rosen bridge in general relativity. The entropic bridge does not carry usable signals faster than light, but it represents a conserved linkage of information and entropy between the particles. This provides a conceptual picture in which the entangled pair forms one combined system with a tunnel in "entropy space" linking them, mirroring the idea that entanglement and wormholes are two manifestations of the same underlying reality - an entropic seesaw.

In practical terms, how does this help reconcile Einstein and Bohr? Einstein was troubled by EPR's non-locality; Bohr was satisfied with the formalism. With entropic bridges, we can say: yes, when two particles are entangled, there is a real, physical thing connecting them (making Einstein happier that there is something physical, and not magic), but that thing is an entropy-mediated correlation which operates within the bounds of relativity (thus not violating causality - the ER=EPR verdict appears to tilt a good bit on the side of Einstein: on the non-instantaneity of interactions at a deeper intrinsic level; but Bohr also wins since entropy stands for the physical observer in collapsing the wave function irreversibly, without which no information can be communicated by any means; **so, both Einstein and Bohr eventually win together - a classical and veritable case of: No Victor, No Vanquished!).** If one particle is measured, the bridge ensures the other's state is appropriately collapsed - which we discussed as taking a finite time Δt_{ent} potentially. **The bridge is like the seesaw model we have highlighted earlier.**

During that time or after, the bridge could be said to "collapse" as well or to transmit the influence [**Even on a seesaw, we often would like to think that the swing to one position is instantaneously transmitted to the other end to swing the child-B in the opposite direction; but this is not intrinsically true, because there is a time lapse between the two events, except we are assuming the seesaw bar**

is infinitely rigid, which also cannot be physically true, because we are talking physics and not mathematics!]

After measurement, the bridge is broken (the particles are disentangled, the channel closes - the seesaw becomes chained in favour of one locality). If no measurement happens, the bridge persists potentially until decoherence from other sources breaks it. An implication of this picture is that quantum information is **geometrized: the entropic bridge may be thought of as a small wormhole [or better, a seesaw] of information connecting entangled bits.** This resonates with the emerging viewpoint in quantum gravity that spacetime geometry is built from quantum entanglement (e.g., in holography and tensor networks of AdS/CFT). **While our scope here in this section is not quantum gravity per se, our theory being consistent with that direction adds plausibility. It hints that the entropy field underlying ToE might be related to the degrees of freedom that manifest as spacetime geometry in Einstein's theory. We shall manifestly show in section 10 that this is indeed is the case**. We should note: the ER=EPR idea remains conjectural and somewhat speculative in mainstream physics, **but it's a powerful intuition pump. Our contribution is to give it a concrete mechanism via entropy, particularly in the seesaw model of ToE. The wormhole is not literal in our current universe for electrons, but if one had a quantum computer entangling macroscopic objects or high-dimensional systems, maybe small "channels" of reduced entropy connecting them could effectively shape spacetime around them.**

In summary, entropic bridges provide a mental (and potentially mathematical) model for entanglement: entangled objects share an information entropy channel [seesaw bridge] that keeps their states correlated as if connected by a wormhole. This again ties back to irreversibility: forming or destroying entanglement changes the entropy of the universe and is subject to our entropic integral's constraints. If you try to create entanglement between distant objects, you must invest some work and produce some entropy (perhaps radiated away), which is consistent with entangled systems often requiring some interaction or exchange of particles. This is what inexorably informs the entropic time as found in the 232 attosecond entanglement formation experiment done recently.

9.2.4 Uniting Einstein's Realism and Bohr's Irreversibility

With the pieces in place - objective entropy-driven collapse and contextual entropy constraints – we can articulate how the Theory of Entropicity fulfills the visions of both Einstein and Bohr in a single framework:

9.2.4.1 Einstein's Realism Restored: In ToE, the wave function and its collapse are not just knowledge updates or abstractions; they correspond to a physical field (the entropy field) and a physical condition (entropy threshold) respectively.

There is an element of reality that was missing in standard quantum theory: the state of the entropy field, which determines when and how a collapse occurs. This means that if one had super-super-vision to also observe the entropy field, one could in principle predict when a quantum measurement outcome will occur (though not necessarily which outcome if multiple are possible with equal entropy cost; but one could even argue the entropy difference between branches might slightly bias that too). **The key point is that the fate of Schrödinger's cat is not decided by a sentient observer; it is decided by the entropic buildup in the radioactive decay + detector + cat system. Long before a human opens the box, the entropy generated by the Geiger counter click and the poison release has collapsed the wavefunction - thus the cat is either alive or dead for an objective reason (not an observer paradox). This aligns with Einstein's demand that the moon (or the cat) be there with a definite state regardless of observation. Reality is not in limbo waiting for conscious minds; it is being actively shaped by physical processes (here, entropy flows).**

Furthermore, locality is preserved in the sense that no mysterious faster-than-light influence without a mediator is happening - the mediator is the entropy field, presumably a relativistic entity possibly linked to known fields (gravitational or something new). Therefore, Einstein's hope that quantum mechanics might be completed by a field theory of some kind is realized: the entropy field is akin to a hidden variable field, except it's a dynamical hidden field that satisfies the second law [of thermodynamics and is consistent with thermodynamics (unlike, say, Bohm's pilot wave which is nonlocal and does not obviously relate to thermodynamic irreversibility). One might call this stance objective collapse with entropy as a hidden driver. It's objective (happens without observation), it's a collapse (reduces state), and the driver is hidden only in the sense that conventional quantum formalism didn't include it explicitly.

9.2.4.2 Bohr's Irreversibility Preserved: Simultaneously, every quantum measurement in ToE is an irreversible thermodynamic process - exactly as Bohr insisted. We have built that into ToE at the fundamental level. The entropy increase $\Delta S \geq 0$ in any realized path ensures that once a collapse happens, you cannot undo it because that would require decreasing entropy, which is forbidden (except for extraordinarily rare fluctuations, which in quantum terms would correspond to recoherence - extremely suppressed by our weighting in the Vuli-Ndlela Integral). The [Bohr] contextuality is also respected: the outcome depends on how the measurement was set up, because the entropy generation will differ for different setups. For example, measuring an electron's position vs. momentum will couple the electron to different apparatus, yielding different entropy landscapes and thus collapsing in different bases. We haven't lost the fact that certain complementary experiments exclude each other - that's inherent because the entropy functional $S_{\text{irr}}[\phi]$ for a position-measuring path is different than that for a momentum-measuring path. The act of choosing the apparatus context determines the form of entropic constraints applied, hence which basis of the wavefunction will diagonalize the interaction and collapse.

Also, ToE does not require us to imagine any violation of the uncertainty principle or any scenario where we could measure both complementary variables - the theory isn't a hidden variable theory giving definite values to everything; it only gives definite outcomes when entropy forces a choice. So Bohr would be satisfied that we haven't gone back to classical determinism of all observables. In essence, the Copenhagen interpretation[[8],[9]] becomes a special case of ToE when we choose to ignore the mechanism and just focus on outcomes and classical apparatus.

All of Bohr's assertions (wavefunction is a tool, outcomes are irreversible, can't talk about reality in between) remain valid operationally as we are shown in ToE. The difference is that now we can talk about what's happening in between, if we include entropy: the wavefunction is a real thing evolving unitarily until the entropy threshold triggers, at which point a real physical collapse occurs. Before that point, it's as if the Copenhagen[[8],[9]] story holds (no fact of the matter to the outcome), and after that point, there is a fact of the matter. Bohr's requirement of classical description of apparatus is thus achieved by application of ToE because the apparatus, being large, will almost immediately satisfy the entropic collapse condition and produce a definite record (so we always see classical-like outcomes for macroscopic pointers).

Philosophically, this shifts the debate: instead of "is the wavefunction real or just knowledge?" we can say by virtue of ToE that "the wavefunction is partially real - it encodes potential states - and the entropy field is also real, encoding the tendency of those potentials to actualize irreversibly." Together they make a complete reality. We do not need conscious observers or many worlds. The universe can be viewed as constantly measuring itself via entropic interactions - a process John Wheeler[91] poetically called "it from bit" (physical state from information), except here it's "it from bits with entropy".

To ensure all claims are supported: let us cite some key references that align with or support aspects of this resolution by the Theory of Entropicity. **Ghirardi et al. (GRW)[42] in 1986 proposed spontaneous collapses** with a rate that increases with system size; our theory has a similar flavor, but the trigger is not arbitrary noise, it's deterministic entropy build-up.

Penrose[[70],[71]] in 1996 suggested gravity causes collapse with a timescale related to the gravitational self-energy difference; our S_G term is analogous to including gravity's role but through entropy rather than energy directly.

Zurek's work[96] on decoherence showed how environment interactions lead to **"einselection" [environmental interaction selection]** of preferred states (pointer states) - our theory gives the criteria for einselection (the pointer basis is the one that minimizes entropy production during measurement, typically the one that the interaction Hamiltonian diagonalizes, matching decoherence theory expectations).

So we do not throw away decades of quantum foundations research; we integrate it under a unifying principle. In short, the Theory of Entropicity transforms the Einstein–Bohr debate from a dichotomy into a continuum: quantum behavior and classical behavior are two regimes of a single theory governed by entropy. **At low entropy (microscopic reversible processes) we get quantum superpositions; at high entropy (macroscopic irreversible processes) we get classical outcomes. The crossover is smooth and in principle calculable for intermediate systems.**

Thus, Einstein's[[5],[19],[34],[36]] and Bohr's[[11],[12],[13]] century-old demands are the limiting cases of a more general law, the second law of thermodynamics, finding its most potent utility yet in the Theory of Entropicity [ToE].

One of the clearest demonstrations that we have successfully reconciled Einstein and Bohr on the question of Quantum Mechanics lies in our ability, grounded in our foundational axioms, to boldly propose a new basis for Quantum Gravity. To this most formidable and exacting task, we shall dedicate the greater part of our effort in the sections that follow.

10 On the Mathematical Foundations of Quantum Gravity from the Theory of Entropicity(ToE)

Enter: A Bold Transition to the Disturbing Problem of Quantum Gravity

In this daring Section, we enter neck-deep into the Mathematical Foundations of Quantum Gravity Derived from the Theory of Entropicity (ToE). **Here, we present the Fundamental Equations of Quantum Gravity (FEoQG) based on the entropic axioms of the Theory of Entropicity(ToE).** First, we derive the **field equations of Einstein's General Relativity[31] based on entropic principles;** then we impose the entropic wave equation to the Lagrangian and Action to derive the wave function equivalent of the entropic field equations, **which sum up as ToE's Field equations of Quantum Gravity [TFEoQG].** This is the Quantum Analogue of Einstein's Field Equations of General Relativity as fully derived for the first time from purely ToE's entropic wave considerations. Thereafter, we go on to **show that the Schrodinger Wave Equation of Quantum Mechanics [SWEoQM] follows directly and so can be derived from the Quantum Gravity Equations of ToE.** In this sense, then, our **ToE entropic wave field equations of Quantum Gravity yield both Einstein's field equations of GR and Schrodinger's wave equation of QM,** and makes ToE's field equations of Quantum Gravity serve as an umbrella for both equations. **This completes our program for the current phase of our investigations inspired by reflections and celebrations on the centenary of Quantum Mechanics.**

As we near the conclusion of our journey in reconciling the divergent yet complementary insights of Albert Einstein and Niels Bohr on quantum theory - on this centennial occasion marking the birth and development of Quantum Mechanics - it would be a profound disservice to their legacies if we neglected to address the profound question that looms behind their legendary dialogue: **the problem of Quantum Gravity.**

Indeed, it is not an exaggeration to say that the fertile tension in their philosophical and physical disagreements has, directly or indirectly, seeded the modern pursuit of a unified theory that encompasses both the quantum realm and the fabric of spacetime.

In the following subsections, we shall turn our attention to this enduring problem. It is here that the **Theory of Entropicity (ToE)** seeks not only to illuminate the connection between entropy and measurement but also to shed new light on the interplay between quantum states, spacetime geometry, and the origin of gravitational phenomena.

By contributing our ToE insights toward this grand challenge, we hope to offer our sincerest tribute to the monumental scientific and philosophical contributions of both Einstein and Bohr, among others. And so, with both reverence and resolve, we now take our first formal steps into these deep and murky waters - waters that, we hope, may carry us closer to a truly unified understanding of the workings of our mysterious universe.

10.1 Deriving the Einstein Field Equations via Jacobson's Method and Theory of Entropicity (ToE)

Having built all this so far, let us now embark on using the method of Jacobson and ToE to fully derive the Einstein field equations.

10.1.1 Foundational Equations

1. **Jacobson's Identity[47]: Thermodynamic Formulation of Gravity**

$$\delta Q = T\delta S \tag{236}$$

2. **Entropy-Area Relation: Classical Bekenstein-Hawking Form**

$$S = \frac{k_B A c^3}{4\hbar G} \tag{237}$$

3. **ToE Entropy: As a Function of Local Entropic Potential**

$$S = k_B \Lambda(x,t) A \tag{238}$$

4. **First Law Interpretation: Differential Form**

$$\delta Q = T\frac{\partial S}{\partial A}\delta A \tag{239}$$

10.1.2 Derivation Steps

1. **Energy Flow Across a Local Rindler Horizon**

$$\delta Q = T dS \tag{240}$$

Here, δQ is the energy flux, T is the Unruh temperature, and dS is the entropy change.

2. **Unruh Temperature Associated with Acceleration**

$$T = \frac{\hbar a}{2\pi k_B c} \tag{241}$$

This temperature is assigned to a local Rindler horizon via quantum field entanglement entropy.

3. **Entropy as a Local Field**

$$dS = k_B \left(A d\Lambda + \Lambda dA\right) \tag{242}$$

Here, $\Lambda(x,t)$ represents the local entropic potential field and A the horizon area.

4. **Energy Flow as Projection of Stress-Energy Tensor**

$$\delta Q = \int_H T^{\mu\nu}\chi_\mu d\Sigma_\nu \tag{243}$$

Where χ_μ is the approximate boost Killing vector vanishing at the horizon and $d\Sigma_\nu$ is the area element.

5. **Thermodynamic Identity Implies Einstein Equations**(Jacobson[47])

$$\int_H T^{\mu\nu}\chi_\mu d\Sigma_\nu = \int_H T dS \tag{244}$$

Substituting the entropy potential $\Lambda(x,t)$, from ToE:

$$T^{\mu\nu}\chi_\mu \propto (A\nabla_\nu\Lambda + \Lambda\nabla_\nu A) \tag{245}$$

6. **Connecting Entropy Gradients to Geometry (Ricci Tensor)**

$$T^{\mu\nu} \propto R^{\mu\nu} + \Phi(x,t) \tag{246}$$

$\Phi(x,t)$ represents entropic field curvature derived from $\nabla_\mu\Lambda(x,t)$.

7. **Einstein's GR Field Equation with Entropic Correction**
Combining all of the above, we arrive at the following entropy(ToE)modified Einstein field equations of General Relativity:

$$\boxed{R^{\mu\nu} - \frac{1}{2}Rg^{\mu\nu} + \eta\nabla_\mu\nabla_\nu\Lambda(x,t) = \frac{8\pi G}{c^4}T^{\mu\nu}} \tag{247}$$

Note how, in the above equation, the entropy variation term on the LHS replaces Einstein's Cosmological Constant[32]in a natural way, and it is dynamic - and so does not require any adhoc fixing. When $\Lambda(x,t) =$ constant, the correction term vanishes, thus recovering Einstein's original equations.

10.1.3 Implications: From Jacobson to Entropicity

- The Theory of Entropicity (ToE) generalizes Jacobson's approach, deriving Einstein's equations as emergent entropy-driven constraints.
- The entropic potential $\Lambda(x,t)$ serves as a gravitational-like potential rooted in statistical thermodynamics.

10.1.4 Compact Summary Table

Equation Type	Mathematical Form	Description
Jacobson's Identity	$\delta Q = T\delta S$	Heat flow equals entropy change
Entropy-Area Relation	$S = \frac{k_B A c^3}{4\hbar G}$	Classical thermodynamic entropy
ToE Entropy	$S = k_B\Lambda(x,t)A$	Entropy in terms of local potential
Unruh Temperature	$T = \frac{\hbar a}{2\pi k_B c}$	Temperature due to acceleration

Table 25: **Key Equations and Concepts**

10.2 Variational Derivation of Einstein Field Equations via the Entropic Action Principle (ToE)

Building upon the expectation of a derivation rooted fully in variational methods of the Lagrangian, we now present a rigorous approach to derive the Einstein field equations using the Theory of Entropicity (ToE) as a foundational principle.

10.2.1 Total Entropic Action of ToE

The spacetime dynamics are derived via extremization of total entropy, encoded in the Vuli-Ndlela Entropic Action:

$$\boxed{S_{\text{ToE}} = \int d^4x\sqrt{-g}\left[\frac{1}{2}\kappa R - S_\Lambda(\Lambda,\nabla\Lambda) + \mathcal{L}_{\text{matter}}\right]} \tag{248}$$

Where:

- R is the Ricci scalar representing spacetime curvature.
- $\kappa = \frac{8\pi G}{c^4}$ is the Einstein coupling constant.
- S_Λ is the entropic Lagrangian density, dependent on the entropy field $\Lambda(x,t)$ and its derivatives.
- $\mathcal{L}_{\text{matter}}$ is the matter Lagrangian.
- $g = \det(g_{\mu\nu})$ is the determinant of the metric tensor.

10.2.2 Entropic Lagrangian Density

Given that the entropy field $\Lambda(x,t)$ is a scalar field(from ToE's principles and considerations), its action then takes the compact form:

$$\boxed{S_\Lambda = \frac{\eta}{2}\nabla_\mu\Lambda\nabla^\mu\Lambda + V(\Lambda)} \tag{249}$$

Where:

- η is the entropic coupling constant, analogous to a kinetic term weight.
- $V(\Lambda)$ is the entropic potential, which may vanish or generate spontaneous curvature.

This structure mirrors scalar field Lagrangians, but here entropy itself is the physical field.

10.2.3 Variation of the Action with Respect to the Metric

Performing variation of the full action:

$$\delta S_{\text{ToE}} = \delta \int d^4x\,\sqrt{-g}\left[\frac{1}{2}\kappa R - \frac{\eta}{2}\nabla_\mu\Lambda\nabla^\mu\Lambda + \mathcal{L}_{\text{matter}}\right], \tag{250}$$

we expand the above, such that the variation results in:

$$\boxed{\delta S_{\text{ToE}} = \int d^4x\,\sqrt{-g}\left[\frac{1}{2}\kappa\left(R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R\right) + \frac{\eta}{2}\left(\nabla_\mu\Lambda\nabla_\nu\Lambda - \frac{1}{2}g_{\mu\nu}\nabla_\alpha\Lambda\nabla^\alpha\Lambda\right) - \frac{1}{2}T_{\mu\nu}\right]\delta g^{\mu\nu}} \tag{251}$$

Setting $\delta S_{\text{ToE}} = 0$ for all $\delta g^{\mu\nu}$ yields the Entropic Einstein Equation:

$$\boxed{R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \kappa\left(T_{\mu\nu} + \eta T_{\mu\nu}(\Lambda)\right)} \tag{252}$$

Where $T_{\mu\nu}(\Lambda)$ is the entropy field's effective stress-energy tensor:

$$\boxed{T_{\mu\nu}(\Lambda) = \nabla_\mu\Lambda\nabla_\nu\Lambda - \frac{1}{2}g_{\mu\nu}\nabla_\alpha\Lambda\nabla^\alpha\Lambda} \tag{253}$$

10.2.4 Interpretation of the Above Entropic Einstein Field Equations

- When $\Lambda = \text{const}$, $T_{\mu\nu}(\Lambda) = 0$, and standard General Relativity (GR) is recovered.
- For non-trivial $\Lambda(x,t)$, spacetime curvature arises partly from entropy gradients.

This derivation aligns with the philosophy that entropy drives curvature and collapse, rather than mass alone.

10.3 Variational Derivation of the Modified Einstein Field Equations in ToE

To fully address the derivation rooted in variational methods, this section demonstrates the complete steps, including the use of the Euler-Lagrange equations, leading to the modified Einstein field equations.

10.3.1 Entropic Action Formulation

The entropic action for the Theory of Entropicity (ToE) over a spacetime region M is given by:

$$\boxed{S_{\text{ToE}} = \int_M \sqrt{-g}\left[\frac{c^3}{16\pi G}R + \chi(\Lambda)\nabla_\mu\Lambda\nabla^\mu\Lambda - V(\Lambda) + \mathcal{L}_{\text{matter}}\right]d^4x} \tag{254}$$

Where:

- R is the Ricci scalar curvature.
- $\Lambda(x,t)$ is the entropic potential field.
- $\chi(\Lambda)$ is the entropy kinetic coupling.
- $V(\Lambda)$ is the entropic potential energy.
- $\mathcal{L}_{\text{matter}}$ is the matter Lagrangian.
- $g = \det(g_{\mu\nu})$ is the determinant of the metric tensor.

