From 2D Quanta to the Amplituhedron: A Vectorial Framework for Unifying Quantum Mechanics and General Relativity

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Abstract:

This thesis introduces a novel mathematical framework linking the discrete, vector-based 2D Quanta lattice to the geometric Amplituhedron—suggesting that spacetime and quantum probability are dual projections of an underlying vectorial logic. The accompanying diagrams reveal a multi-layered correspondence between quantized vector patterns, light-cone geometry, and emergent spacetime curvature. It is proposed that by interpreting vector summations within a normalized ±1 space, an emergent geometric field structure mirrors the shape and behavior of the Amplituhedron. When extended, this may offer a bridge between **quantum probability amplitudes** and the **continuous curvature of spacetime**, thereby approaching a unification between quantum mechanics and general relativity.

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1. Introduction:

Classical physics assumes continuity, while quantum mechanics introduces discreteness.
The triangular lattice of 2D vector quanta reveals symmetrical dualities centered on a normalized zero point—suggesting a discrete informational structure that reflects the geometry of the Amplituhedron bounded by ±1. The visual and numerical alignment of these patterns with the Amplituhedron suggests a deeper structural analogy: **quantized information geometry** (Arkani-Hamed & Trnka, 2014).

This framework resonates with **Tegmark's Mathematical Universe Hypothesis**, which posits that physical reality is not just described by mathematics but *is* mathematics—specifically, a mathematical structure existing independently of human interpretation (Tegmark, 2008). By modeling both spacetime curvature and quantum amplitudes through a discrete combinatorial system, the 2D Quanta lattice may serve as a concrete realization of such a mathematical substrate, in which reality emerges from a vectorial arithmetic.

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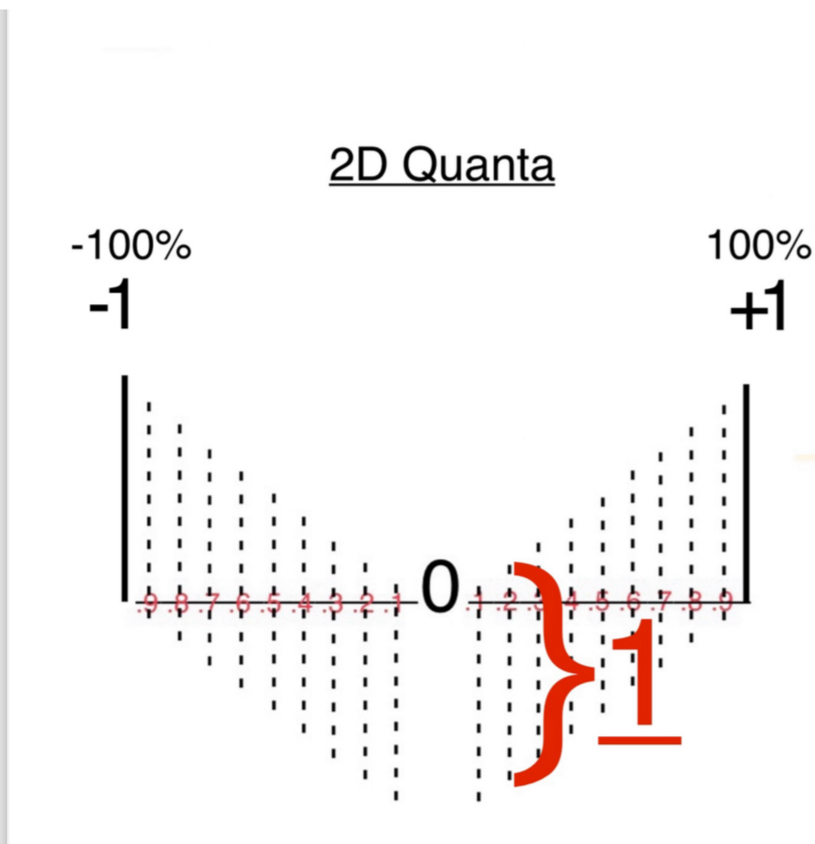
2. The 2D Quanta Framework:

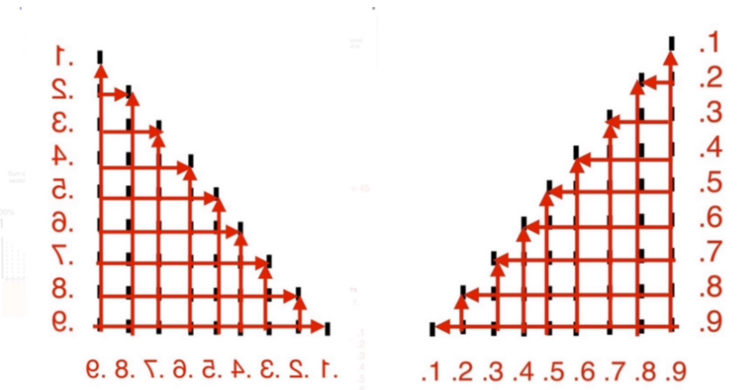
The 2D Quanta framework conceptualizes spacetime not as a smooth continuum, but as a lattice composed of discrete, directional interactions. At each node within this lattice, unit vectors propagate along fixed orientations governed by quantized constraints. These vectors operate within a **±1 normalized field**—meaning that the magnitude of any individual vector component is bounded between -1 and +1. This constraint reflects the conservation of directional amplitude and can be thought of as an energy-normalized space, analogous to quantum amplitude spaces where total probability is conserved.
Each vector in the 2D Quanta framework below contributes to a discrete yet structured field defined by:

