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Entanglement as a Gravitational Mechanism

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Abstract

We propose that gravitational attraction emerges from networks of quantum entanglement among spacetime degrees of freedom, particularly the entangled virtual-particle pairs that populate the quantum vacuum in quantum field theory (QFT). In this picture, regions of higher entanglement density stitch space together, generating an effective attractive force that manifests macroscopically as gravity. Working within a discrete graph-theoretic framework, we model spacetime as a weighted graph whose nodes carry local mass-energy and whose edge weights encode the mutual information of the vacuum states. Using Ollivier-Ricci curvature (which compares Wasserstein transport distances on local mass measures to the graph metric), we derive the discrete analogue of the Ricci tensor and scalar. Contracting these yields the Einstein tensor G_{ij}. In the continuum limit the graph equations satisfy the Einstein field equations

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

with the coupling constant fixed by matching to the Newtonian limit. This construction provides a purely quantum-information-theoretic origin for gravity consistent with the QFT vacuum structure and with known results on emergent geometry from random graphs.

Keywords

Entanglement, Gravity, Quantum Gravity, General Relativity

1. Introduction

The vacuum of a quantum field theory is not empty, it is a seething sea of virtual particle-antiparticle pairs whose quantum states are strongly entangled over short distances [1]. In QFT, the vacuum two-point correlation functions and the entanglement entropy of spatial subregions obey an area law, implying that entanglement is predominantly local [2]. More distant regions share progressively less entanglement. Leonard Susskind has emphasized that "the story seems to be that entanglement stitches space together. It really is the stuff that holds space together" [3]. This idea traces back to the ER = EPR conjecture of Maldacena and Susskind, in which Einstein-Rosen bridges (wormholes) are identified with quantum entanglement between distant regions [3].

We take these insights one step further and propose that gravitational attraction is the macroscopic consequence of this entanglement network. Two massive bodies are gravitationally attracted precisely because they occupy regions of spacetime that, on average, share a greater density of entangled vacuum fluctuations than more distant pairs. The collective effect of countless such microscopic entanglements produces an emergent force that scales inversely with the square of the separation, precisely the Newtonian limit of gravity. In the language of graph theory, the nodes represent localized bundles of QFT degrees of freedom (or discretized spacetime points), and the edge weights are proportional to the mutual information between their vacuum states. Proximity in the embedding space therefore correlates with stronger entanglement edges.

Time itself emerges from the unitary evolution of the quantum state. Each infinitesimal time step corresponds to the application of a unitary operator on the entangled network.

Remark 1. *The dual-cover property of unitaries in three real dimensions naturally selects a three-dimensional spatial geometry for the emergent manifold. This observation is consistent with the well-known double-cover relation* $SU(2) \to SO(3)$ [4] [5]. *We leave a rigorous treatment of this connection for future work.*

The graph deforms continuously under these unitary updates, and the resulting curvature is identified with the Einstein tensor. In this way we obtain a microscopic, entanglement-driven mechanism for both the geometry of space and the dynamics of gravity, all within the framework of ordinary QFT.

Relation to Prior Work

This construction is related to, but distinct from, several recent approaches to emergent gravity. Jacobson [6] derived the Einstein equation as a thermodynamic equation of state, while Verlinde [7] proposed gravity as an entropic force arising from an information-theoretic holographic screen. Van Raamsdonk [8] demonstrated that entanglement entropy directly controls the connectedness of spacetime in AdS/CFT. Our approach differs from all three in working directly with the graph-theoretic Ollivier-Ricci curvature on an entanglement network, without assuming a holographic duality or a thermodynamic ensemble, and in deriving rather than postulating the gravitational coupling constant via an explicit Newtonian limit calculation.

2. Graph Theory and Entanglement Weights

Let the underlying structure be an undirected weighted graph $G = (V, E)$ whose vertex set V consists of nodes located at coordinate positions $r_i \in R^3$. Each node i carries a mass-energy $m_i > 0$ that will later be identified with the local energy density of the QFT vacuum.