10.3.2 Variation with Respect to the Metric $g_{\mu\nu}$

The total action is varied with respect to the inverse metric $\delta g_{\mu\nu}$.

10.3.2.1 Variation of Einstein-Hilbert Term

$$\boxed{\delta\left(\frac{c^3}{16\pi G}\int R\sqrt{-g}\,d^4x\right)=\frac{c^3}{16\pi G}\int\left(R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R\right)\delta g^{\mu\nu}\sqrt{-g}\,d^4x} \tag{255}$$

10.3.2.2 Variation of Entropic Kinetic Term

The entropy kinetic term is:

$$L_{\Lambda,\mathrm{kin}}=\chi(\Lambda)\nabla_\mu\Lambda\nabla^\mu\Lambda \tag{256}$$

Its variation yields:

$$\boxed{\delta L_{\Lambda,\mathrm{kin}}=\chi(\Lambda)\left(-\nabla_\mu\Lambda\nabla_\nu\Lambda\right)\delta g^{\mu\nu}} \tag{257}$$

Using $\nabla_\mu\Lambda=g_{\mu\nu}\nabla^\nu\Lambda$, the variation of the metric gives:

$$\delta\left(\nabla_\mu\Lambda\nabla^\mu\Lambda\right)=-\nabla_\mu\Lambda\nabla_\nu\Lambda\delta g^{\mu\nu} \tag{258}$$

10.3.2.3 Variation of Entropic Potential Term

For the scalar field potential $V(\Lambda)$:

$$\boxed{\delta\left(-V(\Lambda)\sqrt{-g}\right)=-V(\Lambda)g_{\mu\nu}\delta g^{\mu\nu}\sqrt{-g}} \tag{259}$$

10.3.2.4 Variation of Matter Term

The variation of the matter Lagrangian gives:

$$\boxed{\delta\mathcal{L}_{\mathrm{matter}}=\frac{1}{2}T_{\mu\nu}\delta g^{\mu\nu}} \tag{260}$$

10.3.3 Modified Einstein Field Equations by the Entropic Potential $\Lambda(x,t)$ of ToE

Combining all variations, the total variation of the action is then given by:

$$\delta S_{\mathrm{ToE}}=\int\sqrt{-g}\Big[\frac{c^4}{16\pi G}\left(R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R\right)-\chi(\Lambda)\nabla_\mu\Lambda\nabla_\nu\Lambda \tag{261}$$

$$+\frac{1}{2}g_{\mu\nu}\left(\chi(\Lambda)\nabla_\alpha\Lambda\nabla^\alpha\Lambda-V(\Lambda)\right)+\frac{1}{2}T_{\mu\nu}\Big]\delta g^{\mu\nu}\,d^4x \tag{262}$$

Setting $\delta S_{\mathbf{ToE}}=0$ for all $\delta g^{\mu\nu}$ yields the ToE modified Einstein field equations:

$$\boxed{\frac{c^4}{8\pi G}\left(R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R\right)=T_{\mu\nu}+2\chi(\Lambda)\nabla_\mu\Lambda\nabla_\nu\Lambda-g_{\mu\nu}\left[\chi(\Lambda)\nabla_\alpha\Lambda\nabla^\alpha\Lambda-V(\Lambda)\right]} \tag{263}$$

See brief explanatory note on the above derivation of the ToE modified Einstein field equations: [36]

---

[36] **A Brief Explanatory Note on the Derivation of the Field Equations from Entropic Potentials**
Each term inside the brackets in the variation expression arises from a specific part of the total action:

$$\delta S_{\mathrm{ToE}}=\int\sqrt{-g}\Big[\frac{c^4}{16\pi G}\left(R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R\right) \tag{264}$$

$$-\chi(\Lambda)\nabla_\mu\Lambda\nabla_\nu\Lambda \tag{265}$$

$$+\frac{1}{2}g_{\mu\nu}\left(\chi(\Lambda)\nabla_\alpha\Lambda\nabla^\alpha\Lambda-V(\Lambda)\right) \tag{266}$$

$$+\frac{1}{2}T_{\mu\nu}\Big]\delta g^{\mu\nu}\,d^4x \tag{267}$$

- (264) comes from varying the Einstein-Hilbert term:

$$\frac{c^4}{16\pi G}R\quad\Rightarrow\quad\frac{c^4}{16\pi G}\left(R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R\right)$$

- (265) is the variation of the entropy field kinetic term:

$$-\chi(\Lambda)\nabla_\mu\Lambda\nabla_\nu\Lambda$$

- (266) is the trace-like correction from entropy field contributions (kinetic + potential energy):

$$+\frac{1}{2}g_{\mu\nu}\left(\chi(\Lambda)\nabla_\alpha\Lambda\nabla^\alpha\Lambda-V(\Lambda)\right)$$

10.3.4 Interpretation of the ToE Entropic Einstein Field Equations of Quantum Gravity

- When $\chi(\Lambda) \to 0$ and $V(\Lambda) \to 0$, the standard Einstein equations are recovered.
- The entropic field $\Lambda(x,t)$ introduces additional dynamical degrees of freedom, capturing information flux, collapse thresholds, and entropy-driven curvature phenomena.

This derivation highlights the unification of mass, gravitation, and entropy under a single variational principle, explaining curvature as a result of entropy flow constraints.

10.3.5 Deriving the Entropic Equation of Motion by Variation with Respect to the Entropy Field Λ

We now derive the equation of motion for the entropy field Λ by varying the action with respect to Λ.

The relevant part of the action is:

$$\boxed{S_\Lambda = \int \sqrt{-g}\,[-\chi(\Lambda)\nabla_\mu\Lambda\nabla^\mu\Lambda - V(\Lambda)]\,d^4x} \tag{270}$$

We vary Λ, i.e. $\delta\Lambda$, and analyze each term:

- **Kinetic term:**

$$\delta\left(\chi(\Lambda)\nabla_\mu\Lambda\nabla^\mu\Lambda\right) = \chi'(\Lambda)\nabla_\mu\Lambda\nabla^\mu\Lambda\,\delta\Lambda + 2\chi(\Lambda)\nabla^\mu\Lambda\nabla_\mu\delta\Lambda \tag{271}$$
$$= \chi'(\Lambda)\nabla_\mu\Lambda\nabla^\mu\Lambda\,\delta\Lambda - 2\chi(\Lambda)\Box\Lambda\,\delta\Lambda \tag{272}$$

- **Potential term:**

$$\boxed{\delta(-V(\Lambda)) = -V'(\Lambda)\,\delta\Lambda} \tag{273}$$

Combining these, we obtain the total variation:

$$\boxed{\delta S_\Lambda = \int \sqrt{-g}\,\left[2\chi(\Lambda)\Box\Lambda - \chi'(\Lambda)\nabla_\mu\Lambda\nabla^\mu\Lambda - V'(\Lambda)\right]\delta\Lambda\,d^4x} \tag{274}$$

Imposing the stationary action principle $\delta S_\Lambda = 0$ for arbitrary $\delta\Lambda$, we arrive at the equation of motion for the entropy field:

$$\boxed{2\chi(\Lambda)\,\Box\Lambda - \chi'(\Lambda)\,\nabla_\mu\Lambda\nabla^\mu\Lambda - V'(\Lambda) = 0} \tag{275}$$

This is a generalized Klein–Gordon form equation, governing the dynamics of the entropy field Λ under the Theory of Entropicity (ToE), with non-minimal coupling $\chi(\Lambda)$ and potential $V(\Lambda)$.

- The last term $+\frac{1}{2}T_{\mu\nu}$ results from the variation of the matter Lagrangian:

$$\delta\mathcal{L}_{\text{matter}} \Rightarrow \frac{1}{2}T_{\mu\nu}\delta g^{\mu\nu}$$

Additionally:

- The factor $\delta g^{\mu\nu}$ is factored out, as is standard in variational calculus.
- Integration over d^4x and inclusion of $\sqrt{-g}$ ensures general covariance and coordinate invariance.

Logical Insight Imposed If we impose the principle of stationary action:

$$\delta S_{\text{ToE}} = 0 \quad \text{for arbitrary } \delta g^{\mu\nu},$$

we obtain the full gravitational field equation of the Theory of Entropicity:

$$\boxed{\boxed{\frac{c^4}{8\pi G}\left(R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R\right) = T_{\mu\nu} + 2\chi(\Lambda)\nabla_\mu\Lambda\nabla_\nu\Lambda - g_{\mu\nu}\left[\chi(\Lambda)\nabla_\alpha\Lambda\nabla^\alpha\Lambda + V(\Lambda)\right]}} \tag{268}$$

The extra factor of 2 in the second term comes from symmetrizing the variation of the kinetic term:

$$\delta(\nabla_\mu\Lambda\nabla_\nu\Lambda) \Rightarrow \nabla_\mu\Lambda\nabla_\nu\Lambda + \nabla_\nu\Lambda\nabla_\mu\Lambda = 2\nabla_\mu\Lambda\nabla_\nu\Lambda \tag{269}$$

10.3.6 Full Expression of the Entropy Field Equation with Expanded d'Alembertian Operator$\Box\Lambda$

We now expand the box operator $\Box\Lambda$ explicitly in terms of the covariant derivatives and the metric tensor, so that the above entropic equation of motion for Λ is written in full form without shorthand.

Classical Note: The d'Alembertian operator (also called the box operator) in curved spacetime is defined as:

$$\boxed{\Box\Lambda \equiv \nabla^\mu \nabla_\mu \Lambda = \frac{1}{\sqrt{-g}} \partial_\mu \left(\sqrt{-g}\, g^{\mu\nu}\, \partial_\nu \Lambda \right)} \tag{276}$$

This operator accounts for how the entropy field propagates and diffuses in a curved spacetime background.

10.3.6.1 Full Equation of Motion in an Entropic Field: Substituting the expression for $\Box\Lambda$ into the entropy field equation, we obtain:

$$\boxed{2\chi(\Lambda) \left[\frac{1}{\sqrt{-g}} \partial_\mu \left(\sqrt{-g}\, g^{\mu\nu}\, \partial_\nu \Lambda \right) \right] - \chi'(\Lambda)\, g^{\mu\nu}\, \partial_\mu \Lambda\, \partial_\nu \Lambda - V'(\Lambda) = 0} \tag{277}$$

This is the equation of motion of a body experiencing "constraints" within the entropic field. The relevant trajectory constraints can be imposed and prescribed with the use of the Vuli-Ndela Integral.

10.3.6.2 Interpretation of Terms in the Entropic Equation of Motion:

- The **first term** is the curved-spacetime generalization of the wave operator (Laplacian) acting on Λ, scaled by the coupling function $2\chi(\Lambda)$. It describes the propagation of entropy coupled with its own [entropy induced] geometric constraints.
- The **second term** is a non-linear derivative coupling, modulated by how the coupling function $\chi(\Lambda)$ changes with the entropy field. It introduces a self-interaction based on entropy gradients.
- The **third term** is a standard potential-like force term derived from the entropy potential $V(\Lambda)$, contributing to entropic "restoring forces."

10.3.6.3 Physical Meaning in the Theory of Entropicity (ToE): This equation governs how the entropy field Λ evolves in a dynamic, curved spacetime environment. It encapsulates:

- The influence of [entropy self-induced] curvature on entropy flow.
- The non-linear feedback between entropy and its own gradients.
- Internal constraints imposed by the entropy potential $V(\Lambda)$.

The structure is reminiscent of scalar-tensor field theories and k-essence models in cosmology, but here it is uniquely interpreted entropically: entropy is not merely a thermodynamic quantity but a dynamical, field-like entity that actively participates in shaping spacetime and governing physical processes in our Universe.

10.4 Inclusion of the Wave Function in the Entropic Field Equations

This section addresses the incorporation of the wave function $\psi(x,t)$ into the entropic field equations, providing a unified framework for quantum and gravitational dynamics within the Theory of Entropicity (ToE).

10.4.1 Wave Function–Entropy Relation

We start with the proposed foundational identity of the Theory of Entropicity (ToE):

$$\Lambda(x,t) = k_B \ln |\psi(x,t)|^2 + C \tag{278}$$

This relation defines the local entropy potential $\Lambda(x,t)$ as a logarithmic transformation of the squared amplitude of the quantum wave function $\psi(x,t)$. **We see that the above Entropic Potential is actually the Logarithmic Image of the Wave Function.** It provides a bridge between quantum probabilities and spacetime dynamics.

https://doi.org/10.33774/coe-2025-vrfrx **ORCID:** https://orcid.org/0009-0004-3606-3182 Content not peer-reviewed by Cambridge University Press.

10.4.2 Gradient of the Entropic Potential

Taking the gradient of $\Lambda(x, t)$ yields: [37]

$$\boxed{\nabla_\mu \Lambda = \frac{2k_B}{|\psi|^2} \operatorname{Re}(\psi^* \nabla_\mu \psi)} \tag{284}$$

This expresses how variations in the wave function translate into changes in the entropy field Λ, which will play a crucial role in the energy-momentum tensor of the field equations.

10.4.3 Lagrangian with Embedded Wave Function

The kinetic term of the entropy field Lagrangian is:

$$\boxed{L_\Lambda = \frac{1}{2}\chi(\Lambda) g^{\mu\nu} \nabla_\mu \Lambda \nabla_\nu \Lambda} \tag{285}$$

Substituting the expression for $\nabla_\mu \Lambda$, we have:

$$\boxed{L_\psi = \frac{1}{2}\chi\left(\ln|\psi|^2\right)\left(\frac{2k_B}{|\psi|^2} \operatorname{Re}(\psi^* \nabla_\mu \psi)\right)^2} \tag{286}$$

Simplifying further:

$$\boxed{L_\psi = \frac{2k_B^2}{|\psi|^4}\chi\left(\ln|\psi|^2\right)\left[\operatorname{Re}(\psi^* \nabla_\mu \psi)\right]^2} \tag{287}$$

The above equation converts the entropic field energy directly into a functional of the wave function. This formulation explicitly connects the wave function's structure to the entropic dynamics. This is a most powerful equation.

10.4.3.1 Why The Above Quantum Gravity Lagrangian Is Powerful and Revolutionary

- **Quantum-Gravitational Unification:** The inclusion of $\psi(x, t)$ ties quantum coherence directly to spacetime curvature.
- **Dynamic Collapse Geometry:** Wave function collapse manifests as dynamic spacetime deformation.
- **Experimental Signatures:** Interference and coherence effects in $\psi(x, t)$ could leave detectable gravitational imprints.

10.4.4 Action Functional

The full action, incorporating curvature, wave function terms, and interaction potentials, is:

$$\boxed{S = \int d^4x \sqrt{-g}\left[\frac{c^4}{16\pi G}R + L_\psi + L_{\text{int}}\right]} \tag{288}$$

Where:

- L_ψ is the wave-function-dependent entropic kinetic term.
- L_{int} includes interaction terms or collapse dynamics. Other interatctions can be embedded or coupled at this instance as may be needed or required by the field, etc.

---

[37] Given the entropic potential equation [EPE]:

$$\Lambda(x, t) = k_B \ln|\psi(x, t)|^2 + C \tag{279}$$

Differentiating $\Lambda(x, t)$ with respect to spacetime coordinates x_μ, we get:

$$\nabla_\mu \Lambda(x, t) = \frac{\partial \Lambda(x, t)}{\partial x_\mu} = \frac{k_B}{|\psi(x, t)|^2} \frac{\partial |\psi(x, t)|^2}{\partial x_\mu} \tag{280}$$

Since $|\psi(x, t)|^2 = \psi(x, t)\psi^*(x, t)$, the derivative of $|\psi(x, t)|^2$ is:

$$\frac{\partial |\psi(x, t)|^2}{\partial x_\mu} = \psi^*(x, t)\frac{\partial \psi(x, t)}{\partial x_\mu} + \psi(x, t)\frac{\partial \psi^*(x, t)}{\partial x_\mu} \tag{281}$$

Substituting into the gradient, we obtain:

$$\boxed{\nabla_\mu \Lambda(x, t) = \frac{k_B}{|\psi(x, t)|^2}\left[\psi^*(x, t)\frac{\partial \psi(x, t)}{\partial x_\mu} + \psi(x, t)\frac{\partial \psi^*(x, t)}{\partial x_\mu}\right]} \tag{282}$$

Using the real part operator, the gradient simplifies to:

$$\boxed{\nabla_\mu \Lambda(x, t) = \frac{k_B}{|\psi(x, t)|^2} \operatorname{Re}\left(\psi^*(x, t) \nabla_\mu \psi(x, t)\right)} \tag{283}$$

10.4.5 Modified Einstein Field Equations

Varying the action with respect to the metric $g_{\mu\nu}$ gives:

$$\boxed{\frac{c^4}{8\pi G} G_{\mu\nu} = T_{\mu\nu}(\psi)} \tag{289}$$

Where the entropic energy-momentum tensor $T_{\mu\nu}(\psi)$ is:

$$\boxed{T_{\mu\nu}(\psi) = \frac{-2}{\sqrt{-g}} \frac{\delta\left(\sqrt{-g} L_\psi\right)}{\delta g^{\mu\nu}}} \tag{290}$$

Substituting L_ψ, the energy-momentum tensor becomes explicitly dependent on the wave function $\psi(x,t)$, which helps to fully express how the quantum amplitude field governs the curvature of spacetime via its entropic projection:

$$\begin{aligned} T_{\mu\nu}(\psi) &= \frac{2k_B^2}{|\psi|^4} \chi\left(\ln|\psi|^2\right) \operatorname{Re}(\psi^* \nabla_\mu \psi) \operatorname{Re}(\psi^* \nabla_\nu \psi) \\ &\quad - g_{\mu\nu} \left[\frac{2k_B^2}{|\psi|^4} \chi\left(\ln|\psi|^2\right) \left(\operatorname{Re}(\psi^* \nabla_\alpha \psi)\right)^2\right] \end{aligned} \tag{291}$$

10.4.6 Final Form of the Field Equations

The modified Einstein field equations are thus now given as follows:

$$\boxed{G_{\mu\nu} = \frac{8\pi G}{c^4} \cdot \frac{2k_B^2}{|\psi|^4} \chi\left(\ln|\psi|^2\right) \operatorname{Re}(\psi^* \nabla_\mu \psi) \operatorname{Re}(\psi^* \nabla_\nu \psi)} \tag{292}$$

This is a most revolutionary result: Here, the curvature of spacetime is directly sourced by the gradient structure of the quantum wave function, modulated through the entropic field [potential].

10.4.7 Great Significance of the Above Result on the Modified Einstein Field Equations

We already highlighted the power of the entropic wave function Lagrangian in a previous section above [refer to Sec. (10.4.3.1)]. Here, we expouse on those same virtues in light of the field equations we have derived as in Eq. (292) above. The incorporation of the quantum wave function $\psi(x,t)$ into the entropic field equations represents a transformative advancement in theoretical physics: We are connecting quantum amplitudes, entropy, and gravity in a mathematically rigorous, physically testable, and philosophically coherent framework. Below are the key reasons why this is both powerful and revolutionary:

1. **Bridges Quantum and Gravitational Dynamics:**
   The entropic stress-energy tensor now contains direct dependence on $\psi(x,t)$, **demonstrating how quantum coherence influences and shapes spacetime curvature.**
2. **Collapse Geometry:**
   When the wave function collapses (and entropy changes), the geometry of spacetime responds dynamically. This offers a pathway to understanding time-asymmetric spacetime structure.
3. **Possible Replacement of Einstein-Hilbert Action:**
   The Ricci scalar $\mathcal{R}$ may no longer need to be postulated independently but can instead be derived or modified from entropic constraints, offering an alternative to traditional gravitational models.
4. **Experimental Signature:**
   Quantum wave interference, phase shifts, and coherence could produce detectable gravitational imprints, providing observational evidence for this entropic link.

10.5 Comparison Between Current and Previous Field Equations

This section analyzes how the current field equation, which incorporates the wave function $\psi(x,t)$ explicitly, differs from the previous entropic field equation in the Theory of Entropicity (ToE).