$$V(x, y) \in \{-1, 0, +1\}$$

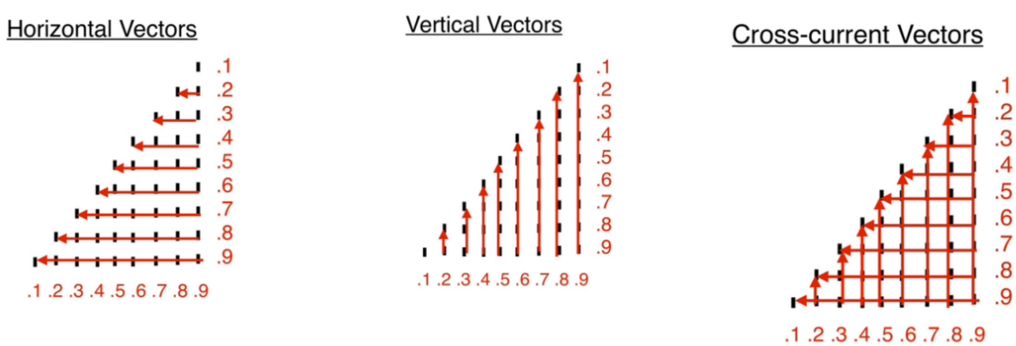


2.1 Cross-current Vectors

Cross-current vectors are defined by their diagonal propagation across the 2D Quanta lattice—moving at 45-degree angles relative to the horizontal and vertical grid axes. These diagonals intersect the quantized vector space in a pattern that generates symmetrical formations.



As illustrated, these 45-degree vector paths establish a dual-current structure that mirrors the symmetry of light cones in relativistic spacetime. This directional behavior aligns with the properties of null geodesics in general relativity, which represent the path that light takes through curved spacetime (Einstein, 1916).



By mapping these diagonal movements within the normalized ±1 vector field, the lattice simulates light-like propagation at discrete intervals—suggesting that these cross-currents may serve as fundamental carriers of information or energy, similar to photons in quantum electrodynamics.

The following formula is a compact representation of how the 2D-quantized lattice encodes **45-degree (light-like)** vector propagation using orthogonal base vectors of equal magnitude. The mathematical underpinning of the **cross-current** concept shows how such vectors simulate null geodesics and propagate energy/information within the discrete vector field:

$$\vec{C}_{xy} = \vec{V}_x + \vec{V}_y \quad \text{where} \quad |\vec{V}_x| = |\vec{V}_y|$$

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3. Time Dilation and Angular Geometry

The diagram below illustrates how the angular composition of vector fields within the 2D Quanta lattice gives rise to relativistic effects such as time dilation and light deflection.

In this framework, diagonal trajectories—referred to as *cross-currents*—are formed by the vector summation of orthogonal components $\mathbf{V_x}$ and $\mathbf{V_Y}$, representing horizontal and vertical motions within a quantized lattice. These vectors combine to produce a resultant:

$\mathbf{C_{xY} = V_x + V_Y}$

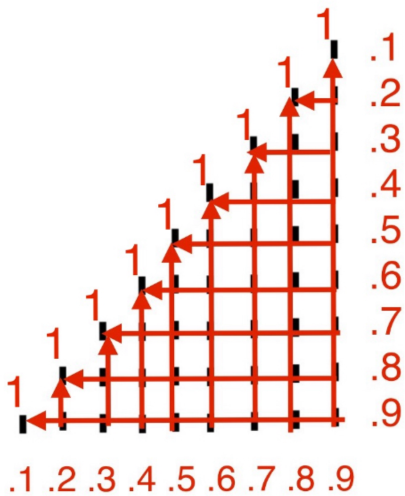
This relationship operates under the normalization condition:

$\mathbf{|V_x| + |V_Y| = 1}$

As described, diagonal paths in the lattice—called **cross-currents**—arise from summing orthogonal vector components:

$$C_{xy} = V + V \quad \text{where} \quad |V| + |V| = 1$$

Crosscurrent Summation



Sum of the Vertical vectors and Horizontal vectors equal One (1) and correspond to Light's (c) 45degree angle

(i.e.) 0.2 + 0.8 = 1
0.3 + 0.7 = 1
0.4 + 0.6 = 1

This constraint ensures that the resulting diagonal lies along a light-like trajectory within the lattice. When both components are equal (e.g., **$|V_x| = |V_y| = 0.5$**), the path follows a perfect 45° diagonal—representing the invariant speed of light across all reference frames, as described by Einstein's theory of special relativity (Einstein, 1916). When the components are asymmetrical (e.g., **$|V_x| = 0.1$**, **$|V_y| = 0.9$**), the trajectory becomes steeper, simulating the angular deflection of light near a gravitational source, similar to predictions from general relativity (Misner, Thorne, & Wheeler, 1973).

