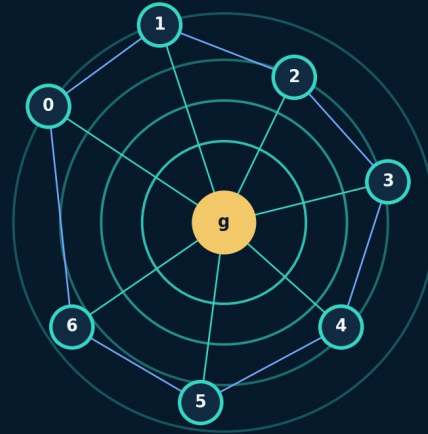


QUANTUM GRAVITON COMPUTING

A five-state register model in 3+1D

Entanglement • Dynamics • Readout



WORKING FRAMEWORK / VERSION 1.0

QUANTUM GRAVITON COMPUTING

A 3+1D framework for five-state gravitational registers, entanglement, dynamics, and classical signal extraction

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Working research manuscript • Version 1.0 • October 2026

READING KEY

This manuscript is deliberately ambitious about the computational architecture and deliberately strict about evidence. The five-level graviton qdit is a working hypothesis; it is not an experimentally established property of the graviton. The reference simulator implements abstract five-level quantum circuits, not quantum gravity.

Author's note: what this manuscript does—and does not —claim

This document consolidates the graviton-computation work developed across the revised 3+1D Theory of Everything manuscript, the dark-sector revision, the four-dimensional wormhole revision, the epistemic-field analysis, the dimensional-cost memorandum, and the recent QGC/QCL discussions. Its architecture supersedes the older use of extra spatial dimensions as a convenient mathematical scaffold. The current framework is written directly on 3+1-dimensional spacetime; internal quantum-state dimension is kept distinct from spacetime dimension.

The chosen working name is **Quantum Graviton Computing (QGC)**. Its software-facing language is called **QCL-1.0** (Quantum Computational Language, provisional). The framework defines a five-level register, operator algebra, multi-register state space, gates, entanglement operations, open-system channels, measurement, parameter estimation, execution semantics, opcode catalogue, a reference simulator, and a falsification program.

A crucial boundary remains: a fully specified abstract quantum-computing model is not yet a complete microscopic theory of gravity. For the latter, QGC still owes a Lorentz-consistent relation between its five-state register and gravitational field degrees of freedom; a covariant action or Hamiltonian; constraint and gauge treatment; a classical limit recovering General Relativity; stability and unitarity; and numerical predictions that differ from the baseline in a controlled, testable way. The manuscript identifies those obligations rather than disguising them as completed calculations.

THE OPERATING RULE

The register algebra is defined here. Its identification with nature is not. Mathematical completeness at the software layer must not be misreported as empirical or microscopic completeness at the physics layer.

Abstract

Quantum Graviton Computing (QGC) is proposed as a computational framework in which a gravitational-sector quantum degree of freedom is represented by a five-level quantum register, or qdit, and assemblies of registers evolve through unitary transformations, entangling interactions, open-system channels, and measurements. The immediate objective is to make the idea operational: define a state space, a compositional semantics, an opcode set, a domain-specific language, a simulator, and criteria for translating abstract state transformations into physical gravitational predictions. The larger Theory of Everything interpretation is that physical distinctions and relations may be instantiated in the dynamics of the gravitational sector, with observable spacetime arising as an effective description. That interpretation remains a hypothesis.

The manuscript separates three propositions that must not be collapsed. First, the mathematics of five-level quantum systems is standard: a single qdit lives in a five-dimensional complex Hilbert space; N qdits occupy a 5^N -dimensional tensor-product space; generalized Pauli operators, the five-point Fourier transform, controlled-add gates, entangled states, density matrices, decoherence channels, and Born-rule measurements can all be defined exactly. Second, the physical graviton model is constrained by conventional spin-2 physics: a massless spin-2 field in 3+1D has two radiative helicities, while a conventional massive spin-2 representation has five physical polarizations. Those are different representations. Third, QGC's claim that a fundamental gravitational degree of freedom behaves as a five-state computational register—and that two designated directions recover the observed massless infrared sector—is a TOE-specific hypothesis that requires derivation.

QCL-1.0 specifies registers, state preparation, generalized single-qdit gates, controlled interactions, model-bound evolution, noise channels, measurement, classical estimation, and validation assertions. A NumPy reference implementation executes the abstract state-vector subset and demonstrates Bell-like five-level entanglement, GHZ-like multipartite states, a simple phase-sensing experiment, and stochastic dephasing trajectories. The manuscript then specifies how physical coupling would need to enter through a derived interaction Hamiltonian, and how signal extraction would proceed from quantum evolution to detector records, likelihoods, uncertainty, and comparison with General Relativity. The epistemic field, dark-

sector extensions, lensing, black holes, and wormhole channels are treated as optional research modules rather than assumptions smuggled into the core.