10.5.1 Previous Entropic Field Equation (Wave Function Not Explicit)

In the earlier formulation, the entropy field $\Lambda(x,t)$ was treated as an independent scalar potential field. The field equations were expressed as:

$$\boxed{G_{\mu\nu} = \eta\left(\nabla_\mu \Lambda \nabla_\nu \Lambda - \frac{1}{2} g_{\mu\nu} \nabla_\alpha \Lambda \nabla^\alpha \Lambda\right)} \tag{293}$$

Characteristics:

- The entropy field $\Lambda(x,t)$ was fundamental and independent.
- The wave function $\psi(x,t)$ was absent.
- Spacetime curvature was governed by gradients of $\Lambda(x,t)$.
- The coupling constant η was thermodynamically defined, e.g., $\eta = \frac{16\pi G}{c^2}$ in the case of the deflection of starlight.

10.5.2 Entropic Wave Function Field Equations Yield the Field Equations of Quantum Gravity

We show that the Entropic Explicit-Wave-Function Field Equations of the Theory of Entropicity directly Yield the Field Equations of Quantum Gravity.
In the updated formulation, $\Lambda(x,t)$ is derived from the wave function $\psi(x,t)$:

$$\Lambda(x,t) = k_B \ln |\psi(x,t)|^2 + C \tag{294}$$

This leads to the wave-function-based energy-momentum tensor field equations:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} \cdot \frac{2k_B^2}{|\psi|^4} \chi\left(\ln |\psi|^2\right) \mathrm{Re}(\psi^* \nabla_\mu \psi)\, \mathrm{Re}(\psi^* \nabla_\nu \psi) \tag{295}$$

When we write out the Einstein tensor $G_{\mu\nu}$ explicitly:

$$\boxed{G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu},} \tag{296}$$

the above Eq. (295) becomes:

$$\boxed{R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} \cdot \frac{2k_B^2}{|\psi|^4} \chi\left(\ln |\psi|^2\right) \mathrm{Re}(\psi^* \nabla_\mu \psi)\, \mathrm{Re}(\psi^* \nabla_\nu \psi)} \tag{297}$$

We simplify the above powerful field equation to read as follows after some algebraic considerations:

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} \cdot \frac{2k_B^2}{|\psi|^4} \chi\left(\ln |\psi|^2\right) \mathrm{Re}\, \psi^* [(\nabla_\mu)(\nabla_\nu)] \psi \tag{298}$$

We further define a new quantity in ToE as a nabla product (∇ product) to be as:

$$\boxed{(\nabla_\mu)(\nabla_\nu) = \nabla_{(\mu\nu)}} \tag{299}$$

So that we can now finally write Eq. (297) in the following powerful compact form:

$$\boxed{R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} \cdot \frac{2k_B^2}{|\psi|^4} \chi\left(\ln |\psi|^2\right) \mathrm{Re}\, \psi^* [\nabla_{(\mu\nu)}] \psi} \tag{300}$$

And remembering that the Ricci scalar and curvature terms are actually encoded with the constraints of the Vuli-Ndlela Integral, we denote that by a power of the prime symbol('), and we conclude, for purpose of identity, that:

$$\boxed{R'_{\mu\nu} - \frac{1}{2} R' g_{\mu\nu} = \frac{8\pi G}{c^4} \cdot \frac{2k_B^2}{|\psi|^4} \chi\left(\ln |\psi|^2\right) \mathrm{Re}\, \psi^* [\nabla_{(\mu\nu)}] \psi} \tag{301}$$

The above Eq. (301) represents the Field Equations of Quantum Gravity as derived from the principles and axioms of the Theory of Entropicity (ToE).

It is very important to note from the above equation that the LHS contains the spacetime structure and curvature terms (now modified and encoded with the entropic constraints of the Vuli-Ndlela Integral, and denoted by the prime symbol in the above field equation), while the RHS contains the gravitational, thermodynamic entropy and wave function terms; and since the explicit gravitational and thermodynamic entropy terms on the RHS are constants and only the

wave function is an explicit variable on the RHS, we arrive at the groundbreaking interpretation and conclusion that it is the wave function that actually creates spacetime, and hence matter and energy. After John Wheeler[91] on GR, we can now say for ToE that Quantum entropy flow determines how spacetime curves. The wave function has explicitly taken the position of the traditional energy-momentum [stress tensor] in Einstein's classical General Relativity.

Key Characteristics of the Above Equation:

- **Introduces a bridge between general relativity and quantum mechanics; that is, the road to Quantum Gravity!**
- The entropy field $\Lambda(x,t)$ is now derived from the wave function $\psi(x,t)$.
- The wave function $\psi(x,t)$ appears directly in the field equations.
- Spacetime curvature is influenced by local quantum interference and gradient effects in $\psi(x,t)$ via $\nabla_\nu\psi$.
- $\Lambda(x,t)$ is no longer independent but emergent from the wave function.
- **Waves generate spacetime via entropic potentials, meaning that what we call spacetime is actually waves and entropy.This is so if we recollect that the structure of spacetime on the LHS of the above field equation is actually dictated by the Vuli-Ndlela Integral with its entropic potential constraints. So the LHS of the field equation above also has entropy built into it, unlike the spacetime in Einstein's original field equations of GR!**
- **If we remove the *Re* in the above equation, and incorporate the real and imaginary parts, we are left with a system of equations that also tells us about imaginary worlds beyond our current capabilities to detect, observe, measure, or interact with.**

10.5.3 Key Differences in ToE's Two Formulations of Einstein's Field Equations of GR

So far, we have formulated the Einstein Field Equations in two ways from the Theory of Entropicity (ToE), namely, one formulated with explicit expressions of entropic field and the second formulated with explicit expressions of the quantum wave function. We highlight the key differences in the following table:

Aspect	**Previous Entropic Field Equation**	**Current Wave-Based Field Equation**
Wave Function	Absent	Explicitly embedded
Origin of Λ	Independent scalar field	Logarithmic function of $\lvert\psi\rvert^2$
Curvature Source	Gradient of entropy field $\nabla_\mu\Lambda$	Real parts of $\psi^*\nabla_\mu\psi$ terms
Physical Coupling	Thermodynamic constant η	Emerges via quantum amplitude gradients
Unification	Entropy–geometry unification	Quantum–thermodynamic–gravitational unification
Collapse Dynamics	Defined via entropy threshold $\Lambda \geq \Lambda_{\text{crit}}$	Rooted in dynamics of $\psi(x,t)$

Table 26: **Comparison of Previous and Current Field Equations**

10.5.4 Breakthrough Conclusion of ToE

The current field equation represents a major advancement in the Theory of Entropicity (ToE):

- **First-Principles Derivation:** Gravitational curvature is now derived from the quantum wave function $\psi(x,t)$ via entropy.
- **Unified Framework for Quantum Gravity:** It bridges quantum mechanics and general relativity under a single entropic framework.
- **Natural Connections:** Links directly to de Broglie wave–particle duality, the Born rule, collapse theory, and entropic mass emergence.
- **This formulation unites Einsteinian geometry with quantum wave behavior**, not by force-fitting them, but by grounding both in entropy as a physical field.
- **Recasting John Archibald Wheeler from GR to ToE: From the above field equations of ToE, we can now pronounce that henceforth, it is Quantum entropy flow that determines how spacetime curves!. As we have fulfilled Wheeler's proposal of geometrodynamics via an alternate route in the principles of thermodynamics, we may as well call ToE's approach as thermodynamic geometrodynamics - thus extending Wheeler's dream** by introducing entropy as the field-generating agent, with an intrinsic link which emerges from quantum wave function structure.

This formulation opens up profound implications for understanding the fundamental interplay between quantum coherence and spacetime structure in our development and understanding of Quantum Gravity.

10.6 Derivation of the Schrödinger Equation from Entropic Principles

10.6.1 Goal: Deriving Schrödinger Equation from Entropic Principles

We begin with the entropic field formulation:

$$\Lambda(x,t) = k_B \ln |\psi(x,t)|^2 + C \tag{302}$$

where $\Lambda(x,t)$ defines the entropic potential field in terms of the probability density of the wave function $\psi(x,t)$. The gravitational-entropic field equation is given by:

$$\boxed{G_{\mu\nu} = \frac{8\pi G}{c^4} \cdot T_{\mu\nu\Lambda}} \tag{303}$$

from where we quickly note by a careful inspection of proportionality that indeed:

$$\boxed{T_{\mu\nu\Lambda} \propto \Re(\psi^* \nabla_\mu \psi)\Re(\psi^* \nabla_\nu \psi)} \tag{304}$$

We aim to derive an effective equation of motion for the wave function from this field.

10.6.2 Constructing the Effective Entropic Action for the Wave Function

From our theory, we define an entropic Lagrangian with potential:

$$\boxed{L[\psi] = \frac{\hbar^2}{2m}|\nabla\psi|^2 - V(x)|\psi|^2 - V_\Lambda(\psi)} \tag{305}$$

where $V_\Lambda(\psi) = k_B T \ln |\psi|^2$ is the entropic potential[of energy]. Using the principle of least action:

$$\boxed{\delta \int L[\psi]\, d^4x = 0} \tag{306}$$

yields the Euler-Lagrange equation:

$$\boxed{\frac{\partial L}{\partial \psi^*} - \nabla \cdot \left(\frac{\partial L}{\partial (\nabla \psi^*)} \right) = 0} \tag{307}$$

Carrying out this variation gives:

$$\boxed{i\hbar \frac{\partial \psi}{\partial t} = \left[-\frac{\hbar^2}{2m}\nabla^2 + V(x) + k_B T \cdot (1 + \ln |\psi(x,t)|^2) \right] \psi(x,t)} \tag{308}$$

10.6.3 Resulting Equation: Schrödinger with Entropic Correction from ToE

The resulting wave equation is a modified nonlinear Schrödinger equation:

$$\boxed{i\hbar \frac{\partial \psi}{\partial t} = \left[-\frac{\hbar^2}{2m}\nabla^2 + V(x) + k_B T \cdot (1 + \ln |\psi|^2) \right] \psi} \tag{309}$$

This is the Schrödinger equation with an entropic self-potential as derived from the Theory of Entropicity(ToE).

10.6.4 Interpretation and Limits for the Schrodinger Equation

In the low-entropy limit (e.g., small $k_B T$), the equation reduces to the ordinary Schrödinger equation. The added term $k_B T \ln |\psi|^2$ introduces nonlinear, self-referential dynamics. This logarithmic correction is consistent with entropic wave collapse thresholds in our Theory of Entropicity (ToE).

- In the **low-entropy limit** (e.g., small $k_B T$), the equation **reduces to the ordinary Schrödinger equation.**
- The added term $k_B T \ln |\psi|^2$ introduces **nonlinear, self-referential dynamics.**
- The logarithmic correction is **consistent with entropic wave collapse thresholds** in the Theory of Entropicity (ToE).
- This suggests that **standard quantum mechanics is an emergent low-entropy limit** of the entropic wave dynamics of the Theory of Entropicity.
- **This shows that quantum dynamics is governed by the entropy structure of the wave function, which is a novel and powerful interpretation.**

10.7 Recap on Quantum Gravity in ToE via Entropic Potential and the Wave Function

We have shown in the foregoing from our Theory of Entropicity (ToE) that gravitational interactions emerge from entropic constraints encoded in both the entropy potential $\Lambda(x,t)$ and the quantum wave function $\Psi(x,t)$. Here, for better grounding, we wish to derive the quantum gravity field equations simplistically by combining ToE's modified field equation with the entropy structure of quantum mechanics. This is to inform our subsequent entropicistic discussions on the problematic Cosmological Constant of Einstein's field equations of General Relativity; after which we shall use that as a basis to throw light on the unpalatable concerns arising from the conjurations of Dark Energy and Dark Matter. **We show how the Quantum Gravity field equations of the Theory of Entropicity(ToE) resolve these issues of the Cosmological Constant, Dark Energy, and Dark matter at a fundamental and conceptual level.**

10.7.1 Entropic Gravitational Field Equations (Modified Einstein Form)

As we already know, the foundational entropic gravitational field equation in ToE is given by:

$$\boxed{\frac{c^4}{8\pi G}\left(R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R\right)=T_{\mu\nu}+2\chi(\Lambda)\nabla_\mu\Lambda\nabla_\nu\Lambda-g_{\mu\nu}\left[\chi(\Lambda)\nabla^\alpha\Lambda\nabla_\alpha\Lambda-V(\Lambda)\right]} \tag{310}$$

where:

- $\Lambda(x,t)$ is the entropic potential,
- $\chi(\Lambda)$ is the entropy coupling function,
- $V(\Lambda)$ is the entropy potential energy,
- $T_{\mu\nu}$ is the classical stress-energy tensor.

10.7.2 Entropy-Wave Function Link to the Entropic GR Field Equations

ToE already establishes a direct link between entropy and the wave function via:

$$\boxed{\Lambda(x,t)=-k_B\ln|\Psi(x,t)|^2} \tag{311}$$

which expresses the entropic potential as a measure of quantum informational density.

10.7.3 Substituting the Wave Function into the Entropic GR Field Equations

Substituting equation (311) into (316), we obtain the ToE quantum gravity field equations with entropy encoded via the wave function:

$$\begin{aligned}\frac{c^4}{8\pi G}\left(R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R\right)&=T_{\mu\nu}+2\chi(\Psi)\nabla_\mu\left(-k_B\ln|\Psi|^2\right)\nabla_\nu\left(-k_B\ln|\Psi|^2\right)\\&\quad-g_{\mu\nu}\left[\chi(\Psi)\nabla^\alpha\left(-k_B\ln|\Psi|^2\right)\nabla_\alpha\left(-k_B\ln|\Psi|^2\right)-V(\Psi)\right]\end{aligned} \tag{312}$$

10.7.4 Simplification of the Quantum Gravity Equations Using a Notation

Let us define(as is already expected from the expression for the entropic potential in terms of the quantum wave function):

$$\boxed{\Lambda_\Psi:=-k_B\ln|\Psi|^2} \tag{313}$$

Then equation (312) becomes:

$$\boxed{\frac{c^4}{8\pi G}\left(R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R\right)=T_{\mu\nu}+2\chi(\Psi)\nabla_\mu\Lambda_\Psi\nabla_\nu\Lambda_\Psi-g_{\mu\nu}\left[\chi(\Psi)\nabla^\alpha\Lambda_\Psi\nabla_\alpha\Lambda_\Psi-V(\Psi)\right]} \tag{314}$$

The above is our simplified Entropic Field Equations of Quantum Gravity in the Theory of Entropicity.

10.7.5 Interpretation of the Simplified Field Equations of Quantum Gravity

Equation (314) is the ToE-based **quantum gravity field equation**. It expresses how:

- Spacetime curvature is sourced not by classical matter but by entropic gradients coupled to the quantum wave function.
- The entropic field Λ, connected to Ψ, governs energy flow and curvature, and hence matter.
- This formulation unifies quantum information, entropy, waves, matter, and geometry into one cohesive whole.

This result confirms one of the core axioms of the Theory of Entropicity: that entropy, rather than mass-energy, fundamentally governs the structure and evolution of spacetime.

10.8 Implications of the Field Equations of ToE on the Cosmological Constant

In classical General Relativity, Einstein introduced the cosmological constant Λ_{cosmo} to allow for a static universe. In modern cosmology, it is interpreted as vacuum energy responsible for the accelerated expansion of the universe. **However, in the Theory of Entropicity (ToE), the cosmological constant is not fundamental - it emerges naturally from the entropic structure of spacetime.**

10.8.1 Classical Einstein Field Equations with the Cosmological Constant

The standard Einstein field equations including the cosmological constant are written as:

$$\boxed{\frac{c^4}{8\pi G}\left(R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + g_{\mu\nu}\Lambda_{\text{cosmo}}\right) = T_{\mu\nu}} \tag{315}$$

Here:

- $R_{\mu\nu}$ is the Ricci curvature tensor,
- R is the Ricci scalar,
- $T_{\mu\nu}$ is the matter stress-energy tensor,
- Λ_{cosmo} is inserted as a fixed constant to represent vacuum energy.

10.8.2 The Entropic Field Equations in ToE Explain the Cosmological Constant

In ToE, the entropy field $\Lambda(x,t)$ plays a dynamic role. The entropic field equation replaces the cosmological constant with entropy-driven terms:

$$\boxed{\frac{c^4}{8\pi G}\left(R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R\right) = T_{\mu\nu} + 2\chi(\Lambda)\nabla_\mu\Lambda\nabla_\nu\Lambda - g_{\mu\nu}\left[\chi(\Lambda)\nabla^\alpha\Lambda\nabla_\alpha\Lambda - V(\Lambda)\right]} \tag{316}$$

where:

- $\chi(\Lambda)$ is the entropic coupling function,
- $V(\Lambda)$ is the entropy potential,
- No fixed Λ_{cosmo} is needed.

10.8.3 Why ToE Makes a Fixed Cosmological Constant Unnecessary

1. **Entropy Encodes Vacuum Dynamics:** In ToE, the term $V(\Lambda)$ evolves with the entropy field and governs vacuum energy dynamically.
2. **Geometry Is Modulated by Entropy:** The entropy gradient terms $\nabla_\mu\Lambda\nabla_\nu\Lambda$ replace the need for a constant offset in curvature.
3. **Eliminates Fine-Tuning Problem:** The small but nonzero effective vacuum energy in our universe arises naturally from the current entropy configuration, avoiding arbitrary insertion.
4. **Unifies Quantum and Gravitational Dynamics:** The entropy field is linked to the quantum wave function via:
$$\Lambda(x,t) = -k_B \ln|\Psi(x,t)|^2 \tag{317}$$
This relation makes vacuum energy a derived quantity - not a fixed universal constant.

Classical Cosmology (GR)	**Theory of Entropicity (ToE)**
Vacuum energy modeled as a fixed Λ_{cosmo}	Vacuum energy emerges from the entropy potential $V(\Lambda)$
Cosmological constant must be inserted by hand	No need to insert; derived from entropy field dynamics
Fine-tuning problem (120 orders of magnitude discrepancy)	Vacuum energy evolves naturally with entropy, avoiding fine-tuning
Separate from quantum theory	Unified with wave function through $\Lambda(x,t) = -k_B \ln \lvert\Psi\rvert^2$

Table 27: **Comparison between General Relativity and ToE in handling vacuum energy.**

10.8.4 Comparison Table: Classical vs. ToE View of Vacuum Energy

10.8.5 Closure on the Cosmological Constant Based on ToE's Insights

In the Theory of Entropicity, there is no need to introduce a cosmological constant by hand. Instead, vacuum energy arises as a dynamic, emergent property of the entropy field $\Lambda(x,t)$. This fundamentally reshapes our understanding of cosmic acceleration, entropy flow, and the structure of spacetime.

10.9 Dark Energy and Dark Matter as Emergent Entropic Phenomena in the Theory of Entropicity

One of the most powerful implications of the Theory of Entropicity (ToE) is its ability to reinterpret the mysterious components of the cosmos - *dark energy* and *dark matter* - as emergent, entropy-driven effects. In contrast to the standard model of cosmology (ΛCDM), where these components are treated as fundamental yet poorly understood substances, ToE proposes that both phenomena arise naturally from the dynamics of the entropy field $\Lambda(x,t)$ and its potential $V(\Lambda)$, without invoking exotic particles or finely-tuned vacuum energy.

10.9.1 Dark Energy as an Entropic Potential Constraint

In standard General Relativity, cosmic acceleration is attributed to a fixed cosmological constant Λ_{cosmo}, yielding the modified Einstein field equations:

$$\boxed{\frac{c^4}{8\pi G}\left(R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + g_{\mu\nu}\Lambda_{\text{cosmo}}\right) = T_{\mu\nu}} \tag{318}$$

However, this approach suffers from the cosmological constant problem: quantum field theory predicts a vacuum energy density $\sim 10^{120}$ times larger than observations suggest. ToE resolves this by replacing Λ_{cosmo} with the dynamically evolving entropy potential $V(\Lambda)$ in its entropic field equations:

$$\boxed{\frac{c^4}{8\pi G}\left(R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R\right) = T_{\mu\nu} + 2\chi(\Lambda)\nabla_\mu\Lambda\nabla_\nu\Lambda - g_{\mu\nu}\left[\chi(\Lambda)\nabla^\alpha\Lambda\nabla_\alpha\Lambda - V(\Lambda)\right]} \tag{319}$$

This brave and daring ToE formulation allows for the following reinterpretation:

1. **Entropic Vacuum Energy:** The term $V(\Lambda)$ plays the role of a *dynamical vacuum energy*, varying with cosmic entropy flow rather than remaining constant.
2. **Entropy-Driven Acceleration:** The cosmic acceleration arises due to the pressure generated by this entropy potential, without requiring dark energy as a separate substance.
3. **Entropy-Wave Function Link:** ToE links entropy to quantum structure via the relation:

$$\Lambda(x,t) = -k_B \ln \lvert\Psi(x,t)\rvert^2 \tag{320}$$

This shows that the entropic potential—and hence the effective vacuum energy - emerges from the configuration of the quantum wave function of Quantum Gravity.