These variations in horizontal-to-vertical weighting mimic the bending of light due to spacetime curvature. A steeper slope represents greater temporal elongation (time dilation), while a compressed horizontal component simulates spatial contraction or gravitational lensing—concepts central to relativistic physics.

$$\theta = \cos^{-1}(\pm\frac{1}{\sqrt{2}}) = 45^\circ$$

Significance of Cross-Current Summation and Normalization

The normalization condition:

$$|V_x| + |V_y| = 1$$

is more than a constraint—it encodes the conservation of energy within the discrete field, echoing fundamental principles of field theory and relativity (Peskin & Schroeder, 1995). When cross-currents sum to unity, each component represents a fraction of a quantized energy packet moving through the lattice, akin to discrete units of light-like propagation.

Examples include:

- **$|V_x| = 0.1$, $|V_y| = 0.9$**

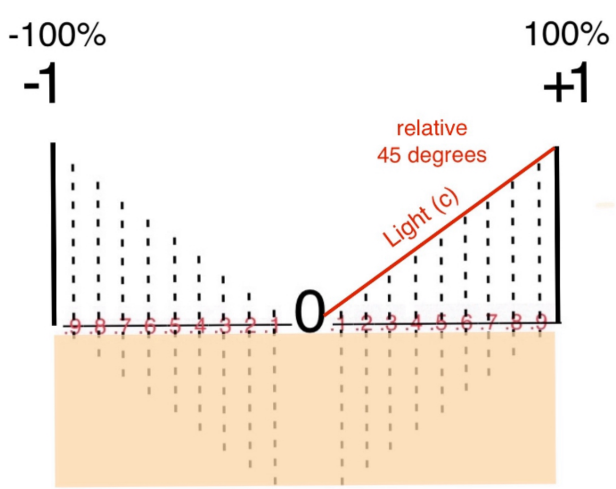
→ A steep diagonal, nearly vertical, representing a highly time-dilated frame—analogous to objects under intense gravitational influence.

- **$|V_x| = 0.5$, $|V_y| = 0.5$**

→ A 45° diagonal, modeling the idealized path of light—a null geodesic.

- **$|V_x| = 0.9$, $|V_y| = 0.1$**

→ A shallow, nearly horizontal path, representing minimal time dilation and rapid spatial propagation.

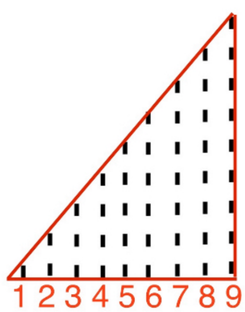


By maintaining the summation to 1, the system ensures that all trajectories adhere to a light-like framework, while the internal ratios determine the angular orientation. This discrete mechanism models relativistic curvature and energy dynamics using simple geometric logic, aligning closely with how null geodesics operate in curved spacetime (Ambjorn, Jurkiewicz, & Loll, 2009).

Discrete Geometry and the Emergence of the Number 45

The triangular diagram representing all normalized cross-current vector combinations within a 9×9 lattice reveals a profound structural insight: the total number of distinct vector pairings sums to 45. This value emerges from the triangular number formula:

1 + 2 + 3 + … + 9 = 45



1+2+3+4+5+6+7+8+9 = 45

or equivalently:

(9 × 10) / 2 = 45

Interestingly, 45 emerges as more than a numerological artifact—it represents the full set of energy-conserving propagation states within the field. This result geometrically encodes the number of **light-like, energy-conserving vector interactions** possible within the bounded lattice region. Each node represents a valid configuration obeying $|V_x| + |V_Y| = 1$, and the full triangle constitutes the **complete discrete spectrum of angular propagations**.

The number 45 is not arbitrary—it reflects:

- The total count of cross-current states under a single quantization constraint.

- A geometric analogue to volume in amplitude space, much like the role of volume in the Amplituhedron (Arkani-Hamed & Trnka, 2014).

- A symbolic measure of **combinatorial completeness**, bridging vector-based modeling and quantum amplitude structures.

Thus, the internal summation of 45 becomes a **quantized geometric amplitude**—a discrete stand-in for path integral calculations in quantum field theory (Witten, 2004). It implies that the lattice does more than simulate motion: it encodes the **underlying probabilistic and geometric logic** of both spacetime curvature and quantum interaction through structured, finite summation.

Cross-current vectors are therefore not just directional—they are relational, relativistic, and **summative**. They encode the flow of time and space, conserve light-like energy, and—through their aggregate count—encode emergent structures akin to geometric amplitudes. This positions the 2D Quanta lattice as a candidate for simulating relativistic and quantum phenomena through purely discrete, combinatorial geometry.

Time Dilation as Angular Steepness in the 2D Quanta Field

Following the combinatorial geometry and cross-current summation explored previously, this next diagram visualizes how **vector slope encodes relativistic time dilation**, directly reflecting the Lorentz factor:

$$t' = \frac{t}{\sqrt{1 - v^2/c^2}}$$

This core principle of special relativity (Einstein, 1916) states that as an object's velocity approaches the speed of light, its experienced time slows relative to a stationary observer. The following diagram titled *"Time Dilation"* visualizes this phenomenon using the angular structure of vector fields within the 2D Quanta lattice.