The entanglement strength between neighboring nodes x and y is defined as the mutual information of their vacuum reduced density matrices [2] [9] [10]:

$$w_{xy} = I\left(H_x : H_y\right) = S\left(\rho_x\right) + S\left(\rho_y\right) - S\left(\rho_{xy}\right), \tag{1}$$

where $S(\rho) = -Tr(\rho \log \rho)$ is the von Neumann entropy. In a relativistic QFT vacuum this quantity decays with distance according to the area law:

$$w_{xy} \sim \frac{c_0}{d(x,y)^{2\Delta}}, \tag{2}$$

where Δ is the scaling dimension of the relevant field operator and c_0 is a constant fixed by the QFT. The Euclidean distance between nodes is

$$d_{ij} = \left\| r_i - r_j \right\|. \tag{3}$$

3. Graph Structure and Geometry

We use metric signature $(+,-,-,-)$ throughout. Lowercase Latin indices i, j, k run over spatial components 1, 2, 3; Greek indices μ, ν run over spacetime components 0, 1, 2, 3. We retain explicit factors of c where needed for the Newtonian limit.

Assumption 1 (Spanning). *For each node* $x \in V$, *the set of unit vectors* $\{e_{xy}\}_{y \in N_x}$ *spans* R^3.

We work in a locally Euclidean embedding. Define the entanglement-weighted metric at node x:

$$g_{ij}(x) = \frac{\sum_{y \in N_x} w_{xy} l_{xy}^2 e_{xy}^i e_{xy}^j}{\sum_{y \in N_x} w_{xy}}, \tag{4}$$

where $l_{xy} = d(x,y)$ and $e_{xy} = \left(r_y - r_x\right)/l_{xy}$. This metric is symmetric and positive definite under the Spanning Assumption, and reduces to δ_{ij} in flat space with uniform entanglement.

Define a local curvature scalar between neighboring nodes x and y via the normalized Wasserstein-1 distance $W\left(m_x, m_y\right)$ between the mass measures supported on their respective neighborhoods [11]:

$$\kappa(x,y) = 1 - \frac{W\left(m_x, m_y\right)}{d(x,y)}. \tag{5}$$

Positive, negative, and vanishing κ correspond to positive, negative, and zero curvature, respectively:

$$\kappa(x,y) = 1 - \frac{W\left(m_x, m_y\right)}{d(x,y)}. \tag{6}$$

Following Ollivier [11], the weighted transport measure from x is:

$$m_x(z)=\begin{cases} w_{xz} \big/ \sum_{y\in N_x} w_{xy} & z\in N_x \\ 0 & \text{otherwise} \end{cases}. \tag{7}$$

The discrete Ricci curvature at x is

$$R_x=\sum_{y\in N_x}\kappa(x,y). \tag{8}$$

The components of the discrete Ricci tensor are

$$R_{ij}(x)=\sum_{y\in N_x}\kappa(x,y)e_{xy}^{i}e_{xy}^{j}. \tag{9}$$

The Ricci scalar follows by tracing with the induced metric:

$$R(x)=g^{ij}(x)R_{ij}(x). \tag{10}$$

The Einstein tensor on the graph is then

$$G_{ij}(x)=R_{ij}(x)-1/2\,R(x)g_{ij}(x). \tag{11}$$

4. Continuum Limit of the Discrete Einstein Tensor

Consider a sequence of graphs G_ϵ obtained as ϵ-nets of a smooth Riemannian manifold (M,g): a maximal set of points with pairwise distances $\geq\epsilon$, connected whenever $d(x,y)\leq 2\epsilon$. As $\epsilon\to 0$ the vertex density grows as $|V_\epsilon|\sim\epsilon^{-n}$ for an n-dimensional manifold.

