

# Gravity from Entanglement Entropy Density

Therodynamic and Covariant Constraints on Emergent Spacetime

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## 1 1. Universe Entropy Constraint

**Rigorous:** From statistical mechanics,

$$S = k_B \ln \Omega,$$

where  $\Omega$  is the number of accessible microstates. For a closed quantum system (the universe), the second law enforces

$$\frac{dS_{\text{universe}}}{dt} \geq 0.$$

We partition total entropy into effective sectors:

$$S_{\text{universe}} = S_{\text{matter}} + S_{\text{ent}}^{(\text{env})} \geq \text{constant}, \quad (1)$$

where  $S_{\text{ent}}^{(\text{env})}$  denotes the entropy associated with vacuum correlations and coarse-grained entanglement degrees of freedom.

**Physical:** No physical process destroys global quantum state accessibility; entropy may be redistributed but not eliminated.

## 2 2. Vacuum vs Operational Entanglement Entropy

**Rigorous:** In relativistic QFT, vacuum entanglement across causal boundaries obeys an *area law* (e.g. Ryu–Takayanagi):

$$S_{\text{vac}} \propto \frac{A}{4G}.$$

However, in finite laboratory systems and coarse-grained many-body states, the relevant entropy is an *operational entanglement entropy density*, defined after tracing over environmental and UV degrees of freedom:

$$S_{\text{ent}}^{(\text{op})} = \int \left( \frac{S_{\text{ent}}}{V} \right) dV. \quad (2)$$

This quantity is not vacuum entanglement in the holographic sense, but a regulated, scale-dependent information density.

**Physical:** The vacuum is maximally entangled microscopically, but only a fraction of that entanglement remains coherent and operationally accessible at macroscopic scales.

## 3 3. Matter-Induced Entanglement Gradients

**Rigorous:** Local energy density  $T_{\mu\nu}$  perturbs vacuum correlations via mode excitation, Unruh-like effects, and decoherence. Tracing over excited modes reduces the local reduced density matrix entropy:

$$\partial_i \left( \frac{S_{\text{ent}}}{V} \right) \propto -\rho_{\text{mass}}. \quad (3)$$

This defines an entanglement entropy gradient sourced by matter.

**Physical:** Mass locally depletes coherent vacuum correlations, producing an informational imbalance.

## 4 4. Thermodynamic Origin of Gravitational Force

**Rigorous:** Extremizing total entropy along worldlines,

$$\delta \int S_{\text{universe}} d\tau = 0,$$

yields an entropic force

$$\vec{F} = -T_{\text{vac}} \nabla S_{\text{ent}}, \quad T_{\text{vac}} \sim \frac{\hbar c}{\ell_P}.$$

Thus,

$$\vec{F}_{\text{grav}} \propto -\nabla \left( \frac{S_{\text{ent}}}{V} \right) \propto +\nabla \rho_{\text{mass}}. \quad (4)$$

**Physical:** Gravity is the relaxation force that restores entanglement equilibrium.

## 5 5. Effective Gravitational Coupling

**Rigorous:** Dimensional analysis:

$$[\hbar c] = ML^2T^{-2}, \quad \left[ \nabla \left( \frac{S_{\text{ent}}}{V} \right) \right] = L^{-4},$$

yields

$$G_{\text{eff}} \sim \hbar c \left| \nabla \left( \frac{S_{\text{ent}}}{V} \right) \right|. \quad (5)$$

**Physical:** Newton's constant emerges from information gradients rather than being fundamental.

## 6 6. Covariant Field Equations and Conservation

**Rigorous:** The effective Einstein equation is

$$G_{\mu\nu} = 8\pi G (T_{\mu\nu} + T_{\mu\nu}^{\text{ent}}), \quad (6)$$

with

$$T_{\mu\nu}^{\text{ent}} = \frac{\kappa}{8\pi G} \frac{c^4}{k_B \ln 2} S_{\text{ent}}(x) g_{\mu\nu}.$$

The Bianchi identity enforces

$$\nabla^\mu (T_{\mu\nu} + T_{\mu\nu}^{\text{ent}}) = 0, \quad (7)$$

implying an energy-momentum exchange:

$$\nabla^\mu T_{\mu\nu} = -\frac{1}{8\pi G} \partial_\nu \left( \kappa \frac{c^4}{k_B \ln 2} S_{\text{ent}} \right). \quad (8)$$

**Physical:** Entanglement gradients do not violate conservation; they mediate energy exchange between coarse-grained sectors.

## 7 7. Screening and Decoherence

**Rigorous:** Only the long-range coherent fraction of entanglement contributes gravitationally. Define

$$\alpha_{\text{screen}}(L) = \frac{S_{\text{ent}}^{\text{coh}}(L)}{S_{\text{ent}}^{\text{total}}(L)} \sim e^{-\Gamma(L)\tau}, \quad (9)$$

where  $\Gamma(L)$  is the decoherence rate at scale  $L$ .

**Physical:** Environmental decoherence screens gravity by destroying long-range quantum correlations.

## 8 8. Universe Health Codes

### Stability Fixed Point

$$\nabla \left( \frac{S_{\text{ent}}}{V} \right) = 0 \quad \Rightarrow \quad \text{stable vacuum} \quad (10)$$

### Hard Rejects

$$\Delta S_{\text{universe}} < 0 \quad \Rightarrow \quad \text{unitarity violation} \quad (11)$$

**Examples:** Closed timelike curves, tachyons, negative-energy runaway states.

### Persistence Feedback

$$\left| \nabla \left( \frac{S_{\text{ent}}}{V} \right) \right| \uparrow \quad \Rightarrow \quad G_{\text{eff}} \uparrow \quad (12)$$

## 9 Predictions

- Inverse-square force from correlation dilution
- Black-hole entropy as horizon entanglement
- Mass–temperature equivalence:  $m \sim k_B T_{\text{vac}} \ln 2$
- Cosmological constant from baseline entanglement density
- Gravity as entanglement homeostasis

## 10 Source

<https://github.com/mssinternetmarketing-cyber/entropy-gravity-coupling>

*Thermodynamics demands covariant quantum accounting.*