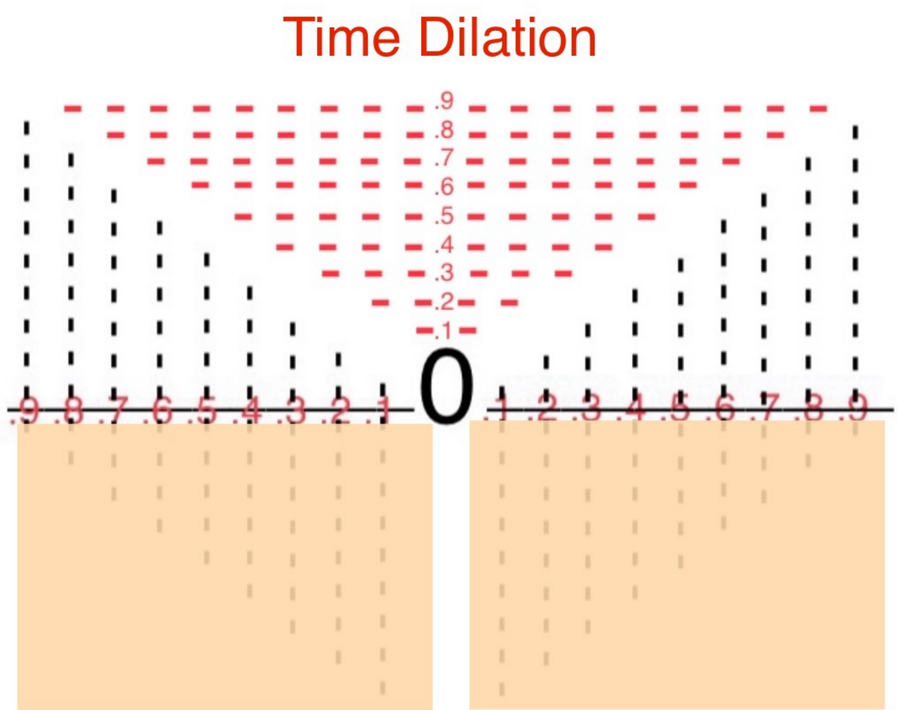


Diagram Interpretation:

- The **vertical axis** represents quantized **elapsed time**, ascending from 0.1 to 0.9 in red dashed intervals.

- The **horizontal axis** represents discrete **spatial intervals**, extending symmetrically from a central origin point.

- **Field steepness**—visualized by the rising black vertical vectors—corresponds to the degree of time dilation, with steeper slopes reflecting longer durations per unit of space.

- The **dashed red time contours** above the origin encode increasing temporal depth, aligned with higher Lorentz dilation values.

This structure shows that **as the vector field steepens**, more time "accumulates" per unit of spatial displacement, simulating observers in slower frames (low velocity or strong gravitational fields). Conversely, as the slope flattens, less time accrues per unit space, modeling frames with greater relative velocity and time dilation.

These visual elements illustrate a central claim of the 2D Quanta framework: **relativistic time emerges geometrically from vectorial steepness**.

Geometric Time from Directional Propagation

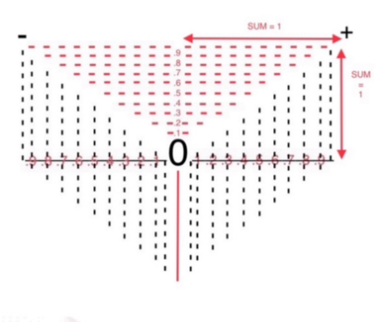
Whereas classical relativity treats time dilation as a byproduct of velocity or gravity within a continuous manifold, this framework proposes a discrete, angular origin for time dilation—generated by directional weighting in the field itself.

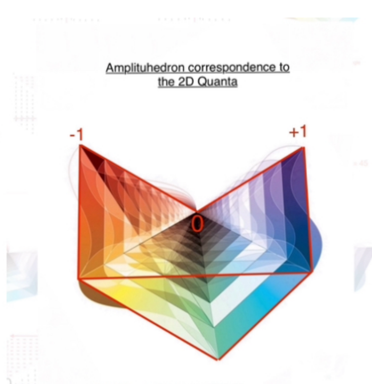
This interpretation echoes approaches in loop quantum gravity and causal dynamical triangulations, where spacetime geometry is built from discrete, combinatorially defined elements (Ambjorn, Jurkiewicz, & Loll, 2009). It also aligns with twistor-based formulations of quantum field theory (Witten, 2004), where geometry and causality are deeply entangled.

In this model:

- The **geometry of direction** defines the **flow of time**.
- The **quantized steepness** of propagation defines **temporal intervals**.
- The **field itself is not passive—**it actively *generates proper time* through angular constraint.

By using simple vector relations within the 2D Quanta lattice, this framework models relativistic time dilation without requiring smooth manifolds or continuous fields. Instead, it encodes relativistic behavior directly into the combinatorics of directional vector addition, bridging quantum and relativistic regimes with a single geometric grammar (Arkani-Hamed & Trnka, 2014).





Together, these two diagrams reveal a critical insight:

The geometry of relativistic time and the shape of quantum amplitude space emerge from the same underlying lattice structure.