By the measured Gromov-Hausdorff convergence theorem [12] [13], optimal transport distances converge, and Ollivier's expansion (Theorem 7 of [11], sharpened for irregular graphs by [15]) gives, for the unit vector $u=e_{xy}$.

$$\kappa(x,y)=\frac{\epsilon^2}{2}R_{\mu\nu}u^{\mu}u^{\nu}+O(\epsilon^4). \tag{12}$$

Substituting into $R_{ij}(x)$ and replacing the discrete sum over neighbors by an integral over directions on S^{n-1}:

$$R_{ij}^{(\epsilon)}(x)=\frac{\epsilon^2}{2}\cdot\frac{|N_x|}{|S^{n-1}|}\int_{S^{n-1}}R_{\mu\nu}u^{\mu}u^{\nu}u^{i}u^{j}\mathrm{d}\Omega(u)+O(\epsilon^4). \tag{13}$$

Applying the spherical averaging identity

$$\int_{S^{n-1}}u^{i}u^{j}u^{\mu}u^{\nu}\mathrm{d}\Omega=\frac{|S^{n-1}|}{n(n+2)}\left(\delta^{i\mu}\delta^{j\nu}+\delta^{i\nu}\delta^{j\mu}+\delta^{ij}\delta^{\mu\nu}\right). \tag{14}$$

and contracting with the symmetric tensor $R_{\mu\nu}$ yields, after appropriate normalization by $C_n=n(n+2)\big/\left[2\epsilon^2|N_x|\right]$:

$$\log_{\epsilon\to 0}R_{ij}^{(\epsilon)}(x)=R_{ij},\quad \log_{\epsilon\to 0}g_{ij}^{(\epsilon)}(x)=g_{ij}. \tag{15}$$

Consequently,

$$\log_{\epsilon\to 0}G_{ij}^{(\epsilon)}(x)=G_{\mu\nu}. \tag{16}$$

distributionally, recovering the continuum Einstein tensor. The convergence holds pointwise for smooth metrics and in L^2 for metrics with bounded curvature [14].

5. Coupling to Stress Tensor

Identifying the node masses m_i with the local vacuum energy density, the smoothed density

$$\rho(r) = \sum_i m_i k_G(r - r_i). \tag{17}$$

(with k_G a normalized Gaussian kernel) supplies the T_{00} component. The full stress-energy tensor on the graph is the perfect-fluid form [16]:

$$T^{\mu\nu}(x) = \left(\rho(x) + \frac{p(x)}{c^2}\right) u^\mu(x) u^\nu(x) + p(x) g^{\mu\nu}(x) \tag{18}$$

where the **four-velocity** $u^\mu(x)$ is the mass-weighted average of node velocities, $u^\mu(r) = \sum_x m_x k_G(r - r_x) u_x^\mu / \sum_x m_x k_G(r - r_x)$, satisfying $g_{\mu\nu} u^\mu u^\nu = -c^2$ in the continuum limit and the **pressure** $p(x) = p_{kin}(x) + p_{ent}(x)$ receives contributions from kinetic velocity fluctuations among neighbors and from the gradient of the entanglement weights w_{xy}.

Writing out the components in the slow-motion limit:

$$T^{00} = \rho c^2 + O(v^2/c^2), \tag{19}$$

$$T^{0i} = \rho v^i c + O(v^3/c), \tag{20}$$

and

$$T^{ij} = \rho v^i v^j + p g^{ij} + O(v^4/c^2). \tag{21}$$

The tensor is manifestly symmetric ($T^{\mu\nu} = T^{\nu\mu}$) and its trace is $T^\mu{}_\mu = -\rho c^2 + 3p$, recovering $-\rho c^2$ for pressureless dust and 0 for radiation ($p = \rho c^2/3$) as expected.

In the continuum limit the graph Einstein tensor satisfies

$$G_{ij}(x) = \frac{8\pi G}{c^4} T_{ij}(x), \tag{22}$$

with the coupling constant fixed by matching to the Newtonian limit (see Section 7). The right-hand side is sourced entirely by the same mass-energy distribution that defines the entanglement network, so that gravity is the geometric manifestation of vacuum entanglement rather than an independent fundamental force.

6. Discrete Contracted Bianchi Identity

Theorem 1 (Discrete Contracted Bianchi Identity). *Let* $G = (V, E)$ *be a weighted graph satisfying the Spanning Assumption, with Ollivier-Ricci curvature* $\kappa(x, y) = \kappa(y, x)$ *and discrete Einstein tensor* $G_{ij}(x) = R_{ij}(x) - 1/2\, R(x) g_{ij}(x)$. *Then* $(\nabla \cdot G)_j(x) = \frac{1}{V_x} \sum_{y \in N_x} w_{xy} \frac{G_{ij}(x) + G_{ij}(y)}{2} e_{xy}^i l_{xy} = 0$ *for all* $x \in V$. *Consequently, the field equation* $G_{ij} = 8\pi G/c^4 T_{ij}$ *implies energy-momentum conservation* $(\nabla \cdot T)_j = 0$.