The result is a comprehensive research architecture, not a claim that gravitons have been manipulated or that QGC has been experimentally confirmed. Its success criterion is demanding: recover known gravitational physics, define a unique physical map from register states to observables, make an independent quantitative prediction, and survive an adversarial comparison with data. Reality retains veto power.

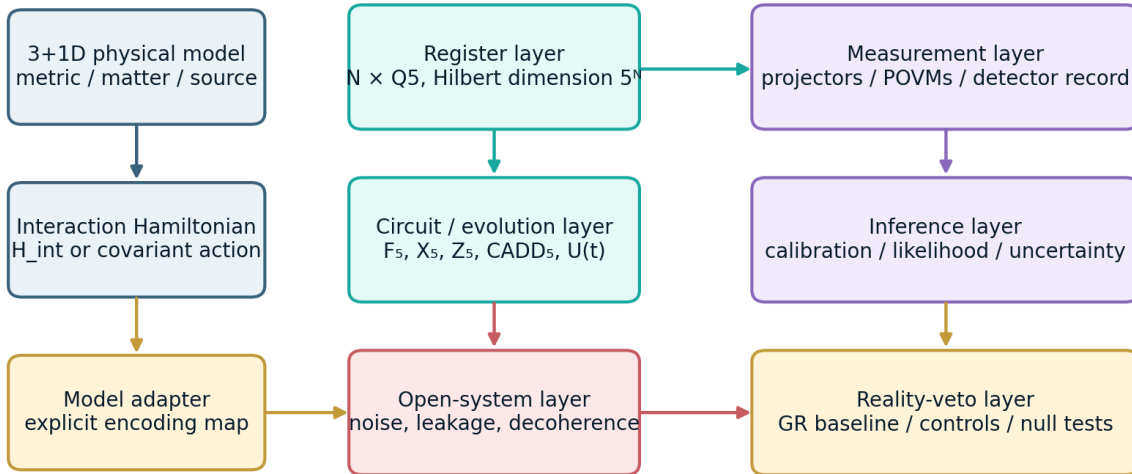
Executive summary

The whole framework can be read as seven linked layers:

- **Physical baseline:** 3+1D General Relativity and quantum theory define the known limits that any gravitational register must respect.
- **Register hypothesis:** a local abstract gravitational register has Hilbert space $\mathcal{H}_5 \cong \mathbb{C}^5$. Five is a computational dimension, not a claim of five massless-helicity states or five spatial dimensions.
- **Composition:** N registers form $\mathcal{H}_5^N$. Interactions produce entanglement; assemblies require tensor-network or hypergraph descriptions when pairwise edges are insufficient.
- **Dynamics:** quantum gates are unitary maps or explicitly defined quantum channels. A physical graviton gate must eventually be derived from an action or Hamiltonian, not named into existence.
- **Open-system behavior:** decoherence suppresses accessible off-diagonal coherence through correlations with unobserved degrees of freedom. It is distinct from measurement, information extraction, and classical inference.
- **Readout:** detector records are classical data. Calibration, statistical estimation, uncertainty analysis, and null tests turn records into defensible claims.
- **Reality veto:** the qdit-to-gravity map, classical limit, stability, covariance, and distinguishing predictions must be derived. An abstract circuit cannot establish a microscopic gravitational ontology.

QGC SYSTEM ARCHITECTURE

Separate the mathematical register from the physical realization



**Only the software/register layer is currently executable in the reference simulator.
Physical adapter and graviton-specific dynamics remain to be derived.**

Figure 1. QGC architecture. The abstract register and software layers are executable in the reference simulator; the model adapter and graviton-specific dynamics remain open physical tasks.

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PART I — FOUNDATIONS

1. Scope and design problem

A computational framework for gravitons has to answer two different questions. The first is an engineering-of-mathematics question: what objects are states, what are legal operations, how do subsystems compose, what does measurement return, and how can results be reproduced? The second is a physics question: which actual gravitational degrees of freedom, if any, instantiate those objects and operations? QGC separates the questions so that the first can be specified and tested while the second remains open to derivation.

The framework has four immediate purposes. It provides a precise language for assemblies of five-level registers; it makes entanglement, noise, and readout operational; it forces a candidate gravity interaction to be specified where the physics enters; and it defines failures in advance. A notation that merely renames unknown physics as “computation” is not enough. Every physical opcode must correspond to a derived transformation, and every proposed new effect must have an observable and a parameterized prediction.

1.1 The computational object

QGC calls an abstract five-level subsystem a **Q5 register** or **graviton qdit**. “Qdit” means a d-level quantum information carrier; here $d = 5$. The name “graviton qdit” is the model interpretation, not proof that a physical graviton has five internal levels. Until a physical realization is derived, Q5 is a mathematically specified register associated with a possible gravitational sector.