The **time dilation field** translates directly into the **geometry of quantum amplitudes**, suggesting that space, time, and quantum interaction amplitudes are not distinct phenomena, but rather **different projections of the same discrete vectorial logic**—a concept supported by twistor theory (Witten, 2004), causal triangulations (Ambjorn, Jurkiewicz, & Loll, 2009), and geometric amplitude formulations (Arkani-Hamed & Trnka, 2014).

- **Time dilation** is encoded in **angular steepness**, echoing the Lorentz factor from special relativity (Einstein, 1916), where steep vector fields represent longer proper time.

- **Probability amplitude** is encoded in **combinatorial area or volume**, reflecting how scattering processes can be derived not from Feynman diagrams, but from emergent geometric regions like the Amplituhedron (Arkani-Hamed & Trnka, 2014).

- **Both phenomena** emerge from a unified **2D Quanta substrate**, operating under **conservation-based summation** (i.e., $|V_x| + |V_Y| = 1$), which discretely encodes null trajectories and vector coherence within a flat combinatorial field.

This **duality** reinforces the central proposition: the **Amplituhedron is not merely an abstract mathematical tool**, but a **geometric hologram of a deeper, vectorially-governed physical reality**—a unified structure where relativistic geometry and quantum probability are derived from the same angular foundations.

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4. Vector Summation as Probability Amplitudes

In contemporary quantum field theory, **probability amplitudes**—which govern the likelihood of particle interactions—are often derived from geometric constructions rather than traditional spacetime-based Feynman diagrams (Feynman, 1949). Again, one of the most elegant formulations of this approach is the **Amplituhedron**, the multidimensional geometric object that encodes scattering amplitudes as abstract volumes in a constrained amplitude space (Arkani-Hamed & Trnka, 2014).

Within the 2D Quanta framework, we uncover a discrete analog to this structure: **the quantized summation of directional vectors within a triangular region**. These vector sums produce a scalar area whose value corresponds to the **magnitude of a quantum amplitude—**not metaphorically, but geometrically and combinatorially.

Triangular Summation as Primitive Geometry

The total number of quantized vector contributions in a triangular domain is governed by the triangular number formula:

$$\sum_{i=1}^{n} i = \frac{n(n+1)}{2}$$

This expression, while elementary, takes on profound significance when applied to the combinatorics of directional vectors under the constraint:

$|V_x| + |V_Y| = 1$

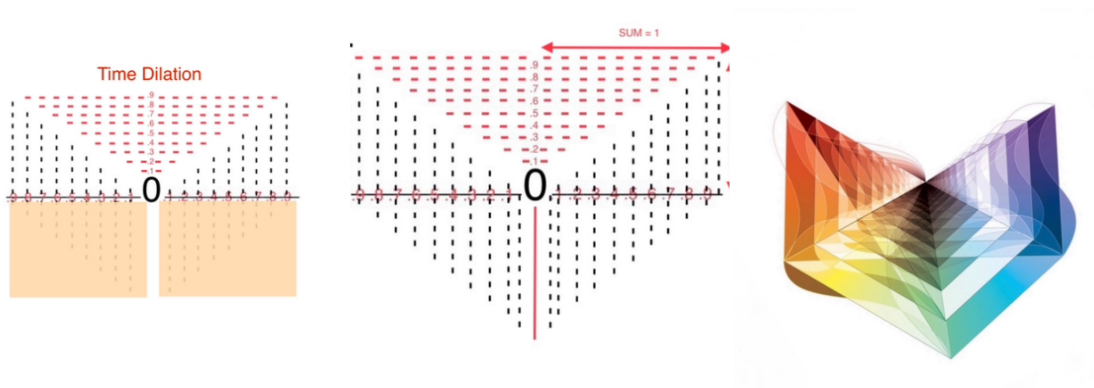
Here, each integer **i** in the summation represents a horizontal cross-section of quantized vector pairings at a given angular configuration. For example, in a 9×9 lattice, the total number of valid summation states is:

$$\sum_{i=1}^{9} i = \frac{9(10)}{2} = 45$$

This “area” is not merely a count—it is a **quantized surface of amplitude**, where each unit reflects a geometrically valid energy-preserving interaction. Unlike previous sections that focused on directional steepness and time dilation, here the emphasis is on **cumulative summation as a geometric analog to amplitude magnitude**.

Correspondence with the Amplituhedron

When this discrete triangular surface is visualized in projection, it can be seen to **curve upward into a volumetric geometry—**one that resembles the **Amplituhedron** in both form and function. The central axis anchors a region of maximal vector balance ($V_x = V_Y$), while the ±1 bounds represent polarized, light-like propagation. The resulting “folded field” defines a **volume in abstract space**, consistent with how the Amplituhedron encodes probability through geometric constraint (Witten, 2004; Arkani-Hamed & Trnka, 2014).