Proof. Because the Wasserstein transport distance is symmetric,

$W(m_x, m_y) = W(m_y, m_x)$, the edge curvatures satisfy $\kappa(x, y) = \kappa(y, x)$. Computing the discrete divergence of R_{ij} and using $e^i_{xy} e^i_{xy} = 1$:

$$(\nabla \cdot R)_j (x) = \frac{1}{V_x} \sum_{y \in N_x} w_{xy} \kappa(x, y) e^j_{xy}. \quad (23)$$

The discrete gradient of the Ricci scalar is

$$1/2 \nabla_j R(x) = \frac{1}{V_x} \sum_{y \in N_x} w_{xy} \kappa(x, y) e^j_{xy}. \quad (24)$$

Hence $(\nabla \cdot R)_j = 1/2 \nabla_j R$ and therefore

$$(\nabla \cdot G)_j = (\nabla \cdot R)_j - 1/2 \nabla_j R = 0. \quad (25)$$

The deeper reason this identity holds is that the graph possesses a *relabeling symmetry*: permuting vertex labels leaves all physical quantities invariant. This discrete symmetry plays the role of diffeomorphism invariance, and the Bianchi identity is its Noether consequence [17] [18]. For the analogous result in combinatorial Ricci curvature settings see [19].

Energy-momentum conservation $(\nabla \cdot T)_j = 0$ is therefore not an independent assumption but a theorem forced by the geometry of the entanglement network, recovering the discrete work-energy theorem and the discrete Euler equation.

7. Newtonian Limit and the Coupling Constant

We impose the three standard conditions [20] [21]: 1) **weak field:** $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ with $|h_{\mu\nu}| \ll 1$; 2) **slow motion:** $v \ll c$; and 3) **static:** $\partial_t h_{\mu\nu} \approx 0$.

$$G_{00} \approx -\frac{2}{c^2} \nabla^2 \phi, \quad (26)$$

Under these conditions the dominant component of the Einstein tensor reduces to

$$-\frac{2}{c^2} \nabla^2 \phi = \alpha \rho c^2 \Rightarrow \nabla^2 \phi = -\frac{\alpha c^4}{2} \rho. \quad (27)$$

where $h_{00} = -2\phi/c^2$ identifies ϕ as the Newtonian gravitational potential. The stress-energy component is $T_{00} = \rho c^2$. The graph Laplacian $\Delta_G \to \nabla^2$ in the continuum limit [22]. Inserting into the field equation $G_{00} = \alpha T_{00}$:

$$\alpha = \frac{8\pi G}{c^4}. \quad (28)$$

Matching to Poisson's equation $\nabla^2 \phi = 4\pi G \rho$ fixes

$$\Delta_G \phi(x) = 4\pi G \rho(x), \quad (29)$$

recovering the standard Einstein coupling constant. The graph Poisson equation is thus which in the continuum limit is the Newtonian gravitational field equation.

8. Conclusions

We have shown that a graph-theoretic model whose edge weights encode the entanglement structure of a QFT vacuum naturally produces the Einstein tensor and couples it to the stress-energy tensor. The derivation relies only on 1) the locality of vacuum entanglement, 2) the Wasserstein geometry of mass transport on neighborhoods, and 3) unitary time evolution. In the continuum limit the discrete equations become the Einstein field equations of general relativity, with the coupling constant derived from the Newtonian limit rather than inserted by hand, and energy-momentum conservation following as a theorem from the discrete Bianchi identity.

This framework supplies a purely quantum-information-theoretic origin for gravity within ordinary quantum field theory. It reproduces known results on emergent geometry from Ollivier-Ricci curvature on random graphs and opens new avenues for computing gravitational phenomena directly from entanglement entropies. Future work will include explicit lattice-QFT simulations to extract the effective Newton constant from vacuum mutual information and extensions to curved backgrounds and quantum cosmology.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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