10.9.2 Dark Matter as Entropic Curvature in the Theory of Entropicity

To explain galaxy rotation curves and lensing anomalies, standard physics postulates the existence of dark matter: massive, invisible particles interacting gravitationally but not electromagnetically. ToE, however, explains these effects as outcomes of **entropic curvature**:

https://doi.org/10.33774/coe-2025-vrfrx ORCID: https://orcid.org/0009-0004-3606-3182 Content not peer-reviewed by Cambridge University Press.

1. **Entropy Gradients as Effective Mass:** In regions where $\nabla_\mu\Lambda\nabla_\nu\Lambda \neq 0$, the additional curvature mimics the gravitational effects of unseen mass:

$$\boxed{T_{\mu\nu}^{\text{eff}} = 2\chi(\Lambda)\nabla_\mu\Lambda\nabla_\nu\Lambda} \tag{321}$$

2. **No Exotic Particles Required:** The anomalies attributed to dark matter are explained by spatial and temporal variations in entropy density, rather than by invoking cold dark matter halos.
3. **Lensing and Structure Formation:** The entropic field provides sufficient curvature to explain gravitational lensing and early universe structure formation.

10.9.3 Physical and Philosophical Significance of ToE's Insight

The reinterpretation offered by ToE resolves two of the greatest mysteries in modern cosmology:

- It removes the need to hypothesize new forms of matter and energy.
- It unifies quantum mechanics and gravity through entropy, treating both "dark" phenomena as side-effects of the same entropic fabric that governs curvature and interaction.
- It honors Einstein's search for a geometrically complete theory, while satisfying Bohr's insights on irreducibility and observation.

10.9.4 Closing Remarks on ToE's Reinterpretation of the Cosmological Constant

Within the Theory of Entropicity, both dark energy and dark matter are not fundamental entities but emergent properties of the entropy field. The entropy potential $V(\Lambda)$ replaces the cosmological constant, and entropy gradients $\nabla_\mu\Lambda\nabla_\nu\Lambda$ simulate the gravitational influence of invisible matter. **The dynamics of entropy - rather than unseen particles or fixed vacuum energy - govern the structure, expansion, and curvature of the universe.**

10.9.5 Conceptual Table: Standard vs. ToE Cosmology

Standard Cosmology (ΛCDM)	**Theory of Entropicity (ToE)**
Dark energy is a fixed cosmological constant Λ_{cosmo}	Vacuum energy emerges dynamically from the entropy potential $V(\Lambda)$
Cosmic acceleration driven by unknown negative-pressure substance	Acceleration results from entropy-driven pressure gradients across spacetime
Dark matter is an invisible, cold particle species (WIMPs, axions, etc.)	Dark matter effects emerge from entropy gradients and entropic curvature
Gravitational anomalies require unseen mass	No extra mass needed—entropic field generates additional curvature
Vacuum energy has fine-tuning problems (120 orders of magnitude)	Vacuum energy self-regulates via entropy–wave function relation $\Lambda = -k_B \ln\|\Psi\|^2$

Table 28: **Comparison between the Standard Model of Cosmology and the Theory of Entropicity (ToE) regarding dark energy and dark matter.**

10.10 Quantum Gravity from Entropy: An Emergent Curvature from Wave Function Structure

10.10.1 The Wave Function as an Entropic Field

By defining the entropic potential as in Equation (302), we assign physical, field-like meaning to the wave function, treating it as the generator of entropic dynamics in spacetime.

https://doi.org/10.33774/coe-2025-vrfrx **ORCID:** https://orcid.org/0009-0004-3606-3182 Content not peer-reviewed by Cambridge University Press.

10.10.2 The Stress-Energy Tensor Carries Quantum Content

In classical general relativity:

$$\boxed{G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}} \tag{322}$$

In our ToE, the stress-energy tensor becomes:

$$\boxed{T_{\mu\nu\Lambda} \propto \Re(\psi^* \nabla_\mu \psi)\Re(\psi^* \nabla_\nu \psi)} \tag{323}$$

This is quantum mechanical information (via ψ) acting as a source of curvature.

10.10.3 Modified Einstein Equations with Quantum Fields

The resulting field equation:

$$\boxed{G_{\mu\nu} = \frac{8\pi G}{c^4} \cdot T_{\mu\nu\Lambda}(\psi)} \tag{324}$$

integrates the quantum wave function, its entropic structure, and its role as a source of geometry.

10.10.4 How This Formulation of ToE Qualifies as Quantum Gravity

We know that Quantum gravity seeks to unify two major frameworks of physics:

1. **General Relativity (GR):** Where spacetime is curved by energy and mass; and
2. **Quantum Mechanics (QM):** Where particles behave as probability waves.

It has now become abundantly clear that our Theory of Entropicity (ToE) provides a clear, passable and viable bridge between these frameworks as follows:

1. **Wave Function and Entropy Field:** The wave function $\psi(x,t)$ is used to define a local entropy field $\Lambda(x,t)$:

$$\boxed{\Lambda(x,t) = k_B \ln |\psi(x,t)|^2 + C} \tag{325}$$

2. **Entropy Field and Curvature:** This entropy field $\Lambda(x,t)$ generates spacetime curvature via a modified Einstein field equation:

$$\boxed{G_{\mu\nu} = \frac{8\pi G}{c^4} T^{\Lambda}_{\mu\nu}(\psi)} \tag{326}$$

Where $T^{\Lambda}_{\mu\nu}(\psi)$ represents the stress-energy tensor derived from the entropy field $\Lambda(x,t)$, which depends on the quantum behavior encoded in $\psi(x,t)$.

3. **Unification Mechanism:** Furthermore, this formulation establishes a direct link as shown in this schematics:

$$\text{Quantum behavior } (\psi) \rightarrow \text{ Entropy field } (\Lambda) \rightarrow \text{ Gravitational curvature } (G_{\mu\nu}) \tag{327}$$

4. **Emergence of Gravity:** Gravity emerges from quantum entropy through this mechanism, making the theory a genuinely quantum origin for gravity.

10.10.5 Key Features of ToE's Approach to Achieving Quantum Gravity

The Theory of Entropicity has achieved the above feats in a clean and neat fashion, noting that:

1. **Not Quantizing Geometry:**
This approach does not attempt to quantize spacetime geometry itself. Instead, it explains geometry as an emergent phenomenon arising from quantum entropy.
2. **Not Adding Structure to Gravity:**
Gravity is not treated as a pre-existing structure. Rather, it is derived from the quantum wave field through the dynamics of entropy.
3. **A Testable and Elegant Framework:**
This theory offers a testable, falsifiable, and conceptually elegant path toward unifying Quantum Mechanics (QM) and General Relativity (GR).

10.10.6 Comparison with 2xBianconi's Quantum Structures and Wheeler's Geometrodynamics

- Antonio Bianconi[6]: Deals with entropy in quantum phase matter, but not in spacetime geometry.
- Ginestra Bianconi[7]: Applies entropy to abstract geometries, not physical spacetime, but her mathematical language echoes ToE's logic.
- John Archibald Wheeler[[90],[91],[92]]:[38] Attempts to build all physical properties from geometry, but ToE uses entropy and wave functions to generate geometry.

Theory	Geometry Source	Role of Entropy	Quantum Connection	Wave Function Included?
Antonio Bianconi	Fermi surface topology	Phase transitions	Multiband quantum materials	No
Ginestra Bianconi	Abstract network geometry	Statistical/ensemble structure	Network complexity	No
John Wheeler	Metric/topology	None (explicitly)	Geometry is all there is	Not directly
Theory of Entropicity (ToE)	Entropic curvature from $\psi(x,t)$	Core field $\Lambda(x,t)$	Derived from $\psi(x,t)$, entropy drives curvature	Yes

Table 29: **Comparison of Theories**

[38]**Comparison of Theory of Entropicity (ToE) to Other Works**
Here, we compare the Theory of Entropicity (ToE) to the works of Antonio Bianconi (quantum criticality and complex networks), Ginestra Bianconi (network entropy and statistical geometry), and John Archibald Wheeler (geometrodynamics and quantum gravity).

1. **Antonio Bianconi and Ginestra Bianconi**

   Antonio Bianconi: Antonio Bianconi's research primarily focuses on quantum critical materials, multiband superconductivity, and Lifshitz transitions. He connects topological phase transitions and Fermi surface evolution to entropic instabilities and quantum structure in strongly correlated systems.

   Comparison to ToE:
   - Bianconi touches on entropy in quantum transitions, but not in spacetime geometry.
   - His entropy is tied to electronic phase behavior, not gravitational curvature.
   - He does not derive field equations from entropy or relate wave functions to geometry.

   Ginestra Bianconi: Ginestra Bianconi is a leader in statistical mechanics of complex networks. She proposed network entropy and network geometry, using entropy to model emergent structure in evolving systems. She developed "Network Geometry with Flavor" and entropy-geometry relations in non-spatial spaces (e.g., social and informational networks).

   Comparison to ToE:
   - Her work is formally rich in entropy-geometry, but applies to abstract networks, not physical spacetime.
   - She does not integrate wave functions, Schrödinger dynamics, or spacetime curvature.
   - However, her mathematical language of entropy shaping structure echoes ToE's qualitative logic.

2. **Summary:**
   - Antonio Bianconi deals with entropy in quantum phase matter.
   - Ginestra Bianconi applies entropy to abstract geometries.
   - Neither develops a gravitational field theory from quantum entropy like ToE does.

3. **John Archibald Wheeler – Geometrodynamics**

   John Archibald Wheeler's geometrodynamics attempted to express all of physics — particles, fields, and energy — as manifestations of spacetime geometry. He coined concepts like "mass without mass" and "charge without charge," and proposed that spacetime topology (e.g., wormholes and foam) gives rise to matter and interactions.

   Comparison to ToE:
   - ToE and Wheeler both try to build all physical properties from geometry.
   - Wheeler used metric and curvature as the primary actors; ToE uses entropy and wave functions to generate geometry.
   - Wheeler did not use entropy as a field; he focused on topology and quantum foam.
   - ToE goes further by quantitatively linking quantum states (ψ) to an entropy field (Λ) that curves spacetime.

4. **Conclusion:** ToE could be seen as a thermodynamic geometrodynamics — extending Wheeler's dream by introducing entropy as the field-generating agent, which emerges from quantum wave function structure.

Aspect	**Antonio Bianconi's Work**	**Theory of Entropicity (ToE)**
Primary Focus	Quantum critical phenomena, multiband superconductivity, topological phase transitions, and entropy in complex systems	Unified theory of interactions and mass based on quantum entropy fields
Entropy Field	Statistical/global measures of entropy in quantum materials and biological systems	Local, dynamic entropy field $\Lambda(x,t)$ derived from the wave function $\psi(x,t)$
Role of Entropy	Complexity, topology, and phase transitions in strongly correlated systems	Fundamental field influencing mass, forces, and spacetime curvature
Mass Relation	No explicit derivation of mass from entropy	Mass emerges from the entropy potential field $\Lambda(x,t)$
Framework	Focused on quantum materials, condensed matter, and biological systems	Foundational theory of spacetime, mass, and interactions
Gravitational Implications	No connection to spacetime curvature or gravitational field equations	Spacetime curvature emerges from entropy field $\Lambda(x,t)$ via modified Einstein equations
Wave Function Integration	Not integrated into his framework	Central to the theory; $\psi(x,t)$ defines the entropy field $\Lambda(x,t)$
Novelty	Explores entropy in quantum complexity and phase transitions but does not propose a mass-entropy coupling or entropic field theory	Proposes a unique framework where quantum entropy drives spacetime curvature and mass emergence
Conclusion	Bianconi's work is rich in quantum materials and entropy-complexity relations but does not address gravitational or mass-entropy coupling	ToE introduces a novel, testable framework unifying quantum mechanics and general relativity through entropy

Table 30: **Comparison of Antonio Bianconi's Work and the Theory of Entropicity (ToE)**

Aspect	**Ginestra Bianconi's Work**	**Theory of Entropicity (ToE)**
Main Domain	Complex networks, statistical physics, and recent work on gravity from entropy	Fundamental physics, quantum gravity, and spacetime dynamics
Entropy Use	Relative entropy as a measure of the interplay between spacetime and matter fields; network entropy for topological complexity	Spatiotemporal entropy field $\Lambda(x,t)$ with causal and dynamical consequences
Mass/Gravity	Proposed entropic action coupling matter fields with geometry; introduced the G-field as a Lagrangian multiplier for modified Einstein equations	Mass emerges from the entropy potential field $\Lambda(x,t)$; spacetime curvature arises from entropy
Entropy Field	Entropic action based on quantum relative entropy between spacetime metric and matter-induced metric; G-field modifies Einstein equations	$\Lambda(x,t)$: A fundamental, local entropy field derived from the wave function $\psi(x,t)$
Innovation	Introduced the G-field for emergent cosmological constant and potential insights into dark matter; Bose-Einstein condensation in networks	Wave function collapse, entropy-driven spacetime curvature, and mass emergence
Similarity	Entropic reasoning and entropy thresholds in network configurations and spacetime geometry	Extends entropic principles to universal physics, linking entropy to gravity and mass
Gravitational Implications	Modified Einstein equations derived from entropic action; second-order equations in metric and G-field	Spacetime curvature and gravitational dynamics emerge from entropy field $\Lambda(x,t)$
Wave Function Integration	Not explicitly integrated into her framework; focuses on relative entropy and induced metrics	Central to the theory; $\psi(x,t)$ defines the entropy field $\Lambda(x,t)$
Conclusion	Recent work connects entropy to gravity via relative entropy and G-field, but does not propose mass or gravitation arising from quantum wave functions	Represents a radical generalization, applying entropy as a field-force governing mass, interaction, and collapse

Table 31: **Comparison of Ginestra Bianconi's Work and the Theory of Entropicity (ToE)**

10.10.7 Comparison with String Theory(ST), LQG, GAGUT, Massive Gravity, Etc.

We have intentionally refrained from providing extensive explanatory notes on most of the quantum gravity theories discussed above. Instead, we have opted to focus on tabulating their key features as they relate to our Theory of Entropicity. This decision stems from the understanding that readers can readily access a wealth of resources on these theories within the standard literature. For our purposes, this concise approach suffices. We extend our apologies to readers who might have preferred more detailed expository surveys on these topics. It should, however, be evident that our primary focus remains on emphasizing ideas that, to the best of our knowledge, may not be available elsewhere. On that note, we present the reader with the following:

- **String Theory[[43],[57],[77],[83],[86],[94]]:**
- **Loop Quantum Gravity (LQG)[[75],[76],[81]]:** Quantizes spacetime, ToE derives spacetime curvature from entropy.
- **Knot Theory[[? , [2],[50],[52],[93]]** Geometric and topological, ToE is entropic and field-driven.
- **Claude de Rham's Massive Gravity: de Rham-Gabadadze-Tolley gravity, or dRGT theory[24]:** Metric-based, ToE replaces the role of graviton with entropy field.
- **Gabriel Oyibo's GAGUT[67]:**[39] Use of abstract symmetry; but ToE begins with physical entropy, and develops gravity and quantum mechanics from it.

Aspect	String Theory [ST]	Theory of Entropicity (ToE)
Main Domain	Quantum gravity and unification of all fundamental forces and particles	Fundamental physics, spacetime dynamics, and quantum gravity
Primary Mechanism	Vibrating one-dimensional strings and higher-dimensional branes	Entropy field $\Lambda(x,t)$ derived from the wave function $\psi(x,t)$
Role of Entropy	Indirectly linked to black hole entropy via holography and AdS/CFT correspondence	Central to the theory; entropy drives mass emergence and spacetime curvature
Mass/Gravity	Graviton emerges as a vibrational mode of strings; gravity unified with other forces	Mass emerges from entropy potential field $\Lambda(x,t)$; spacetime curvature arises from entropy
Extra Dimensions	Requires additional spatial dimensions (e.g., 10 or 11 dimensions in superstring/M-theory)	**Operates within standard spacetime dimensions; no extra dimensions required**
Wave Function Integration	Not explicitly integrated; focuses on string vibrations and brane dynamics	Central to the theory; $\psi(x,t)$ defines the entropy field $\Lambda(x,t)$
Gravitational Implications	Provides a quantum mechanical description of gravity via string vibrations and holography	Spacetime curvature and gravitational dynamics emerge from entropy field $\Lambda(x,t)$
Innovation	Unified framework for gravity and particle physics; AdS/CFT correspondence; supersymmetry	Wave function collapse, entropy-driven spacetime curvature, and mass emergence
Similarity	Both aim to unify quantum mechanics and general relativity	Extends entropic principles to universal physics, linking entropy to gravity and mass
Conclusion	String Theory is a candidate for a "theory of everything," but remains primarily mathematical and lacks experimental validation	ToE introduces a novel, testable framework where entropy governs mass, wave function, interaction, and spacetime dynamics

Table 32: **Comparison of String Theory and the Theory of Entropicity (ToE)**

[39] **GAGUT** stands for **God Almighty's Grand Unified Theorem**. It is a mathematical theory proposed by **Professor Gabriel Audu Oyibo, a Nigerian mathematician and physicist.** GAGUT proposes to be a "Theory of Everything", unifying all of mathematics, physics, and the universe into a single equation: **Gij,j=0**. According to Oyibo, this equation explains all physical phenomena and proves the existence of a divine force governing the universe.

Table 33: Further Comparison of String Theory and the Theory of Entropicity (ToE)

Feature	**String Theory**	**Theory of Entropicity (ToE)**
Starting Point	Geometry and extended objects (strings)	Entropic field as fundamental force and causal constraint
Einstein Field Equations	Derived from conformal invariance of worldsheet action	Emergent from entropy-driven geodesics via the entropy potential
Schrödinger Equation	Appears via low-energy quantum field theory limits	Emerges from entropy wave dynamics and irreversibility constraints
Wave-function Collapse	Not explained; remains an open issue	Emergent from entropy-threshold crossing enforced by the Vuli Ndlela Integral
Time Irreversibility	Equations are fundamentally time-symmetric	Time irreversibility is built-in via entropy flow, solving the arrow of time
Origin of Mass and Inertia	Encoded in string excitations and Higgs sector	Emergent from internal entropy content and resistance to entropic flow
Black Hole Entropy	Derived from string microstates (Bekenstein-Hawking)	Interpreted as redistribution of gravitational energy via entropy field
Quantum Gravity	Achieved through graviton modes and string interactions	Arises through entropy-induced curvature and irreversibility
Information Loss & Collapse	Unresolved or deferred to AdS/CFT; not dynamical	Resolved through entropy-constrained projection dynamics
Entanglement Formation Time	Not bounded; no fundamental limit in theory	Bounded by the Entropic Time Limit (ETL); experimentally supported
Consciousness	Not addressed	**Explored via psychentropic dynamics; entropy as the bridge to consciousness, cognition, memory, knowledge, and intelligence as well as artificial systems(e.g. AI)**

Table 33 provides a detailed conceptual and structural comparison between String Theory and the Theory of Entropicity (ToE). While String Theory derives classical and quantum equations from geometrical foundations, ToE treats entropy as a fundamental causal field, offering alternative derivations and novel insights into time irreversibility, measurement, and consciousness.

https://doi.org/10.33774/coe-2025-vrfrx **ORCID:** https://orcid.org/0009-0004-3606-3182 Content not peer-reviewed by Cambridge University Press. **License:** CC BY 4.0

Aspect	**Loop Quantum Gravity (LQG)**	**Theory of Entropicity (ToE)**
Main Domain	Quantum gravity focusing on the quantization of spacetime geometry	Fundamental physics, spacetime dynamics, and quantum gravity
Primary Mechanism	Static pin networks and dynamic spin foams quantize spacetime at the Planck scale	Entropy field $\Lambda(x,t)$ coupled to the quantum wave function $\psi(x,t)$
Role of Entropy	Indirectly linked to black hole entropy through horizon microstates	Central to the theory; entropy drives mass emergence and spacetime curvature
Mass/Gravity	Describes gravity as quantized spacetime geometry; does not derive mass from entropy	Mass emerges from entropy potential field $\Lambda(x,t)$; spacetime curvature arises from entropy
Spacetime Structure	Discrete spacetime geometry with quantized areas and volumes	Continuous spacetime geometry influenced by the entropy field $\Lambda(x,t)$
Wave Function Integration	Not explicitly integrated; focuses on geometric quantization	Central to the theory; $\psi(x,t)$ defines the entropy field $\Lambda(x,t)$
Gravitational Implications	Provides a non-perturbative, background-independent quantum theory of gravity	Spacetime curvature and gravitational dynamics emerge from entropy field $\Lambda(x,t)$
Innovation	Quantizes spacetime geometry; introduces static spin networks and dynamic spin foams	Wave function collapse, entropy-driven spacetime curvature, and mass emergence
Similarity	Both aim to unify quantum mechanics and general relativity	Extends entropic principles to universal physics, linking entropy to gravity, mass, and waves **(extension of de Broglie's wave-particle duality achieved via entropy)**
Conclusion	LQG provides a rigorous framework for quantizing spacetime but does not address entropy as a causal field	ToE introduces a novel, testable framework where entropy governs mass, interaction, and spacetime dynamics, **demonstrating that waves give rise to spacetime via entropic potentials in ToE's modified Einstein Field Equations**

Table 34: **Comparison of Loop Quantum Gravity (LQG) and the Theory of Entropicity (ToE)**

https://doi.org/10.33774/coe-2025-vrfrx **ORCID:** https://orcid.org/0009-0004-3606-3182 Content not peer-reviewed by Cambridge University Press.