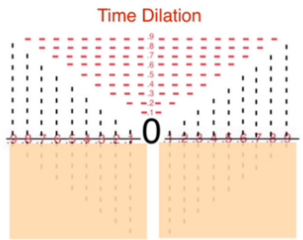


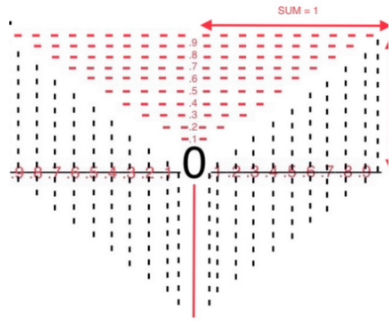
Unlike Feynman diagrams, which trace paths over spacetime, the Amplituhedron operates without spacetime entirely. Similarly, this 2D Quanta lattice does not require a background metric—it generates amplitude purely through **angular alignment and quantized summation**. The analogy is not coincidental; it is structural.

In this framework:

- **Amplitude arises as area**, not as an abstract wavefunction.
- **Volume emerges from vector coherence**, not integration over paths.
- The **Amplituhedron becomes a holographic projection** of vectorial interactions within a flat, two-dimensional lattice.

This perspective allows us to reinterpret quantum probabilities not as abstract statistical effects, but as **geometric results of directional symmetry and conserved interaction logic—**unfolding through combinatorial summation rather than field-theoretic integrals (Peskin & Schroeder, 1995).





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5. Synthesizing Quantum and Relativistic Geometry: Toward a Unified Field Interpretation

Having established that both **vector summation** and **angular curvature** can be discretely modeled within the 2D Quanta lattice, we now turn toward synthesis. This section explores how quantum amplitudes (traditionally computed via geometric volume in abstract space) and spacetime curvature (defined by differential geometry) can both be described by the **same combinatorial vector system—**paving the way for a unified interpretation of quantum and gravitational behavior, and unifying the amplitude-based formulations of quantum theory with the curvature-dependent geometry of general relativity.

5.1 In Quantum Mechanics

- The **Amplituhedron** encodes particle scattering amplitudes without reliance on spacetime locality. Instead, it computes probability magnitudes from constrained geometric volumes in abstract twistor-like spaces (Arkani-Hamed & Trnka, 2014; Witten, 2004).

- Within the **2D Quanta lattice**, vector summation defines a discrete geometry that mirrors these amplitude calculations. Each normalized vector pairing contributes to a bounded, combinatorial area whose structure reflects quantum amplitude magnitudes.

- This logic builds upon Penrose's early attempts to replace spacetime-based quantum dynamics with **combinatorial geometry**, where causal structure is emergent from directional relations (Penrose, 1971).

In short, **quantum amplitudes emerge from summation geometry**, not space-time continuity.

5.2 In General Relativity

The **curvature of spacetime** is defined by the **Einstein Field Equations** (Einstein, 1916), which relate the curvature tensor to the stress-energy tensor:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

In this equation:

- $G_{\mu\nu}$ represents spacetime curvature.
- $T_{\mu\nu}$ encodes local energy, momentum, and stress.
- G is Newton's gravitational constant, and c is the speed of light.

Lattice Interpretation:

If **local curvature** can be interpreted as emerging from **vector density** or **directional skew**—as visually encoded in the 2D Quanta diagrams—then these patterns may **mimic the effects of stress-energy** on curvature.

For example, an imbalance in vector flow—such as a higher concentration of steep, time-dilating vectors—produces a **bending of the overall lattice angle**, analogous to a **curved geodesic path** in spacetime.

Thus, in the 2D Quanta model:

- **Vector summation regions** function analogously to **localized energy-momentum tensors**.
- The **aggregate angular deviation** of the field corresponds to **spacetime curvature**, as in general relativity.

This interpretation parallels discrete gravity approaches such as **causal dynamical triangulations**, where curved manifolds emerge from the statistical weighting of local geometric elements (Ambjorn, Jurkiewicz, & Loll, 2009).

5.3 Toward Unification

The insights from Sections 5.1 and 5.2 converge in a powerful way:

- In **quantum theory**, the **volume** of allowable vector summations defines **probability amplitudes**.

- In **general relativity**, the **directional skew** of local vector configurations defines **spacetime curvature**.

Both amplitude and curvature—two seemingly distinct phenomena—are now seen as emergent from **the same conserved lattice structure**, governed by:

- Normalized directional summation: $|V_x| + |V_y| = 1$

- Angular composition and divergence

- Triangular and volumetric geometry

This perspective offers a candidate for **discrete unification**, where spacetime and quantum behavior emerge from **vectorial constraint and symmetry—**without requiring a continuous manifold.

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6. Unification Proposal: From 2D Quanta to the Amplituhedron

It is propose that the **Amplituhedron** may be interpreted not merely as a computational replacement for Feynman diagrams (Feynman, 1949), but as a **higher-dimensional projection** of structured vector behavior within a **2D Quanta lattice**. In this interpretation, **local vector configurations, cross-current summations, and angular density** encode both **quantum probability amplitudes** and **relativistic curvature**, uniting two previously disparate geometrical frameworks.

Each **triangular summation region** within the lattice acts as a **discrete geometric microstate**. Its orientation and combinatorial area correspond to:

- **Quantum amplitudes**, emerging from the cumulative structure of normalized vector pairings (Witten, 2004; Arkani-Hamed & Trnka, 2014), and

- **Spacetime curvature**, modeled by angular deviation, directional skew, and vector density—paralleling the influence of stress-energy in general relativity (Einstein, 1916; Misner, Thorne, & Wheeler, 1973).