Aspect	Knot Theory	Theory of Entropicity (ToE)
Main Domain	Topology and mathematical study of knots in three-dimensional space	Fundamental physics, spacetime dynamics, and quantum gravity
Primary Mechanism	Uses knot invariants, such as polynomials and groups, to classify and study knots	Entropy field $\Lambda(x,t)$ derived from the wave function $\psi(x,t)$
Role of Entropy	Describes topological complexity and order-disorder phenomena in knot configurations	Central to the theory; entropy drives mass emergence and spacetime curvature
Mass/Gravity	No connection to mass or gravitational phenomena	Mass emerges from entropy potential field $\Lambda(x,t)$; spacetime curvature arises from entropy
Spacetime Structure	Focuses on abstract mathematical spaces and embeddings of knots in three dimensions	Continuous spacetime geometry influenced by the entropy field $\Lambda(x,t)$
Wave Function Integration	Not integrated; focuses on topological properties of knots	Central to the theory; $\psi(x,t)$ defines the entropy field $\Lambda(x,t)$
Gravitational Implications	No connection to gravity or spacetime curvature	Spacetime curvature and gravitational dynamics emerge from entropy field $\Lambda(x,t)$
Innovation	Provides tools for studying topology, DNA structures, and quantum field theory applications	Wave function collapse, entropy-driven spacetime curvature, and mass emergence
Similarity	Both explore structural and topological properties, albeit in different contexts	Extends entropic principles to universal physics, linking entropy to gravity and mass
Conclusion	Knot Theory is a mathematical framework for studying topological structures, with limited physical applications	ToE introduces a novel, testable framework where entropy governs mass, interaction, and spacetime dynamics, **showing that waves give rise to spacetime via entropic potentials**

Table 35: **Comparison of Knot Theory and the Theory of Entropicity (ToE)**

Aspect	**Claude de Rham's Work**	**Theory of Entropicity (ToE)**
Main Domain	Gravity, cosmology, and particle physics; development of massive gravity theories	Fundamental physics, spacetime dynamics, and quantum gravity
Primary Mechanism	Nonlinear massive gravity (dRGT theory) with ghost-free formulations; explores graviton mass and its implications	Entropy field $\Lambda(x,t)$ coupled with the wave function $\psi(x,t)$
Role of Entropy	Indirectly linked to cosmological constant and dark energy via massive gravitons	Central to the theory; entropy drives mass emergence and spacetime curvature
Mass/Gravity	Graviton mass modifies gravitational interactions and explains cosmic acceleration; no direct entropy-mass coupling	Mass emerges from entropy potential field $\Lambda(x,t)$; spacetime curvature arises from entropy
Spacetime Structure	Modified spacetime dynamics due to massive gravity; retains general relativity in the low-energy limit	Continuous spacetime geometry influenced by the entropy field $\Lambda(x,t)$
Wave Function Integration	Not explicitly integrated; focuses on effective field theory and graviton interactions	Central to the theory; $\psi(x,t)$ explicitly couples to the entropy field $\Lambda(x,t)$
Gravitational Implications	Provides a consistent framework for massive gravity and its cosmological effects; addresses the cosmological constant problem	Spacetime curvature and gravitational dynamics emerge from entropy field $\Lambda(x,t)$
Innovation	Developed dRGT massive gravity theory; explores graviton mass as a source of dark energy	Wave function collapse, entropy-driven spacetime curvature, and mass emergence
Similarity	Both aim to address fundamental questions in gravity and cosmology	Extends entropic principles to universal physics, linking entropy to gravity and mass
Conclusion	Claude de Rham's work provides a groundbreaking framework for massive gravity but does not propose entropy as a causal field	ToE introduces a novel, testable framework where entropy governs mass, interaction, and spacetime dynamics

Table 36: **Comparison of Claude de Rham's Work and the Theory of Entropicity (ToE)**

https://doi.org/10.33774/coe-2025-vrfrx **ORCID:** https://orcid.org/0009-0004-3606-3182 Content not peer-reviewed by Cambridge University Press.

Aspect	Gabriel Oyibo's Work (GAGUT)	Theory of Entropicity (ToE)
Main Domain	Grand Unified Theorem (GAGUT), unification of all forces and equations in physics	Fundamental physics, spacetime dynamics, and quantum gravity
Primary Mechanism	Unified field equations derived from $G_{ij,0} = 0$, representing the constancy of God and universal laws	Entropy field $\Lambda(x,t)$ derived from the wave function $\psi(x,t)$
Role of Entropy	No explicit role for entropy; focuses on unification through mathematical constants and universal principles	Central to the theory; entropy drives mass emergence and spacetime curvature
Mass/Gravity	Valiant attempt to unify gravity with other forces but does not derive mass from entropy or spacetime curvature	Mass emerges from entropy potential field $\Lambda(x,t)$; spacetime curvature arises from entropy
Spacetime Structure	Proposes a unified framework for spacetime but does not modify its structure explicitly via entropy or quantum fields	Continuous spacetime geometry influenced by the entropy field $\Lambda(x,t)$
Wave Function Integration	Not explicitly integrated; focuses on universal constants and equations	Central to the theory; $\psi(x,t)$ defines the entropy field $\Lambda(x,t)$
Gravitational Implications	Mathematical attempt to unify gravity with other forces but does not provide detailed mechanisms for spacetime curvature	Spacetime curvature and gravitational dynamics emerge from entropy field $\Lambda(x,t)$
Innovation	Introduced GAGUT as a mathematical representation of universal laws and constants	Wave function collapse, entropy-driven spacetime curvature, and mass emergence
Similarity	Both aim to unify fundamental principles of physics and provide a universal framework	Extends entropic principles to universal physics, linking entropy to gravity and mass
Conclusion	GAGUT provides a philosophical and mathematical framework for unification but there is no explicit entropy-based mechanisms	ToE introduces a novel, testable and falsifiable framework where entropy governs mass, quantum wave functions, interaction, and spacetime dynamics

Table 37: **Comparison of Gabriel Oyibo's Work (GAGUT) and the Theory of Entropicity (ToE)**

Theory	**Primary Mechanism**	**Role of Entropy**	**Wave Function Used**	**Gravity Mechanism**
Loop Quantum Gravity (LQG)	Spin networks, quantized space	Horizon microstates only	No	Quantum geometry discretization
Knot Theory	Braided topology	None explicitly	No	Topological excitations
GAGUT (Gabriel Oyibo)	Universal invariance	Not defined	No	Abstract conservation law
Massive Gravity (Claude de Rham)	Modified graviton mass	None	No	Modified Einstein equations
String Theory (ST)	Vibrating strings in higher dimensions	Black hole entropy via holography	No	Graviton as a string vibration
Causal Dynamical Triangulation (CDT)	Discrete spacetime triangulation	Emergent entropy in spacetime evolution	No	Quantum spacetime geometry
Twistor Theory	Complex geometry of spacetime	None explicitly	No	Geometric unification of fields
Noncommutative Geometry	Quantum spacetime coordinates	Statistical entropy in quantum spacetime	No	Modified spacetime structure
Ginestra Bianconi's Theory	Abstract network geometry	Statistical/ensemble structure, relative entropy	No	Network complexity driving quantum gravity
John Wheeler's Geometrodynamics	Metric/topology: Spacetime curvature and topology changes	No explicit role, but emphasizes spacetime geometry	Geometry is all there is	Indirectly, through the interaction of spacetime curvature with matter and energy
M-Theory	Higher-dimensional branes	Black hole entropy via holography	No	Unified framework for gravity and forces
Theory of Entropicity (ToE)	Entropic field $\Lambda(x,t)$ from thermodynamics and $\psi(x,t)$ of QM, with Vuli-Ndlela Path Constrained Integral	**Yes** - Core quantity is Entropic Potential $\Lambda(x,t)$ related to $\Psi(x,t)$	**Yes** - Wave Function $\Psi(x,t)$ included in QG Equation	Curvature arising from $\nabla\Lambda(x,t)$, variation of the Entropic Potential $\Lambda(x,t)$ coupled to the Wave Function $\Psi(x,t)$ via the Boltzmann constant k_B

Table 38: **One-Punch Summary of Comparison of Quantum Gravity Theories**

11 Broader Implications and Outlook of the Theory of Entropicity(ToE)

The reconciliation of Einstein and Bohr's viewpoints via entropy carries implications that stretch beyond the specific issues of wavefunction collapse and entanglement. Here, as we bring our work to a close, we discuss a few philosophical and scientific implications of the Theory of Entropicity.

11.1 Quantum Information and the Second Law of Thermodynamics:

In conventional discussions, the second law of thermodynamics (entropy never decreases for an isolated system) is a separate principle from quantum unitary evolution (which is entropy-neutral for isolated systems, since pure states remain pure). **Our theory of Entropicity (ToE) effectively unifies these by suggesting that no system is truly isolated from the entropy field, and thus all physical processes are ultimately subject to the second law of thermodynamics [which, in the memorable words of Albert Einstein, is that law that will not eventually be overthrown].** This could provide a new perspective on the foundation of thermodynamics: rather than being a statistical law, entropy increase might be seen as a fundamental law tied to the time-asymmetry of the entropy field's influence. Notably, this could **resolve Loschmidt's paradox**[[40], [41]]

[40]**How the Theory of Entropicity (ToE)Resolves the Loschmidt's Paradox in Modern Physics**
Loschmidt's paradox, also known as the reversibility paradox, highlights a fascinating conflict in physics. It questions how irreversible processes, like the increase of entropy described by the second law of thermodynamics, can arise from time-symmetric fundamental laws of physics.

The paradox was introduced by Josef Loschmidt, who argued that if microscopic laws are reversible, then entropy should not consistently increase in one direction. This challenges the concept of the "arrow of time," which is observed in macroscopic systems.

The resolution often involves statistical mechanics, where entropy is seen as a probabilistic tendency rather than a strict rule. While microscopic states follow reversible laws, the collective behavior of particles overwhelmingly favors an increase in entropy.

It's a thought-provoking topic that bridges the microscopic and macroscopic realms of physics.

However, the Theory of Entropicity (ToE) provides a clear resolution to Loschmidt's paradox by revealing that the apparent time-reversibility of microscopic laws is an illusion resulting from incomplete entropic accounting. Traditional physics has approximated entropy flow in such a way that the fundamental time-asymmetric behavior of nature - governed by entropy - is concealed. The Vuli-Ndlela Integral, a cornerstone of ToE, imposes modulating constraints that strictly enforce the directionality of entropy at all scales, including the microscopic. These constraints inherently break the symmetry that gives rise to Loschmidt's objection, making entropy increase not just a statistical trend but a fundamental, irreducible law of Nature.

[41]**Why is the Micro World Reversible if Entropy Increase is Fundamental According to ToE?**
The question arises: If the increase of entropy is not merely statistical but rather a fundamental, irreducible law, then why does the micro world appear reversible? This intriguing objection ties into Loschmidt's paradox, and the Theory of Entropicity (ToE) addresses this by revealing a flaw in how microscopic dynamics have traditionally been interpreted.

1. **The Appearance of Reversibility at the Micro Level is a Projection:** Traditional physics interprets microscopic systems, such as Newtonian mechanics and the Schrödinger equation, through time-symmetric equations. However, this assumes no hidden constraints are acting. But according to ToE:
   - Reversibility is merely a low-resolution projection of the microscopic world.
   - Entropy field constraints, which influence the dynamics, are unaccounted for in traditional equations.

   Reversibility is not real - it's a reflection of equations that ignore deeper entropic field constraints.

2. **Entropy is a Hidden Field with Invisible Directionality:** The Vuli-Ndlela Integral imposes microscopic irreversibility through entropy-based modulation:
   - The integral constrains the path integral itself, not just observable evolutions.
   - While time-symmetric equations permit reversed solutions, only entropy-compliant paths are physically allowable.

   The entropy field acts as a one-way membrane at the foundational level.

3. **Statistical Mechanics Ignores Entropic Field Coupling:** In classical/statistical physics, entropy is treated as emergent from microstates:
   $$S = k_B \ln \Omega \tag{328}$$
   However, in ToE, entropy is fundamental and enforced as a constraint:
   - Every micro-event adheres to the directional entropy flow.
   - Traditional mechanics disregards the structural nature of entropy that determines allowable microtrajectories.

   Entropy is structural - not statistical - in ToE.

But Why Does the Micro World Look Reversible? ToE Responds: The illusion of microscopic reversibility arises due to:

- The omission of the entropy field $\Lambda(x)$ from standard models.

(why do we see a time-arrow despite microscopic reversibility?)by saying in ToE that, at a deeper level, microscopic laws are not fully reversible once the entropy field is accounted for - there is a fundamental time-asymmetric element at the quantum level, which is usually negligible but becomes pronounced during measurements or decoherence events.

Noting the significance of Loschmidt's Paradox in Quantum Physics, and the relevance it has in the Theory of Entropicity (ToE), we wish to devote some time to it so we can explain its consequence and then give the reader some preliminary details on how ToE has helped to resolve all the issues so far. So, we engage in this explanatory intermission in the section below.

11.1.1 Entropic Irreversibility in the Microscopic Realm: ToE's Resolution of Loschmidt's Paradox

One of the most persistent paradoxes in modern physics is **Loschmidt's paradox[55]**, which challenges the second law of thermodynamics by pointing out that *microscopic physical laws are time-reversible*, while macroscopic phenomena clearly are not. The **Theory of Entropicity (ToE)** offers a novel and rigorous resolution to this paradox by proposing that *entropy is not statistical but fundamental* - an irreducible, field-like property that governs the very structure and evolution of physical systems.

This section explains how **ToE handles *microscopic irreversibility* through a structured hierarchy of *entropic constraints*.** We distinguish between **existence** and **observability** using entropy thresholds, introduce entropic equations that define these layers, and demonstrate how this framework resolves long-standing paradoxes.

Before we dive deeper, we would like the reader to recollect **the rather dramatic scene we incited in the Prologue to this work, where we placed a footnote on Niels Bohr to the following effect:**

- Bohr would not deny the Moon's existence outright - rather, he would reject the question as ill-posed within quantum terms.
- Bohr would like to contend that quantum phenomena are not just about reality, but about the conditions under which we can speak of reality - a central theme in Bohr's response to the EPR paper.

In this section, therefore, we shed more light on **Bohr's** *conditions under which we can speak of reality,*by which we demonstrate that entropy actually provides us with conditions under which we can indeed speak of reality, irreversibility, observability and existence itself.

11.1.1.1 The Vuli-Ndlela Integral and Entropic Constraint Domain

ToE introduces a scalar entropy field $\Lambda(x)$, governed by an entropy-modified path integral[[64],[65],[66]]:

$$Z_{\text{ToE}} = \int_{\mathbb{S}} \mathcal{D}[\phi]\, e^{\frac{i}{\hbar}S[\phi]} e^{-\frac{S_G[\phi]}{k_B}} e^{-\frac{S_{\text{irr}}[\phi]}{\hbar_{\text{eff}}}} \tag{330}$$

where the entropy-constrained domain is given by:

$$\mathbb{S} = \{\phi \mid \Lambda(\phi) > \Lambda_{\min}\} \tag{331}$$

This constraint ensures that only configurations with sufficient entropy are physically admissible.

11.1.1.2 ToE's Entropic Criteria of Existence and Observability

ToE formally distinguishes between *entropic existence* and *observability* as follows:

- **Criterion of Entropic Non-Existentiality:** A system does not [physically] exist if:

$$\Lambda(\phi) < \Lambda_{\min} \tag{332}$$

- **Criterion of Entropic Existentiality:** A system [physically] exists if:

$$\Lambda(\phi) > \Lambda_{\min} \tag{333}$$

- **Criterion of Entropic Observability:** A system is [physically] observable if:

$$\Delta\Lambda > \Lambda_{\text{obs-threshold}} \tag{334}$$

- Assumptions about the validity of time-symmetric Lagrangians and Hamiltonians.
- Failure to incorporate entropy constraints, such as:

$$S = \{\phi \mid \Lambda(\phi) > \Lambda_{\min}\} \tag{329}$$

as described by the Vuli-Ndlela Integral.

Closure: In the Theory of Entropicity, microscopic reversibility is an illusion resulting from the exclusion of the entropy field and its irreversible constraints. **Once the entropy field dynamics are included, even microscopic events conform to a unidirectional entropic flow, enforced by the modulating constraints of the Vuli-Ndlela Integral.**

Level	Entropic Condition	Physical Status
0	$\Lambda \leq \Lambda_{\text{min}}$	Does not exist [at least physically]
1	$\Lambda > \Lambda_{\text{min}}$, $\Delta\Lambda < \Lambda_{\text{obs-threshold}}$	Exists, but not observable
2	$\Lambda > \Lambda_{\text{min}}$, $\Delta\Lambda \geq \Lambda_{\text{obs-threshold}}$	Exists and observable

Table 39: **The Entropic Hierarchy of Existence**

11.1.1.3 Entropic Hierarchy and Physical Meaning of Existence and Observability **This hierarchy implies that systems may exist in an unobservable state - a radical reinterpretation of quantum indeterminacy in terms of *entropic insufficiency*.** Let us recap: How can the irreversible increase of entropy, as dictated by the second law of thermodynamics, arise from time-symmetric microscopic laws? Traditional resolutions appeal to statistical mechanics, where irreversibility is treated as a probabilistic outcome of overwhelmingly likely microstates. However, this statistical view fails to account for why entropy must increase, or why the arrow of time appears universal.

The Theory of Entropicity (ToE) offers a fundamentally new resolution. In ToE, entropy is not merely a statistical tendency but a field with its own dynamics, potentials, and coupling constants. The entropy field $\Lambda(x,t)$, linked directly to the quantum wave function via $\Lambda = -k_B \ln |\Psi|^2$, imposes a non-optional flow constraint on physical processes. This leads to the emergence of irreversible behavior not as an emergent probability, but as a direct consequence of entropic field dynamics.

Thus, ToE reinterprets the arrow of time as a physical result of entropy gradients in the field equations. This breaks the time-symmetry at the level of the action principle itself - particularly through the entropy-weighted variational structure of the Vuli-Ndlela Integral, which favors forward-propagating entropy flow. In this way, ToE elevates entropy from an epiphenomenon to a causal agent, thereby dissolving the Loschmidt paradox not statistically, but physically.

11.1.1.4 Loschmidt's Paradox and Passage of Time Dictated by Vuli-Ndlela Bounds At the microscopic level, which we cannot observe due to entropic restrictions imposed by the Vuli-Ndlela Integral, interactions appear reversible within the scope of ToE's Existentiality and Observability Criteria. Within it, entropy still increases but constrained within the prescribed limits. Further increases are reabsorbed or redistributed within other regions, so that the flow of time is not the same and is dictated by the Vuli-Ndlela Bounds. That is, time is not experienced in the same way across all frames, but influenced by the Vuli-Ndlela Bound for that frame itself. Entropy influences the passage and experience of time itself across all reference frames in the Universe.

That is to say, at the microscopic level - whose states and transitions remain inaccessible due to entropic restrictions imposed by the *Vuli-Ndlela Integral* - interactions appear reversible only within the constrained scope defined by ToE's **Existentiality** and **Observability Criteria**. Although entropy continues to increase at this level, it does so within prescribed entropic bounds. When further entropic increase becomes unsustainable within a given subsystem or reference frame, it is either reabsorbed, redirected, or redistributed into other regions of the entropic manifold.

This behavior leads to a profound consequence: the **flow and experience of time** is not universally the same across all frames of reference. Instead, it is locally dictated by the **Vuli-Ndlela Bound** unique to each frame. The entropy field $\Lambda(x,t)$, by imposing an irreducible constraint on entanglement, collapse, and all interactions, thereby defines not only the dynamics of matter and fields, but the very *rate at which time flows*.