The synthesized formulation suggests that:

- **Quantum behavior**, as encoded by the Amplituhedron, arises from **primitive vector interactions**. Each triangle in the 2D Quanta lattice represents a **volumetric unit of amplitude space**, governed by symmetric, energy-conserving summation rules ($|V_x| + |V_y| = 1$) (Penrose, 1971; Peskin & Schroeder, 1995).

- **Gravitational curvature**, described classically by the **Einstein Field Equations**:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

emerges as a macroscopic manifestation of **localized vector skew and summation imbalance**, analogous to how mass-energy curves spacetime (Ambjorn, Jurkiewicz, & Loll, 2009).

A Unified Substrate

Rather than viewing quantum and relativistic geometry as mutually incompatible, this framework suggests they are **dual projections** of the same **underlying vectorial substrate**. The **2D Quanta lattice** offers a candidate for this substrate—one in which:

- Geometry arises from directional summation,
- Probability emerges from combinatorial structure,
- Curvature is the angular echo of vector imbalance.

This view aligns with discrete quantum gravity models, such as **causal dynamical triangulations**, where continuum behavior emerges from **combinatorial coherence** (Ambjorn et al., 2009).

A Discrete Geometric Grammar

If validated, this model offers a novel unifying language—a **discrete, visual, and vectorial grammar** that bridges **amplitude-based quantum models** with **curvature-based relativistic ones**. The Amplituhedron becomes not an abstract computational artifact, but a **geometric holograph of a deeper reality—**one rooted in **2D combinatorial geometry**, where amplitude and curvature are **emergent consequences of vectorial constraint**.

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7. Implications and Future Research

The synthesis of quantum amplitude geometry and relativistic curvature within a discrete vector framework opens a new landscape of inquiry. The **2D Quanta lattice**, initially conceived as a symbolic geometric construct, may serve as a **foundational substrate—**capable of expressing core physical phenomena through vectorial summation, angular modulation, and combinatorial structure.

Several lines of research naturally follow:

- **Unitary Evolution and Quantum Logic**: The stepwise transformation of vector states within the lattice may be interpreted as discrete analogs of **unitary evolution operators—**with potential applications in modeling quantum gates, decoherence, and entanglement structure (Peskin & Schroeder, 1995).

- **Gravitational Lensing as Vector Skew**: Gravitational lensing, typically modeled as curvature of spacetime by mass, could be reinterpreted as a **vectorial skewing of cross-current pathways** within the lattice—producing observable deflection patterns consistent with general relativity (Misner, Thorne, & Wheeler, 1973).

• **Resonant Harmonics and Quantized Geometry**: Patterns of constructive interference among cross-currents may reveal **harmonic resonances**—potentially corresponding to **quantized curvature states** or standing-wave structures akin to early lattice gauge theory approaches to gravity (Kogut, 1979).

• **Spin Networks and Loop Quantum Gravity**: The angular connections and combinatorial joins of vector fields in the 2D Quanta model may reflect the logic of **spin networks** used in loop quantum gravity—where quantum states of geometry are defined by discrete links and nodes rather than continuous fields (Rovelli & Smolin, 1995; Ambjorn, Jurkiewicz, & Loll, 2009).

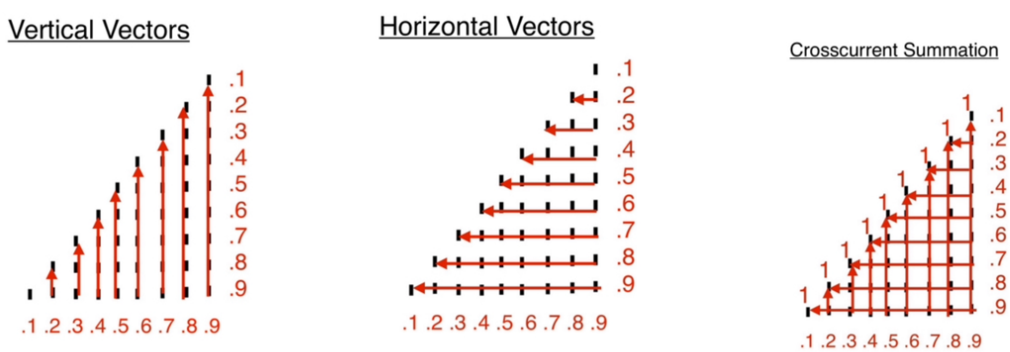
These research paths suggest that **space, time, and curvature** may all be **secondary constructs—** emerging from deeper patterns of **directional coherence and combinatorial constraint** within a discrete vector space.

Conclusion

This thesis has shown that quantum probabilities and spacetime curvature are not separate phenomena but discrete emergent expressions of a unified vectorial structure.