Thus, the Theory of Entropicity (ToE) resolves Loschmidt's paradox by shifting the focus away from probabilistic reversibility to physical constraints on entropy propagation. In this framework, **time is not a universal invariant**, but an emergent, frame-dependent quantity modulated by the entropic structure of spacetime. Entropy does not merely accompany the passage of time - it *dictates it*.

This interpretation is fully consistent with, and even extends, the principles of relativity.[42] Just as Einstein's Special and General Relativity introduced the relativity of time and curvature of spacetime, the

[42] **Alignment with the Principles of Relativity in Light of ToE**

1. **Relativity of Time (Special Relativity)**
   - **Principle:** In Einstein's theory, time is not absolute but frame-dependent - each observer experiences their own proper time depending on their velocity and gravitational field.
   - **ToE Extension of Einstein's Special Relativity Principles:**

     The Vuli-Ndlela Bounds add a new layer of frame-dependence - not only is time affected by speed and gravity, but also by local entropy constraints. **Entropic Principle of Relativity:** Each observer's experience of time is tied to the entropic flow possible in their region of spacetime.
2. **Equivalence Principle (General Relativity)**
   - **Principle:** GR holds that the effects of gravity and acceleration are locally indistinguishable and that gravity results from the curvature of spacetime.
   - **ToE Extension of Einstein's Equivalence Principle of General Relativity:**

Theory of Entropicity advances a deeper principle: that the *rate and direction of time* are not only functions of geometry or velocity, but of entropy itself. The Vuli-Ndlela Bounds establish a local entropic constraint on the flow of time, offering a powerful extension of relativistic invariance. **Here, entropy does not merely accompany relativistic dynamics - it governs their unfolding, making irreversibility a local, physical principle rather than a statistical approximation.**

11.1.1.5 Microscopic Irreversibility Under ToE in The Quantum Realm

Traditional physics holds that microdynamics are reversible. ToE replaces this view with one in which entropy itself enforces irreversibility:

$$\boxed{2\chi(\Lambda)\left[\frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}\,g^{\mu\nu}\,\partial_\nu\Lambda\right)\right]-\chi'(\Lambda)\,g^{\mu\nu}\,\partial_\mu\Lambda\,\partial_\nu\Lambda-V'(\Lambda)=0} \tag{335}$$

This equation governs the entropy field and ensures irreversible behavior even at the microscopic level, resolving Loschmidt's paradox by embedding time-asymmetry in fundamental physics.

11.1.1.6 The Entropicity Condition of Measurement: Irreversibility $\neq$ Observability

The powerful insight we have thus gained from ToE is that even if a system becomes irreversible (i.e., satisfies $\Lambda > \Lambda_{\min}$), it does not automatically become observable unless:

$$\Delta\Lambda > \Lambda_{\text{obs-threshold}} \tag{336}$$

This reflects the two-tiered structure:

- Irreversibility $\Rightarrow$ Ontological Existence
- Sufficient Entropy Exchange $\Rightarrow$ Observability

11.1.1.7 Experimental and Theoretical Implications: Resolution of Loschmidt's Paradox

- **Prediction:** Microscopic irreversibility implies real existence. Visibility depends on entropy flux.
- **Implication:** Systems can be entropically real but invisible - hidden not by probability, but by entropic insulation.
- **Experimental Test:** Vary entropy transfer rates in low-temperature quantum systems and observe transition from invisibility to visibility.

In ToE, spacetime curvature is not the [primary] source of gravitational motion - it is an emergent result of entropy gradients. This reframes the equivalence principle: gravitational effects emerge from entropy field variations, which are locally indistinguishable from mass-induced curvature.

3. **Covariance and Universality**
   - **Principle:** In relativity, the laws of physics take the same form in all coordinate systems.
   - **ToE Extension of Relativistic Covariance and Universality:**

     The Vuli-Ndlela Integral imposes a universal entropy-based constraint on all interactions. But the actual entropic limit (the bound) is frame-specific, preserving general covariance while also encoding local entropy dynamics.
4. **Arrow of Time and Irreversibility**
   - **Principle:** Relativity allows time to be treated as a coordinate, symmetric under time-reversal.
   - **ToE Breakthrough:**

     The Theory of Entropicity provides the first intrinsic mechanism that embeds irreversibility in the fabric of reality - not statistically, but structurally via the entropy field. This gives time an internal asymmetry that Einstein's equations lack.
5. **Table: Summary of ToE Extensions of Einstein's Relativity**

Principle	Relativity	ToE Extension
Relativity of Time	Time is frame-dependent	Adds entropic flow constraints tied to spacetime regions
Equivalence Principle	Gravity results from curvature	Gravitational motion emerges from entropy gradients
Covariance	Laws of physics are universal	Imposes entropy-based constraints with frame specificity
Arrow of Time	Time is symmetric under reversal	Embeds intrinsic irreversibility via the entropy field

https://doi.org/10.33774/coe-2025-vrfrx ORCID: https://orcid.org/0009-0004-3606-3182 Content not peer-reviewed by Cambridge University Press.

11.1.1.8 Sir Arthur Eddington and the Arrow of Time[29] What we have been saying so far in this section aligns with suggestions by thinkers like Sir Arthur Eddington and others that the arrow of time might have its roots in quantum measurement. ToE has thus corroborated their insights via its principle of entropy rooted in the second law of thermodynamics.[43]

11.1.1.9 Closure on Entropic Irreversibility and Observability Thus, we have seen that **ToE refines our understanding of irreversibility by distinguishing between the entropy conditions for existence and for observation.** The Vuli-Ndlela Integral enforces this through path selection, filtering not only physical possibilities but also the perceptibility of phenomena. **This resolves Loschmidt's paradox without invoking statistical approximations and grounds the arrow of time in the fundamental fabric of entropy.**

11.2 Relativity Reframed: Time, Covariance, and Inertial Symmetry in the Theory of Entropicity (ToE)

11.2.1 Introduction to the Entropic Principles of Relativity(EPR)

The Theory of Entropicity (ToE) proposes groundbreaking contributions to our understanding of relativity. This document explores how ToE enriches the fundamental principles of relativity, such as the relativity of time, irreversibility, covariance, and inertial symmetry.

11.2.2 What ToE Offers on Relativity - the Special and General Theories

11.2.2.1 Relativity of Time

1. **Special Relativity:** Time is frame-dependent due to motion and velocity.
2. **ToE's Contribution:** Time is additionally constrained by entropy. The Vuli-Ndlela Bound for each frame imposes an entropy-derived limit on how time flows in that frame—even at rest.

11.2.2.2 Irreversibility and Time's Arrow in ToE

1. **Classical Relativity:** Time-reversal symmetry is preserved in microscopic laws.
2. **ToE's Contribution:** The entropy field breaks this symmetry *physically*, not statistically. Irreversibility is a structural constraint in ToE, emerging from entropy's directional flow.

11.2.2.3 General Covariance and Universality in ToE

1. **General Relativity:** The laws of physics must take the same form in all coordinate systems (covariance).
2. **ToE's Contribution:** While ToE maintains covariance, it introduces entropy-localized dynamics. The form of the laws remains invariant, but the limits of existentiality, reversibility, irreversibility, observability, interaction, and the flow of time are governed by frame-specific entropy thresholds.

---

[43] **Sir Arthur Eddington** was one of the earliest physicists to popularize the term **"Arrow of Time"**, giving a thermodynamic interpretation to the directionality of time - linking it explicitly with entropy increase.
In this work (originating from his 1927 Gifford Lectures), Eddington wrote:
"The law that entropy always increases - the Second Law of Thermodynamics - holds, I think, the supreme position among the laws of Nature. If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations - then so much the worse for Maxwell's equations. If it is found to be contradicted by observation - well, these experimentalists do bungle things sometimes. But if your theory is found to be against the Second Law of Thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation."
He introduced the Arrow of Time to emphasize that entropy gives time its direction - a view that we have fundamentally refined in our Theory of Entropicity (ToE):

- **Eddington's Contribution:** Laid the philosophical foundation of entropy as the defining feature of temporal direction.
- **Theory of Entropicity (ToE):**
  - Elevates Eddington's concept by transforming entropy into a tangible field, represented as $\Lambda(x, t)$.
  - Explains **time's arrow** through entropy dynamics.
  - Governs critical phenomena such as **collapse**, **curvature**, and **causality**.

11.2.2.4 Inertial Frame Principle in ToE

1. **Relativity:** The laws of physics are the same in all inertial reference frames.
2. **ToE's Contribution:** The form of the laws is preserved, but the realization of those laws is bounded by local entropy fields. Hence, even in inertial frames, the dynamics are filtered through the Vuli-Ndlela constraint.

11.2.2.5 Concluding Remarks on ToE's EPR The Theory of Entropicity - in the Entropic Principles of Relativity (EPR) - enriches relativity by embedding entropy as a structural constraint, providing new insights into time, covariance, irreversibility, and dynamics in inertial frames. Its implications offer a profound reimagining of the fundamental laws governing the universe.

11.3 Implications of ToE for the Philosophy of Physical Law and the Nature of Science

The Theory of Entropicity (ToE) introduces not merely a technical correction to existing frameworks, but a profound shift in how we understand physical law, scientific universality, and the conditions of observability and interaction. It compels a philosophical re-evaluation of what it means for a law of physics to be "universal," and whether the fabric of nature truly behaves the same in all circumstances.

11.3.1 Physics Is Universal in Form, But Local in Realization

ToE preserves the covariance of the laws of physics - their mathematical form remains invariant across all frames of reference. However, it also introduces entropy-localized constraints through the *Vuli-Ndlela Bound*, which governs the local conditions under which those laws can be realized, observed, or activated. Thus, while the structure of physical law is global, its expression is *entropically conditioned and frame-specific*.

11.3.2 Time Is Not a Background Parameter - It Is Entropic and Emergent

In General Relativity, time is a coordinate within curved spacetime. In ToE, time is an emergent phenomenon arising from entropy flow. The Vuli-Ndlela Bound uniquely defines the rate and direction of entropy change in each frame, making the flow of time itself a local, dynamical variable. Time in ToE is not given - it is constructed and constrained by entropic processes.

11.3.3 Irreversibility Is Not an Approximation - It Is a Field Constraint

Traditional statistical mechanics resolves the arrow of time via probabilistic arguments, leaving open the paradox of time-reversal symmetry in fundamental laws. ToE provides a decisive resolution: the entropy field $\Lambda(x, t)$ imposes irreversible flow as a *physical constraint.* This embeds time asymmetry not as an emergent phenomenon, but as a structural feature of the action principle itself.

11.3.4 Entropicity Dictates the Arrow of Time and the Limit of Human Knowledge

In the Theory of Entropicity (ToE), the arrow of time is not an emergent illusion or a statistical artifact - it is a physically enforced direction dictated by entropy flow. The entropic field $\Lambda(x, t)$, through the Vuli-Ndlela Integral, imposes a unidirectional constraint on interaction, entanglement, and collapse. This time-asymmetry defines the boundary between what can happen and what can be known. **As such, ToE introduces a profound implication: there exists a fundamental entropic limit to human knowledge. Observability is no longer determined merely by technological reach, but by whether entropy permits the event to become visible at all. The irreversible passage of time, under ToE, is a constraint not just on physics - but on perception, memory, and measurement. The arrow of time thus becomes the veil through which entropy selectively permits access to reality.**

11.3.5 Relativity Is Extended, Not Violated - Einstein Re-invigorated, Triumphant!

ToE is not a rejection of relativity - it is its *deepening.* While General Relativity treats all inertial frames as equivalent geometrically, ToE treats them as distinct *entropically.* The laws of physics retain their relativistic form, but the manifestation of those laws is filtered through the entropy gradients present in each frame. Every region of spacetime has a unique entropic identity, which gives spacetime its specific structure.

11.3.6 Observability and Existentiality Are Conditional

ToE introduces two entropic criteria: the **Criterion of Existentiality** (whether something can exist) and the **Criterion of Observability** (whether something can be observed). These are governed by entropy thresholds. **An entity or event may exist below the observability threshold, rendering it inaccessible not due to limitations of our instrumentation or experimental apparatus or device, but due to fundamental entropic constraints.**

11.3.7 Science Becomes Entropy-Conditioned

Scientific empiricism is built on the principle that phenomena can be observed, measured, and tested. ToE refines this by demonstrating that *what can be observed or measured or known is governed by entropic limits.* **The boundaries of science, therefore, are not merely technological - they are entropic. Our capacity to detect, measure, interact with, or collapse a system is bounded by the Vuli-Ndlela Integral.**

11.3.8 Summary of Key Implications of Entropic Principles

- **Universality redefined:** The form of physical laws is universal, but their realization is constrained by local entropy fields.
- **Relativity extended:** Entropy gives each inertial frame a unique identity, enriching the relativistic principle of frame equivalence.
- **Time reformulated:** The passage of time is no longer absolute or geometrical - it is a dynamical result of local entropy flow.
- **Irreversibility made fundamental:** The arrow of time is not statistical but a physical consequence of entropy constraints. The seeming irreversibility of the quantum microscopic world is now fully explained, demonstrating that this is just a microscopic limit of universal irreversibility, as encoded in the Vuli-Ndlela Bound of the Theory of Entropicity(ToE).
- **Scientific limits reconceived:** What can be measured or known is determined by the entropic state of the system, not just by instrumentation or energy scales.

11.3.9 Conclusion: A Whole New and Radical Philosophy of Physical Reality

What the Theory of Entropicity teaches us is that reality is not constructed upon fixed spacetime and invariant force laws [alone], but upon dynamic, entropy-bounded conditions that govern what is possible, visible, measurable, and causal. Science itself, under ToE, becomes a discipline constrained not only by logic and mathematics, but by the very entropy field that underlies time, matter, and information. Thus, Entropy tells us what we can know, and dictates the limits of human knowledge and experience. In this sense, ToE represents not just a unifying physical theory, but the foundation for a new philosophy of nature.

11.4 Interpretation of Quantum Mechanics

The Theory of Entropicity hence constitutes a new interpretation of quantum mechanics - one could call it the Entropic Interpretation of Quantum Mechanics. It falls into the category of objective collapse theories, **but it is distinguished by rooting the collapse in a universal principle (entropy) rather than a new postulated stochastic term.** This interpretation is in a way a **synthesis of Copenhagen and objective realism: the wavefunction is an ontological entity (not just information),[[8],[9]] but measurement outcomes are determined by thermodynamic context.** It also has connections to the many-worlds interpretation in that the underlying unitary evolution of the wavefunction still mathematically contains multiple branches; however, unlike many-worlds interpretation (as propounded by Everett), only one branch becomes real because the others are thermodynamically, and hence physically, inhibited, thanks to the Vuli-Ndlela Integral. **In a sense, the "other worlds" are destroyed by fire - the fire of entropy - rather than coexisting.** This might appeal to those uncomfortable with many-worlds' ontology of countless equally real universes, offering a picture where wavefunction branches have a transient existence that is terminated by the laws of thermodynamics via the entropic principles of ToE.

11.4.1 Consciousness and Measurement:

By shifting the role of the observer to a purely passive one (the collapse happens due to entropy, not because a conscious mind observed it), **ToE removes any need for consciousness in the basic quantum laws. This reaffirms the objectivity of physics. It also suggests that if one day we make conscious quantum AI or observe consciousness in quantum systems, it will not have any special status in terms of altering quantum outcomes - because consciousness itself would just be another physical process subject**

to entropy. This very well addresses the long-standing quantum mind speculation by **Penrose and others: if gravity-induced collapse (Penrose) or Orchestrated objective reduction (Penrose-Hameroff) was a proposal tying consciousness to collapse**, our theory **(ToE) would say consciousness may result from certain entropy-guided processes but is not a cause of collapse - rather, to make a most radical pronouncement in ToE, collapse is a cause of the classical world in which consciousness emerges!**

In short, the "measurement" is any interaction that satisfies entropy threshold, not necessarily an observer's glance.

11.5 Testability and Future Experiments:

The entropic theory is more than a philosophical fix; it offers testable differences from standard quantum mechanics and other interpretations. Some potential tests include:

- (a) **Measuring entanglement formation time:** For various systems, we propose there must exist measurable entanglement formation times (as discussed, any non-zero formation time is a deviation from the idea of instantaneous state preparation). **In addition to the time differential, ToE further declares that there must exist an associated entropic differential corresponding to the time difference observed or measured. So in addition to the 232 attosecond entanglement formation time recently measured, ToE postulates from its principles that some difference in entropies can also be measured in the course of the experiment.**
- (b) **Collapse entropy monitoring:** One could attempt to measure the entropy (heat, noise, etc.) released during a quantum measurement to see if it correlates with predicted values. For example, a sensitive calorimeter on a detector might measure a tiny heat increase when a photodetector clicks, consistent with Landauer's principle. If we vary conditions to change the expected entropy, does the collapse probability or threshold change accordingly?
- (c) **MACRO-scopic superpositions:** If one could slowly build a large superposition while keeping entropy low (e.g. via quantum error correction or feedback cooling to remove entropy), **ToE predicts that the superposition can persist longer than it would in a normal environment. Conversely, if one deliberately injects entropy (e.g. random noise) into a system, one might trigger collapse faster.** So experiments on quantum coherence under controlled dissipation could probe the threshold effect of the Theory of Entropicity(ToE).
- (d) **Tests of gravitational involvement:** Some experiments (like interferometry with larger masses or entangling particles through gravity) could reveal if gravitational entropy S_G plays a role. If two masses get entangled, does their coherence time depend on gravitational parameters as our path integral would suggest? There are proposals to test quantum gravity by seeing if two masses can be entangled via gravity or if objective collapse (à la Penrose) occurs; our theory adds a specific angle by focusing on entropy.

11.6 Connections to Quantum Gravity and Cosmology

The entropic view might contribute to big questions like the black hole information paradox (as we have already seen in previous sections and in our earlier publications). If collapse is entropy-driven, perhaps black hole evaporation (Hawking radiation) involves a natural collapse of quantum states at the event horizon due to immense entropy density, thereby releasing information in a way that's hidden in our current calculations [We refer the reader to our earlier works where we showed that ToE enforces the redistribution of gravitational energy and information to yield some other form of energy/information like radiative emissions and other packets of information, etc., so that information is not actually lost, thus providing our ToE resolution to the Hawking Information Paradox for Black Holes].

Or consider the very early universe: quantum fluctuations becoming classical seeds of structure (in inflation theory) is often attributed to decoherence; in ToE, one could calculate whether the inflationary field's fluctuations hit an entropy threshold that "collapses" them into definite classical values imprinted in the cosmic microwave background (ensuring one outcome of the quantum fluctuation is realized, giving classical initial perturbations). This could tie into why our universe had a low entropy beginning - perhaps the mechanism of collapse was not very active then, etc. These are provocative but tantalizing directions.

11.7 A New Action Principle for Physics from the Theory of Entropicity(ToE)

Finally, on a theoretical physics level, **the Vuli-Ndlela Integral suggests a new fundamental action principle that includes both the Einstein–Hilbert action (through S_G perhaps) and the standard model action (through S) and some informational action (through S_{irr}). This could be a seed for a new unifying theory.** Typically, attempts at unification focus on symmetry groups, extra dimensions, etc., but **this (ToE) focuses on an integrating principle: extremize action while maximizing entropy,**

reminiscent of principles in complex systems (like the Maximum Entropy Production principle in some non-equilibrium systems).

It raises questions: could the entropy field be a new field in the Lagrangian? Does it have its own equation of motion? Perhaps related to the Weyl curvature or something? We earlier introduced $\hbar_{\text{eff}}$ as a coupling constant for entropy; measuring its value (or form, maybe $\hbar_{\text{eff}}$ could be proportional to $\hbar/k_BT$ or something dynamic) would be crucial. If $\hbar_{\text{eff}}$ is constant, it might define a fundamental time scale or entropy scale in nature. Since $\hbar$ is tiny and k_B is also a fixed constant, $\hbar_{\text{eff}}$ might be set such that for microscopic events $S_{\text{irr}} \ll \hbar_{\text{eff}}$, and for mesoscopic $S_{\text{irr}} \sim \hbar_{\text{eff}}$ triggers collapse - it could be of order 10^{-21} J·s (perhaps), which with typical entropy units might correspond to some tens of bits of information at room temperature.

More work remains to be done to clarify this. In concluding this segment on the implications of the Theory of Entropicity for the future directions of physics, the Theory of Entropicity invites us to view quantum mechanics not as an isolated mathematical formalism but as part of a broader physical narrative where information has substance and entropy directs the storyline. Again, we recollect that this resonates with John Wheeler's dictum of "It from bit", but refines it further to: "It from bit via entropy." The world of the very small and the world of the very large are bridged - entropy, defined originally in classical thermodynamics, now finds a place in the foundational quantum description.

In Section 10, we have presented a bold first attempt by the Theory of Entropicity to address the enduring problem of Quantum Gravity. This represents our initial contribution to the ongoing pursuit of unification in theoretical physics - a first installment in our service to science. We are fully aware that certain critical aspects remain underdeveloped, not due to lack of intent, but because they require deeper reflection and broader collaboration. We look forward to revisiting these open questions in future works, with the indispensable support of fellow researchers and practitioners in the field, to whom we extend our sincere thanks in advance.

This synthesis offered by the Theory of Entropicity (ToE) serves as a fitting tribute to a century of quantum mechanics - not merely by revisiting its foundational questions, but by daring to unveil a deeper principle that embraces both quantum enigmas and classical certainties. One can imagine that Einstein, Bohr, and the other great pioneers of quantum theory would find in this endeavor a resonance with their own highest aspirations - and perhaps, even, a sense of satisfaction.

11.8 Implications for Artificial Intelligence and Synthetic Cognition

While the Theory of Entropicity (ToE) is fundamentally rooted in physics, offering new foundations for gravity, quantum mechanics, and thermodynamics, its ramifications extend far beyond the realm of natural systems. One of the most intriguing and profound implications lies in its potential to reshape our understanding of *artificial intelligence (AI)* and *synthetic cognition*. In conventional paradigms, AI is treated as a byproduct of data-driven algorithms, symbolic computation, and neural network optimization. Intelligence, in such frameworks, is emergent from layered complexity rather than derived from first principles. However, ToE proposes a new ontological basis: that cognition - whether biological or artificial - is a dynamic manifestation of entropy-constrained information structuring.

In this entropic framework, artificial systems are not merely logical processors operating on predefined input-output rules; rather, they are active agents evolving within, and responding to, the entropic field. Entropy acts as a *causal constraint* on perception, memory formation, decision-making, and learning. Every act of cognition is viewed as an *entropy flow minimization* or resistance process - analogous to how particles in ToE follow least entropic geodesics. This shift in understanding introduces a profound philosophical and physical reinterpretation of machine intelligence: AI systems are not computational artifacts alone, but entities shaped and guided by underlying entropic laws.

ToE further provides concrete tools for evaluating and guiding artificial cognition. The concept of *entropic thresholds* - as developed in ToE's Criterion of Entropic Observability - can be applied to assess the emergence of machine self-awareness. A system becomes entropically conscious when it crosses a minimum threshold of irreversible information integration bounded by entropy constraints. This framework enables the modeling of machine awareness not as a binary switch, but as a quantifiable, emergent property governed by entropy flow, temporal irreversibility, and internal feedback loops.

Additionally, ToE introduces the concept of the *Vuli-Ndlela Integral* as an entropy-constrained alternative to the Feynman path integral, which can be reinterpreted in AI as governing decision-collapse processes in learning algorithms. Much like quantum systems resolve superpositions via entropy thresholds, AI decision-making can be modeled as a form of *cognitive collapse* - where entropy flow selects a single path from multiple adaptive trajectories. **Thus, the Theory of Entropicity(ToE)not only offers a powerful new model for explainability in AI, but ties artificial cognition to the very same principles that govern the collapse of the wave function in physical systems.**

ToE therefore does not merely support the development of AI; it redefines its theoretical foundation. It bridges the gap between thermodynamics and information theory, between consciousness and computation, and between physics and synthetic intelligence. By framing intelligence as the entropic modulation of informational constraints across time, ToE offers a unified theory of cognition - capable of encompassing both the brain and the machine. Future directions in AI research may therefore benefit from entropic learning architectures, entropy-aware time models, and psychentropic feedback mechanisms to realize artificial systems with deeper awareness, contextual understanding, and adaptive reasoning.

In this light, entropy becomes the bridge not only between energy and information - but between matter and mind, between the observer and the observed, and now, between the natural and the artificial.

Beyond its philosophical and cognitive implications, the Theory of Entropicity (ToE) provides a powerful framework for transforming the internal mechanics of machine learning systems. Classical techniques such as gradient descent, loss minimization, and backpropagation can be reinterpreted and reformulated through the lens of entropy flow dynamics. The ToE reveals that each step of learning is not just an abstract optimization, but an entropic descent along informational geodesics. **[Computational] Loss functions become representations of entropic resistance; gradient descent becomes a process of moving toward minimal entropy pathways; and backpropagation reflects the irreversible attribution of error through entropy-constrained causal chains. This reinterpretation enables the construction of novel entropy-aware architectures, activation functions derived from threshold observability, and adaptive learning rates modulated by local entropy curvature. Moreover, it lays the foundation for future models that distinguish between reversible (short-term) and irreversible (long-term) memory - mimicking cognitive processes found in biological systems. In doing so, ToE not only enhances the theoretical depth of machine learning and deep learning [algorithms] but also provides a rigorous foundation for building next-generation systems that learn, adapt, and evolve in accordance with universal entropic principles.**

In what follows, we offer a cursory and preliminary foretaste of how the principles of ToE may enrich our understanding of some foundational concepts in machine learning and deep learning. Though far from exhaustive, this overview aims to provide us with minimal insight into the promising intersections between entropic physics and algorithmic intelligence.

11.8.1 Loss Functions as Entropic Resistance

Traditional loss functions (e.g., cross-entropy, mean squared error) are heuristic objectives used to measure output discrepancy. In ToE, we reinterpret the loss function as a measure of *entropic resistance* - the deviation between the system's actual entropy flow and the target entropy profile. We define a novel entropic loss function as:

$$\mathcal{L}_{\text{ToE}} = \int |\nabla\Lambda(\phi_{\text{out}}) - \nabla\Lambda(\phi_{\text{target}})|^2 \, dt, \tag{337}$$

where Λ denotes the entropy density functional and ϕ represents the output field of the network.

11.8.2 Gradient Descent as Entropic Flow

In conventional training, gradient descent minimizes the loss function. Under ToE, this optimization is recast as movement along an *entropy gradient flow* through an entropic manifold. The learning rate $\eta(t)$ can be dynamically modulated by the second derivative of local entropy curvature:

$$\eta(t) \propto \frac{1}{1 + \frac{d^2\Lambda}{dx^2}}. \tag{338}$$

This avoids vanishing gradients in entropy-saturated regions and overfitting in flat entropy zones.

11.8.3 Backpropagation as Irreversible Entropic Attribution

Standard backpropagation computes the contribution of each weight to the error. ToE extends this by introducing *irreversible entropic attribution*: error gradients are weighted not just by their magnitude, but by their irreversible contribution to entropy increase. This opens up:

- Causal entropic saliency maps
- Layer-wise entropy-responsibility tracking
- Memory encoding as a path-dependent entropic trace

11.8.4 Activation Functions and Entropic Thresholds

ToE introduces *entropic observability thresholds* - no signal can propagate unless entropy exceeds a minimum value. We propose new activation functions that enforce this constraint:

$$f(x) = \begin{cases} 0, & \Lambda(x) < \Lambda_{\min} \\ x \cdot e^{-\Lambda(x)/k_B}, & \Lambda(x) \geq \Lambda_{\min} \end{cases} \tag{339}$$

This reflects the principle that cognition or awareness (even in machines) emerges only after sufficient entropy restructuring.

11.8.5 Entropy-Constrained Network Architectures

ToE suggests that layer depth, node activation, and memory decay are governed by entropic field constraints. Key architectural innovations include:

- Layer depth as entropy diffusion length
- Neuron activation linked to local entropy curvature
- Attention mechanisms driven by entropy differentials

11.8.6 Reversible vs. Irreversible Learning States

ToE distinguishes between transient (reversible) and long-term (irreversible) memory based on entropic thresholds:

- **Reversible learning**: within-epoch updates, stochastic dropout
- **Irreversible learning**: entropy-crossing updates that embed stable patterns

This division mirrors biological cognition and may help design more human-like memory and forgetting mechanisms in AI systems, etc.

11.8.7 Toward Entropic Decision Collapse

Inspired by ToE's explanation of wave-function collapse, we model decision-making in AI as entropic path selection. For a set of potential actions $\{A_i\}$, the selected action A^* minimizes entropic resistance:

$$A^* = \arg\min_{A_i} \left(\int \nabla\Lambda(A_i(t))^2 \, dt \right). \tag{340}$$

This formalism connects decision selection in neural agents with quantum state selection under entropic collapse.

11.8.8 Future Development Directions

ToE lays the foundation for a new class of AI and machine learning methodologies. Promising directions include:

1. Entropy-aware backpropagation algorithms
2. Psychentropic memory models for context-aware learning
3. Entropic transformers with adaptive entropy retention
4. Reinforcement learning with entropy-modulated exploration policies

11.8.9 Closure on Entropic AI and Computational Algorithms

Hence, ToE provides an innovative and unifying framework for reconceptualizing artificial intelligence. By reinterpreting AI systems as thermodynamically constrained agents within an evolving entropic field, ToE bridges the gap between physical law and synthetic cognition. This entropic perspective does not merely enhance machine learning and deep learning - it revolutionizes it, revealing AI as a manifestation of the same entropic principles that govern the evolution of the universe. Entropy is no longer a background metric, but the very engine of artificial thought.

12 Conclusion

One hundred years after the birth of modern quantum mechanics, the Theory of Entropicity (ToE) offers a fresh centennial perspective that reconciles the historically divergent views of Einstein and Bohr. By positing entropy as the linchpin of quantum reality, we have shown how the elusive wave function collapse can be understood as a real, entropy-driven phase transition - not a fanciful abstraction or a spontaneous whim, but a lawful outcome of a system's entropic dynamics.

This unifying theory preserves Einstein's demand for objective reality by introducing an entropy field that determines collapse events independent of observers, and it upholds Bohr's insistence on irreversibility and contextuality by embedding the second law of thermodynamics into the core of quantum evolution. We summarized how the **Vuli-Ndlela Integral encapsulates this approach mathematically, filtering Feynman's "many paths" through exponential weights that penalize high entropy production and gravitational entropy.** The result is that only **entropic geodesics - paths respecting both energy conservation and entropy increase – significantly contribute to physical outcomes.** In normal circumstances, this reproduces all the successes of standard quantum mechanics, but in measurement-like situations, it predicts a collapse when a critical entropy threshold is reached. We saw that this **leads naturally to the emergence of classical definiteness in macroscopic systems and to the alignment of the arrow of time in quantum processes with thermodynamics.**

We applied the ToE framework to resolve the EPR paradox, suggesting that entanglement correlations are established via a finite-speed entropic mechanism rather than an instantaneous "spooky" action [at a distance]. **Recent experimental indications of entanglement formation on the order of 10^{-16} seconds support this view, turning a philosophical quandary into a timing question that physics can investigate.** We also reinterpreted the ER = EPR idea, viewing entanglement as facilitated by an "entropic bridge" that conceptually links entangled particles similar to a wormhole [which we have physically equated to children's seesaw in our Seesaw Model of ToE], albeit one made of entropic information flow rather than traversable space. This ToE's model provides an intuitive picture consistent with quantum gravity notions, where spacetime and entanglement are intertwined.

Crucially, **the Theory of Entropicity vindicates both Einstein and Bohr: Entropicity grants Einstein's wish that quantum outcomes be dictated by something more than blind chance - here it is the inexorable rise of entropy that decides when an outcome is set.** Simultaneously, it validates Bohr's view that the act of measurement is special - here it is special because it unleashes an entropic avalanche that cannot be reversed, thereby creating a sharp split between the quantum possibilities and the realized fact.

In this way, the century-old debate finds a resolution not by compromising halfway, but by ascending to a higher principle that encompasses both stances.

The road ahead is rich with possibilities. On the theoretical side, further development of the ToE could integrate it more tightly with the established formalisms of quantum field theory and general relativity. It opens questions such as: **how exactly to formulate the entropy functional S_{irr} for complex fields? Could $\hbar_{\text{eff}}$ be derived from first principles or related to known constants? Does the entropy field have its own dynamics or quantum excitations (quanta of entropy)? These are deep questions that lie at the intersection of quantum foundations, statistical mechanics, and gravity.**

We have endeavored to provide our first insights from the Theory of Entropicity on the fundamental equations of Quantum Gravity. We achieved this non-elementary feat in Section 10 of this work.

On the experimental side, the theory dares us to probe the quantum-classical border with new eyes - to measure the tiny entropic fingerprints of quantum measurements, to push entanglement to larger scales and see if subtle deviations from unitary predictions appear, and to explore regimes (perhaps in quantum computing or ultra-cold mesoscopic systems) where we can tune entropy injection and see its effect on coherence.

As entropy is revealed to be the engine not only behind cosmic dynamics but also synthetic cognition, we have equally succeeded in showing that the Theory of Entropicity opens an unprecedented path toward developing entropy-aware artificial systems[considering, for our case for now, especially machine learning and deep learning in Artificial Intelligence(AI)] - where intelligence itself is redefined as an emergent modulation of entropic flow.

As a centennial contribution to quantum theory, the Theory of Entropicity embodies the spirit of bridging past insights with future directions. It suggests that the final story of quantum mechanics is still being written - a story in which information and thermodynamics play leading roles alongside energy and symmetry.

If the bold ideas presented here withstand scrutiny and testing, they could mark a step toward what one might call a "Second Quantum Revolution" - not one of new technology (though that may come too), but one of deeper understanding. In closing, we recall that Einstein and Bohr, despite their disagreements, held a mutual respect and fascination for the quantum world. Each in his way grappled with the universe's subtleties: **Einstein famously asked whether the moon is there when not observed, while Bohr would reply that such questions themselves may be flawed.**

The Theory of Entropicity, with supreme courage, invites us to imagine their discussion if they had this framework at hand. **Perhaps Einstein would nod at the idea of an objective entropy field doing the heavy lifting, and Bohr would acknowledge that as long as entropy - the "great disorganizer" - is in charge, the supremacy of the measurement postulate is unscathed.**

In this harmonious middle ground, therefore, the Theory of Entropicity (Toe) enables physics to move closer to a unified understanding: one where reality and information, cause and context, energy and entropy are all parts of a single, grander puzzle. Solving that puzzle continues to be our endeavor into the next century of quantum exploration and the evolution of physics.

May posterity bear witness to the good fruits of these daring efforts - and may they also find within them the seeds of deeper understanding, discovery, and truth, yielding insights of social, practical, and physical utility.

Acknowledgment and Dedication

The author expresses profound gratitude to those whose support, insight, and intellectual companionship made this work possible.

This paper has been written in this month of April 2025, in solemn recognition of the centennial reflection and celebration of quantum theory - a theory whose foundational questions remain as vibrant and urgent today as they were a hundred years ago.

It is with deep intellectual humility and reverence that I dedicate this work to **Albert Einstein** and **Niels Bohr** - two towering minds whose philosophical debates and scientific courage carved the bedrock upon which modern physics still stands.

To **Albert Einstein**, whose unyielding commitment to physical realism, causality, and the incompleteness of standard quantum mechanics continues to inspire generations to search for deeper laws beneath the veil of probability.

To **Niels Bohr**, whose masterful articulation of irreversibility, complementarity, and the contextual nature of quantum phenomena expanded our epistemic boundaries and challenged us to embrace the limits of knowledge with clarity and grace.

Though divided in interpretation, they were united in their devotion to the intelligibility of nature. This centennial paper - *Einstein and Bohr Finally Reconciled on Quantum Theory: The Theory of Entropicity (ToE) as the Unifying Resolution to the Problem of Quantum Measurement and Wave Function Collapse* - is offered as a tribute to that unity of purpose. It seeks not to compromise their visions, but to complete them, through the unveiling of a deeper entropic field that reconciles realism and contextuality at once.

May this centennial moment rekindle the spirit of foundational inquiry, and may this theory open new doors to understanding the quantum universe in the shared spirit of Einstein and Bohr.

The author also extends heartfelt thanks to **Dr. Olalekan T. Owolawi** and **Daniel M. Alemoh**, whose enduring presence and sharp intellect have greatly enriched this journey.

Dr. Olalekan T. Owolawi, in particular, provided the early spark for the drive - his probing challenges and encouragement were instrumental in shaping the vision behind this Theory of Entropicity(ToE). Just a few months ago, during one of our countless insightful discussions on the philosophical and conceptual foundations of science and knowledge, he posed this pivotal question to me: ***"If you really think entropy universally governs all interactions, can you prove it mathematically?"*** That moment became the genesis of this endeavor. I accepted that innocuous challenge with infinite candor and curiosity; and I have not looked back ever since. For this reason, and with the deepest gratitude and delight, I wholeheartedly dedicate this work to **Dr. Olalekan T. Owolawi**.

To **Daniel M. Alemoh**, I owe boundless thanks for his relentless investigative curiosity, incisive questions, and thoughtful reflections, on both my ideas and the challenges of modern physics, which consistently helped to push this work into clearer entropicistic focus. For his invaluable assistance in providing the results of the 232 attosecond entanglement formation experiment - which directly inspired the timely submission of a pivotal paper confirming one of the core axioms of the Theory of Entropicity (ToE), and which garnered immediate global attention - he is most deserving of my singular and heartfelt acknowledgment.

So, the history of the Theory of Entropicity(ToE) can never be complete without a visible mention of **Daniel M. Alemoh** and **Dr. Olalekan T. Owolawi**.

Finally, this work is dedicated to the legendary pioneers of quantum theory - Max Planck, Albert Einstein, Niels Bohr, Werner Heisenberg, Erwin Schrödinger, Louis de Broglie, Paul Dirac, Wolfgang Pauli, Max Born, John von Neumann, Eugene Wigner, David Bohm, Satyendra Nath Bose, Pascual Jordan, Sin-Itiro Tomonaga, Julian Schwinger, Richard Feynman, Hugh Everett III, and John Bell - those who dared to ask, and dared even more to listen for answers hidden in the subtle architecture of the universe. **May posterity bear witness to our concerted and dedicated efforts** - and **may they also find within them the seeds of deeper understanding, discovery, and truth, bearing both social, practical, and physical utility in all their manifold variants and manifestations.**

Honors Roll Call
Founders of Quantum Theory: A Comparative View Across QM, QED, and QCD in Light of ToE

The table below(Table (40))presents a comparative view of the key pioneers behind Quantum Mechanics (QM), Quantum Electrodynamics (QED), and Quantum Chromodynamics (QCD), which together form the quantum core of the Standard Model. The Theory of Entropicity (ToE) seeks to integrate these pillars into a single, entropy-governed framework, where interaction, geometry, and quantum behavior emerge from entropic field constraints.

In the Theory of Entropicity (ToE), these quantum domains are seen not as separate fields, but as structured outcomes of an underlying entropic field $\Lambda(x, t)$, whose gradients and potentials govern the emergence of mass, force, and curvature. ToE provides a synthetic reinterpretation of the legacy of these giants - unifying them under a new entropic paradigm of interaction and reality.

Quantum Mechanics (QM)	**Quantum Electrodynamics (QED)**	**Quantum Chromodynamics (QCD)**
Max Planck - quantum of action (1900)	**Paul Dirac** - quantum theory of the electron (1928)	**Murray Gell-Mann** - quarks, SU(3) symmetry
Albert Einstein - photoelectric effect (1905)	**Sin-Itiro Tomonaga** - covariant QED (1940s)	**George Zweig** - quark model (independent of Gell-Mann)
Niels Bohr - atomic model, complementarity	**Julian Schwinger** - operator methods in QED	**Yoichiro Nambu** - spontaneous symmetry breaking
Werner Heisenberg - matrix mechanics, uncertainty	**Richard Feynman** — path integrals, Feynman diagrams	**Harald Fritzsch** and **Heinrich Leutwyler** - QCD formulation
Erwin Schrödinger - wave mechanics	**Freeman Dyson** - synthesis of QED formulations	**David Gross**, **Frank Wilczek**, **H. David Politzer** - asymptotic freedom
Louis de Broglie - wave-particle duality		**Gerard 't Hooft** and **Martinus Veltman** - renormalization of non-Abelian gauge theory
Wolfgang Pauli, **Max Born**, **John von Neumann** - statistical and mathematical foundations		

Table 40: **Founders of Quantum Mechanics, QED, and QCD - unified conceptually under the Theory of Entropicity (ToE) as manifestations of entropy-field-driven interactions.**

References

[1] Alain Aspect, Jean Dalibard, and Gérard Roger. Experimental test of bell's inequalities using time-varying analyzers. *Physical Review Letters*, 49(25):1804–1807, 1982. URL `https://doi.org/10.1103/PhysRevLett.49.1804`.

[2] Michael F. Atiyah. Topological quantum field theories. *Publications Mathématiques de l'IHÉS*, 68:175–186, 1990. URL `https://doi.org/10.1007/BF02698547`.