I propose that **2D Quanta lattices** are not merely illustrative abstractions, but potential candidates for a **foundational geometric substrate** from which both **quantum mechanics** and **general relativity** can emerge. Through the combinatorics of **directional vector summation** and the constraint:

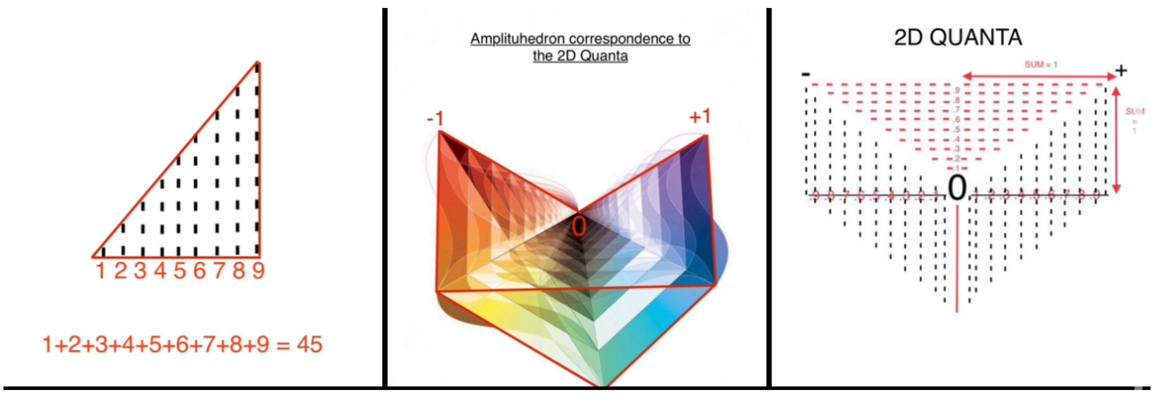
$$|V_x| + |V_y| = 1,$$



the lattice encodes both **quantum amplitudes—**via geometric area and probabilistic coherence (Witten, 2004; Arkani-Hamed & Trnka, 2014)—and **spacetime curvature**, as angular deviation and vector skew that mirror the influence of stress-energy tensors in Einstein's field equations (Einstein, 1916; Misner, Thorne, & Wheeler, 1973).

In this view, **space, time, and probability are not fundamental—they are emergent properties of a deeper, directional grammar.**

By reinterpreting the **Amplituhedron** as a **higher-dimensional projection** of discrete vector structures within the 2D Quanta lattice, this model bridges quantum field theory and general relativity through a shared geometric language. It does not attempt to unify these domains by forcefully reconciling their equations, but rather by revealing their **common origin in vectorial and combinatorial structure** (Penrose, 1971; Rovelli & Smolin, 1995).



This framework offers a compelling path toward the **unification of quantum mechanics and general relativity—**not through continuous fields or higher-dimensional strings, but through **discrete, recursive, and geometrically grounded symmetries** (Ambjorn, Jurkiewicz, & Loll, 2009; Peskin & Schroeder, 1995).

This discrete lattice-based approach not only supports emerging theories of quantum geometry but may also fulfill Tegmark's mathematical universe hypothesis by revealing spacetime itself as an emergent projection of vectorial arithmetic (Tegmark, 2008).

Ultimately, this thesis points to a new physical language—**symbolic, structural, and universal**—in which **probability and curvature are revealed to be dual projections of a single vectorial logic**.

References:

Ambjorn, J., Jurkiewicz, J., & Loll, R. (2009). *Quantum Gravity, or The Art of Building Spacetime*. In D. Oriti (Ed.), *Approaches to Quantum Gravity: Toward a New Understanding of Space, Time and Matter* (pp. 341–359). Cambridge University Press. ISBN: 978-0521860450

Arkani-Hamed, N., & Trnka, J. (2014). *The Amplituhedron*. *Journal of High Energy Physics*, 2014(10), 30. https://doi.org/10.1007/JHEP10(2014)030

Einstein, A. (1916). *The Foundation of the General Theory of Relativity*. In H. A. Lorentz, A. Einstein, H. Minkowski, & H. Weyl (Eds.), *The Principle of Relativity* (pp. 109–164). Dover Publications, 1952. (Original work published 1916)

Feynman, R. P. (1949). *Space-time approach to quantum electrodynamics*. *Physical Review*, 76(6), 769–789. https://doi.org/10.1103/PhysRev.76.769

Kogut, J. B. (1979). *An introduction to lattice gauge theory and spin systems*. *Reviews of Modern Physics*, 51(4), 659–713. https://doi.org/10.1103/RevModPhys.51.659

Misner, C. W., Thorne, K. S., & Wheeler, J. A. (1973). *Gravitation*. W. H. Freeman. ISBN: 978-0716703440

Penrose, R. (1971). *Angular momentum: An approach to combinatorial spacetime*. In T. Bastin (Ed.), *Quantum Theory and Beyond* (pp. 151–180). Cambridge University Press. ISBN: 978-0521081688

Peskin, M. E., & Schroeder, D. V. (1995). *An Introduction to Quantum Field Theory*. Westview Press. ISBN: 978-0201503975

Tegmark, M. (2008). *The Mathematical Universe*. *Foundations of Physics*, 38(2), 101–150. https://doi.org/10.1007/s10701-007-9186-9

Witten, E. (2004). *Perturbative gauge theory as a string theory in twistor space*. *Communications in Mathematical Physics*, 252(1–3), 189–258. https://doi.org/10.1007/s00220-004-1187-y