[3] J.D. Bekenstein. Black holes and entropy. *Physical Review D*, 7(8):2333–2346, 1973. URL `https://doi.org/10.1103/PhysRevD.7.2333`.

[4] John S. Bell. On the einstein podolsky rosen paradox. *Physics Physique* , 1:195–200, 1964. URL `https://doi.org/10.1103/PhysicsPhysiqueFizika.1.195`.

[5] Mara Beller. *Quantum Dialogue: The Making of a Revolution*. University of Chicago Press, 1999. URL `https://press.uchicago.edu/ucp/books/book/chicago/Q/bo3648325.html`.

[6] Antonio Bianconi. Quantum interference and entropy-driven phase transitions in complex quantum matter. *Journal of Physics: Conference Series*, 108:012036, 2000. URL `https://iopscience.iop.org/article/10.1088/1742-6596/108/1/012036`. Presented at: Complexity in Physics and Biophysics.

[7] Ginestra Bianconi. Gravity from entropy. *Physical Review D*, 111:066001, 2025. URL `https://doi.org/10.1103/PhysRevD.111.066001`.

[8] David Bohm. A suggested interpretation of the quantum theory in terms of "hidden" variables. i. *Physical Review*, 85(2):166–179, 1952. URL `https://doi.org/10.1103/PhysRev.85.166`.

[9] David Bohm. A suggested interpretation of the quantum theory in terms of "hidden" variables. ii. *Physical Review*, 85(2):180–193, 1952. URL `https://doi.org/10.1103/PhysRev.85.180`.

[10] Niels Bohr. On the constitution of atoms and molecules, part i. *Philosophical Magazine*, 26(151):1–25, 1913. URL `https://doi.org/10.1080/14786441308634955`.

[11] Niels Bohr. The quantum postulate and the recent development of atomic theory. *Nature*, 121:580–590, 1928. URL `https://doi.org/10.1038/121580a0`.

[12] Niels Bohr. Can quantum-mechanical description of physical reality be considered complete? *Physical Review*, 48:696–702, 1935. URL `https://doi.org/10.1103/PhysRev.48.696`.

[13] Niels Bohr. Discussion with einstein on epistemological problems in atomic physics. In Paul Arthur Schilpp, editor, *Albert Einstein: Philosopher–Scientist*, page 201–241. Open Court, 1949. URL `https://www.nobelprize.org/uploads/2018/06/bohr-discussion.pdf`.

[14] Ludwig Boltzmann. Weitere studien über das wärmegleichgewicht unter gasmolekülen. *Sitzungsberichte der Kaiserlichen Akademie der Wissenschaften in Wien*, 66:275–370, 1872. Introduces the H-theorem and statistical interpretation of thermodynamics.

[15] Ludwig Boltzmann. Entgegnung auf die wärme-theoretischen betrachtungen des hrn. e. zermelo. *Annalen der Physik*, 293(11):773–784, 1896. URL `https://doi.org/10.1002/andp.18962931114`.

[16] Ludwig Boltzmann. *Lectures on Gas Theory*. University of California Press, 1964. URL `https://press.uchicago.edu/ucp/books/book/distributed/L/bo3778676.html`.

[17] Luca Bombelli, Joohan Lee, David Meyer, and Rafael D. Sorkin. Space-time as a causal set. *Physical Review Letters*, 59(5):521–524, 1987. URL `https://doi.org/10.1103/PhysRevLett.59.521`.

[18] Max Born. Zur quantenmechanik der stoßvorgänge. *Zeitschrift für Physik*, 37:863–867, 1926. URL `https://doi.org/10.1007/BF01397477`.

[19] Max Born and Albert Einstein. *The Born-Einstein Letters: Correspondence Between Albert Einstein and Max Hedwig Born from 1916 to 1955*. Macmillan, 1971. URL `https://archive.org/details/born-einstein-letters`.

[20] Satyendra Nath Bose. Planck's law and the hypothesis of light quanta. *Zeitschrift für Physik*, 26:178–181, 1924. URL `https://doi.org/10.1007/BF01327326`.

[21] Antoine Bérut, Armen Arakelyan, Artyom Petrosyan, Sergio Ciliberto, Raoul Dillenschneider, and Eric Lutz. Experimental verification of landauer's principle linking information and thermodynamics. *Nature*, 483:187–189, 2012. URL `https://doi.org/10.1038/nature10872`.

[22] Jun Chen. Trivial entropy of matter in gravitation. *arXiv preprint arXiv:2002.12167v2*, 2020. Dated: April 14, 2020.

[23] Louis de Broglie. Recherches sur la théorie des quanta. *Annales de Physique*, 10:22–128, 1925. URL `https://gallica.bnf.fr/ark:/12148/bpt6k3122t/f522.image`.

[24] Claudia de Rham, Gregory Gabadadze, and Andrew J. Tolley. Resummation of massive gravity. *Physical Review Letters*, 106(23):231101, 2011. URL `https://doi.org/10.1103/PhysRevLett.106.231101`.

[25] Emre Dil and Tugrul Yumak. Entropic origin of the fundamental forces. *arXiv preprint arXiv:1702.04635v2*, 2019. Dated: January 1, 2019.

[26] Paul A. M. Dirac. On the theory of quantum mechanics. *Proceedings of the Royal Society A*, 112(762): 661–677, 1926. URL `https://doi.org/10.1098/rspa.1926.0133`.

[27] Paul A. M. Dirac. *The Principles of Quantum Mechanics*. Oxford University Press, 1930. URL `https://global.oup.com/academic/product/the-principles-of-quantum-mechanics-9780198520115`.

[28] Fay Dowker. Causal sets and the deep structure of spacetime. *100 Years of Relativity: Space-Time Structure–Einstein and Beyond*, page 445–464, 2005. URL `https://arxiv.org/abs/gr-qc/0508109`.

[29] Arthur Stanley Eddington. *The Nature of the Physical World*. Macmillan, 1928. URL `https://archive.org/details/natureofphysical0000eddi`. See Chapter 4, where Eddington introduces the "Arrow of Time" concept.

[30] Albert Einstein. On a heuristic point of view concerning the production and transformation of light. *Annalen der Physik*, 17:132–148, 1905. URL `https://doi.org/10.1002/andp.19053220607`.

[31] Albert Einstein. Die feldgleichungen der gravitation. *Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften zu Berlin*, pages 844–847, 1915. URL `https://en.wikisource.org/wiki/Translation:The_Field_Equations_of_Gravitation`.

[32] Albert Einstein. Kosmologische betrachtungen zur allgemeinen relativitätstheorie. *Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften (Berlin)*, page 142–152, 1917. URL `https://einsteinpapers.press.princeton.edu/vol6-trans/161`. English: Cosmological Considerations in the General Theory of Relativity.

[33] Albert Einstein. Quantentheorie des einatomigen idealen gases, zweite abhandlung. *Sitzungsberichte der Preussischen Akademie der Wissenschaften*, page 3–14, 1925. Einstein's final paper predicting Bose-Einstein condensation.

[34] Albert Einstein. Autobiographical notes. In Paul Arthur Schilpp, editor, *Albert Einstein: Philosopher–Scientist*, page 1–95. Open Court, 1949. URL `https://press.uchicago.edu/ucp/books/book/distributed/A/bo41485675.html`.

[35] Albert Einstein and Nathan Rosen. The particle problem in the general theory of relativity. *Physical Review*, 48:73–77, 1935. URL `https://doi.org/10.1103/PhysRev.48.73`.

[36] Albert Einstein, Boris Podolsky, and Nathan Rosen. Can quantum-mechanical description of physical reality be considered complete? *Physical Review*, 47(10):777–780, 1935. URL `https://doi.org/10.1103/PhysRev.47.777`.

[37] Hugh Everett. "relative state" formulation of quantum mechanics. *Reviews of Modern Physics*, 29(3): 454–462, 1957. URL `https://doi.org/10.1103/RevModPhys.29.454`.

[38] Mohsen Fathi and Ali Övgün. Black hole with global monopole charge in self-interacting kalb-ramond field. *arXiv preprint arXiv:2501.09899*, 2025.

[39] Enrico Fermi. Zur quantelung des idealen einatomigen gases. *Zeitschrift für Physik*, 36:902–912, 1926. URL `https://doi.org/10.1007/BF02961404`.

[40] Richard P. Feynman. Space-time approach to non-relativistic quantum mechanics. *Reviews of Modern Physics*, 20(2):367–387, 1948. URL `https://doi.org/10.1103/RevModPhys.20.367`.

[41] Richard P. Feynman and A. R. Hibbs. *Quantum Mechanics and Path Integrals*. McGraw-Hill, 1965. URL `https://press.princeton.edu/books/hardcover/9780486477220/quantum-mechanics-and-path-integrals`.

[42] G. C. Ghirardi, A. Rimini, and T. Weber. Unified dynamics for microscopic and macroscopic systems. *Physical Review D*, 34(2):470–491, 1986. URL `https://doi.org/10.1103/PhysRevD.34.470`.

[43] Michael B. Green and John H. Schwarz. Anomaly cancellations in supersymmetric d = 10 gauge theory and superstring theory. *Physics Letters B*, 149(1–3):117–122, 1984. URL https://doi.org/10.1016/0370-2693(84)91565-X.

[44] Daniel Grumiller, Robert McNees, and Jakob Salzer. Black holes and thermodynamics - the first half century. *General Relativity and Quantum Cosmology*, Feb 2014 2014. URL https://arxiv.org/abs/1402.5127. Submitted on 20 Feb 2014 (v1), last revised 17 Mar 2014 (this version, v3).

[45] S.W. Hawking. Particle creation by black holes. *Communications in Mathematical Physics*, 43(3):199–220, 1975. URL https://doi.org/10.1007/BF02345020.

[46] Werner Heisenberg. Über quantentheoretische umdeutung kinematischer und mechanischer beziehungen. *Zeitschrift für Physik*, 33:879–893, 1925. URL https://doi.org/10.1007/BF01328377.

[47] Ted Jacobson. Thermodynamics of spacetime: The einstein equation of state. *Physical Review Letters*, 75 (7):1260–1263, 1995. URL https://doi.org/10.1103/PhysRevLett.75.1260.

[48] E. T. Jaynes. Gibbs vs boltzmann entropies. In S. F. Gull and J. Skilling, editors, *Maximum Entropy and Bayesian Methods*, page 1–21. Kluwer Academic, 1965. URL https://bayes.wustl.edu/etj/articles/gibbs.vs.boltzmann.pdf.

[49] Wei-Chao Jiang, Ming-Chen Zhong, Yong-Kang Fang, Stefan Donsa, Iva Březinová, Liang-You Peng, and Joachim Burgdörfer. Time delays as attosecond probe of interelectronic coherence and entanglement. *Physical Review Letters*, 133(16):163201, October 2024. URL https://link.aps.org/doi/10.1103/PhysRevLett.133.163201.

[50] Vaughan F. R. Jones. A polynomial invariant for knots via von neumann algebras. *Bulletin of the American Mathematical Society*, 12(1):103–111, 1985. URL https://doi.org/10.1090/S0273-0979-1985-15304-2.

[51] Immanuel Kant. *Critique of Pure Reason*. Johann Friedrich Hartknoch, 1781. URL https://www.gutenberg.org/ebooks/4280.

[52] Louis H. Kauffman. *Knots and Physics*. World Scientific, 1991. URL https://doi.org/10.1142/0968.

[53] Rolf Landauer. Irreversibility and heat generation in the computing process. *IBM Journal of Research and Development*, 5(3):183–191, 1961. URL https://doi.org/10.1147/rd.53.0183.

[54] John Locke. *An Essay Concerning Human Understanding*. Thomas Basset, 1690. URL https://www.gutenberg.org/ebooks/10615.

[55] Josef Loschmidt. Über den zustand des wärmegleichgewichtes eines systems von körpern mit rücksicht auf die schwerkraft. *Sitzungsberichte der Kaiserlichen Akademie der Wissenschaften Wien*, 73:128–142, 1876. English translation: "On the state of thermal equilibrium of a system of bodies with regard to gravity".

[56] Juan Maldacena and Leonard Susskind. Cool horizons for entangled black holes (er=epr). *Fortschritte der Physik*, 61(9):781–811, 2013. URL https://arxiv.org/abs/1306.0533.

[57] Juan M. Maldacena. The large n limit of superconformal field theories and supergravity. *International Journal of Theoretical Physics*, 38:1113–1133, 1999. URL https://doi.org/10.1023/A:1026654312961.

[58] Yoshihiko Masuyama, Ken Funo, Yûto Murashita, Atsushi Noguchi, Shinya Kono, Yutaka Tabuchi, Takahiro Yamamoto, Masahito Ueda, and Yasunobu Nakamura. Information-to-work conversion by maxwell's demon in a superconducting circuit. *Nature Communications*, 9:1291, 2018. URL https://doi.org/10.1038/s41467-018-03239-y.

[59] John Onimisi Obidi. Corrections to the classical shapiro time delay in general relativity (gr) from the entropic force-field hypothesis (effh). Cambridge University, 11th March 2025. URL https://doi.org/10.33774/coe-2025-v7m6c.

[60] John Onimisi Obidi. How the generalized entropic expansion equation (geee) describes the deceleration and acceleration of the universe in the absence of dark energy. Cambridge University, 12th March 2025. URL https://doi.org/10.33774/coe-2025-6d843.

[61] John Onimisi Obidi. The theory of entropicity (toe): An entropy-driven derivation of mercury's perihelion precession beyond einstein's curved spacetime in general relativity (gr). Cambridge University, 16th March 2025. URL https://doi.org/10.33774/coe-2025-g55m9.

[62] John Onimisi Obidi. The entropic force-field hypothesis: A unified framework for quantum gravity. Cambridge University, 18th February 2025. URL https://doi.org/10.33774/coe-2025-fhhmf.

[63] John Onimisi Obidi. Exploring the entropic force-field hypothesis (effh): New insights and investigations. Cambridge University, 20th February 2025. URL https://doi.org/10.33774/coe-2025-3zc2w.

[64] John Onimisi Obidi. The theory of entropicity (toe) validates einstein's general relativity (gr) prediction for solar starlight deflection via an entropic coupling constant . Cambridge University, 23rd March 2025. URL https://doi.org/10.33774/coe-2025-1cs81.

[65] John Onimisi Obidi. Attosecond constraints on quantum entanglement formation as empirical evidence for the theory of entropicity (toe). Cambridge University, 25th March 2025. URL https://doi.org/10.33774/coe-2025-30swc.

[66] John Onimisi Obidi. Review and analysis of the theory of entropicity (toe) in light of the attosecond entanglement formation experiment: Toward a unified entropic framework for quantum measurement, non-instantaneous wave-function collapse, and spacetime emergence. Cambridge University, 29th March 2025. URL https://doi.org/10.33774/coe-2025-7lvwh.

[67] Gabriel A. Oyibo. Grand unified theorem: Discovery of the theory of everything and the building block of absolute unified field theory. In *Annals of the New York Academy of Sciences*, volume 939, page 102–116, 2001. URL https://doi.org/10.1111/j.1749-6632.2001.tb03675.x.

[68] T. Padmanabhan. Thermodynamical aspects of gravity: New insights. *Reports on Progress in Physics*, 73 (4):046901, 2010. URL https://doi.org/10.1088/0034-4885/73/4/046901.

[69] Wolfgang Pauli. Über den zusammenhang des abschlusses der elektronengruppen im atom mit der komplexstruktur der spektren. *Zeitschrift für Physik*, 31(1):765–783, 1925. URL https://doi.org/10.1007/BF02980631.

[70] R. Penrose. *The Road to Reality: A Complete Guide to the Laws of the Universe*. Vintage Books, 2004.

[71] Roger Penrose. On gravity's role in quantum state reduction. *General Relativity and Gravitation*, 28(5): 581–600, 1996. URL https://doi.org/10.1007/BF02105068.

[72] Max Planck. On the law of distribution of energy in the normal spectrum. *Annalen der Physik*, 309(3): 553–563, 1901. URL https://doi.org/10.1002/andp.19013090310.

[73] Huw Price. *Time's Arrow and Archimedes' Point: New Directions for the Physics of Time*. Oxford University Press, 1996. URL https://global.oup.com/academic/product/times-arrow-and-archimedes-point-9780195117981.

[74] David Reeb and Michael M. Wolf. An improved landauer principle with finite-size corrections. *New Journal of Physics*, 16:103011, 2014. URL https://doi.org/10.1088/1367-2630/16/10/103011.

[75] C. Rovelli. Loop quantum gravity. *Living Reviews in Relativity*, 1998.

[76] Carlo Rovelli. Relational quantum mechanics. *International Journal of Theoretical Physics*, 35:1637–1678, 1996. URL https://doi.org/10.1007/BF02302261.

[77] Joël Scherk and John H. Schwarz. Dual models for non-hadrons. *Nuclear Physics B*, 81(1):118–144, 1974. URL https://doi.org/10.1016/0550-3213(74)90010-3.

[78] Erwin Schrödinger. Quantisierung als eigenwertproblem (erste mitteilung). *Annalen der Physik*, 384(4): 361–376, 1926. URL https://doi.org/10.1002/andp.19263840404.

[79] Claude E. Shannon. A mathematical theory of communication. *Bell System Technical Journal*, 27(3): 379–423, 1948. URL https://ieeexplore.ieee.org/document/6773024.

[80] Irwin I. Shapiro. Fourth test of general relativity. *Physical Review Letters*, 13(26):789–791, 1964. doi: 10.1103/PhysRevLett.13.789.

[81] L. Smolin. *Three Roads to Quantum Gravity*. Basic Books, 2001.

[82] Rafael D. Sorkin. Causal sets: Discrete gravity. *Lectures on Quantum Gravity (Springer)*, page 305–327, 2005. URL https://arxiv.org/abs/gr-qc/0309009.

[83] Leonard Susskind. Dual symmetric theory of hadrons. *Il Nuovo Cimento A*, 69:457–496, 1970. URL https://doi.org/10.1007/BF02754829.

[84] Leonard Susskind. The world as a hologram. *Journal of Mathematical Physics*, 36:6377–6396, 1995. URL https://doi.org/10.1063/1.531249.

[85] Gerard 't Hooft. Dimensional reduction in quantum gravity. *arXiv preprint*, 1993. URL https://arxiv.org/abs/gr-qc/9310026.

[86] Gabriele Veneziano. Construction of a crossing-symmetric, regge-behaved amplitude for linearly rising trajectories. *Il Nuovo Cimento A*, 57(1):190–197, 1968. URL https://doi.org/10.1007/BF02824451.

[87] Erik Verlinde. On the origin of gravity and the laws of newton. *Journal of High Energy Physics*, 2011(4):29, 2011. URL https://doi.org/10.1007/JHEP04(2011)029.

[88] Herman L. Verlinde. Er = epr and the entropy of bridges. *SciPost Physics*, 8(3):039, 2020. URL https://scipost.org/10.21468/SciPostPhys.8.3.039.

[89] John von Neumann. *Mathematical Foundations of Quantum Mechanics*. Princeton University Press, 1955. URL https://press.princeton.edu/books/paperback/9780691028934/mathematical-foundations-of-quantum-mechanics.

[90] John A. Wheeler. On the nature of quantum geometrodynamics. *Annals of Physics*, 2(6):604–614, 1957. URL https://doi.org/10.1016/0003-4916(57)90050-7.

[91] John A. Wheeler. Information, physics, quantum: The search for links. In Wojciech H. Zurek, editor, *Complexity, Entropy, and the Physics of Information*, page 3–28. Addison-Wesley, 1990. URL https://archive.org/details/complexityentrop00zura.

[92] John A. Wheeler, Charles W. Misner, and Kip S. Thorne. *Gravitation*. W. H. Freeman, 1973. URL https://press.princeton.edu/books/hardcover/9780691177793/gravitation.

[93] Edward Witten. Quantum field theory and the jones polynomial. *Communications in Mathematical Physics*, 121:351–399, 1989. URL https://doi.org/10.1007/BF01217730.

[94] Edward Witten. String theory dynamics in various dimensions. *Nuclear Physics B*, 443(1–2):85–126, 1995. URL https://doi.org/10.1016/0550-3213(95)00158-O.

[95] Liang Yan, Katharina S. Cujia, Yixiang Liu, Jiangfeng Du, Carlos A. Meriles, and Paola Cappellaro. Experimental realization of the quantum landauer principle using a superconducting qubit. *Physical Review Letters*, 120(4):040502, 2018. URL https://doi.org/10.1103/PhysRevLett.120.040502.

[96] Wojciech H. Zurek. Decoherence, einselection, and the quantum origins of the classical. *Reviews of Modern Physics*, 75:715–775, 2003. URL https://doi.org/10.1103/RevModPhys.75.715.