1.2 The operational boundary

The minimum executable model comprises state initialization, quantum gates, entanglement operations, unitary evolution, projective measurement, repeated shots, and a simple stochastic open-system channel. Density-matrix analysis, generalized POVMs, calibrated detector response, parameter fitting, and gravity-specific model adapters are specified at the language level; some require future backend implementation beyond the included pure-state reference simulator. The distinction between specified semantics and implemented code is tracked explicitly.

1.3 What counts as progress

- A claim is **formal progress** when terms are defined and equations are internally consistent.
- A claim is **model progress** when dynamics, parameters, constraints, and initial/boundary conditions are fixed well enough to compute outputs.
- A claim is **physical progress** when outputs are tied to operational observables and survive comparison with conventional alternatives.
- A claim is **empirical support** only when relevant data discriminate it from the alternatives with stated uncertainty.

2. Epistemic contract and claim hierarchy

The wider TOE begins with A0: **ALL IS EPISTEMIC**. In this project, “epistemic” is used as an ontological proposal about physical differentiation, relation, and measure—not merely as the familiar statement that human knowledge is mediated by observations. QGC translates that philosophical starting point into a research direction: lawful state changes and correlations may be computational primitives of physical reality. A0 is the chosen premise of the TOE; it does not logically force a unique five-state register, a graviton qdit, an I-field, or a particular interaction law.

The project therefore adopts a claim ladder. The lower levels can be validated without assuming the higher ones. A software pass does not prove the physical hypothesis; a quantum-gravity signature would not by itself prove the entire TOE; and a fit to a dark-sector dataset would not establish a new ontology if conventional models explain it equally well.

Level	Claim	What would support it	What it does not establish
C0 — Mathematics	A five-level quantum circuit model is well-defined.	Unitary checks, normalized states, correct probabilities, independent reproduction.	Any physical graviton exists or uses Q5.
C1 — Quantum model	The selected register dynamics show predicted entanglement/coherence behavior.	State tomography or equivalent observables in a real platform; channel characterization.	That the platform is made of gravitons.
C2 — Gravity interface	A derived gravitational interaction realizes a QCL operation or channel.	Action/Hamiltonian, conserved quantities, calibrated prediction, controls.	That the five-state register is fundamental.
C3 — Five-state hypothesis	A physical gravitational subsystem requires the Q5 state structure.	A distinctive, replicated signature excluding two-helicity-only models and alternatives.	The rest of the TOE automatically follows.
C4 — TOE interpretation	Q5 dynamics are a computational primitive of spacetime/geometry.	A complete microscopic-to-classical derivation and independent predictions.	A0 becomes experimentally proven by definition.

NO SACRED VARIABLES

A0 is preserved as the TOE’s chosen assumption, but no downstream object is immune from correction. “Reality wins” is a methodology, not an empirical finding.

3. The physical graviton baseline

In perturbative General Relativity, one writes a metric as a background plus a small perturbation, for example $g_{\mu\nu} = \bar{g}_{\mu\nu} + \kappa h_{\mu\nu}$. In a regime where the linearized gravitational field is quantized, the graviton is the hypothetical quantum associated with $h_{\mu\nu}$. Classical gravitational waves are experimentally observed, beginning with the direct detection reported in 2016 [14]. That observation is not the same as detecting one graviton or measuring a five-state gravitational register.

3.1 Two-helicity massless baseline

In 3+1 dimensions, a conventional **massless spin-2** field has two physical radiative helicities, $\lambda = +2$ and $\lambda = -2$. In the classical wave description these correspond to the two independent tensor polarizations often expressed as plus and cross. Gauge constraints remove unphysical components. Any QGC model claiming to recover ordinary long-range gravity must reproduce this low-energy sector and its successful tests [1].

$$h_{\mu\nu}(x) = \sum_{\lambda \in \{-2, +2\}} h_{\lambda}(x) \epsilon(\lambda)_{\mu\nu}(x) \quad (\text{massless radiative sector})$$

3.2 Five polarizations in a massive spin-2 representation

A conventional **massive spin-2** field has five physical polarizations, commonly labelled by spin projection $m \in \{-2, -1, 0, +1, +2\}$ in an appropriate rest-frame description. Fierz–Pauli theory supplies a standard free linear template; a consistent nonlinear theory faces additional constraints and stability requirements [2–4]. The fact that this representation has five states is useful mathematical scaffolding for a five-state qdit hypothesis. It is not evidence that the ordinary massless graviton has five helicities, and it does not by itself identify a massive graviton with QGC’s proposed internal register.

3.3 Experimental status and the 2026 context

At the date of this manuscript, an experimentally confirmed individual graviton has not been reported. The field is not without experimental proposals: quantum-sensing work has analyzed possible single-graviton absorption/emission signatures in highly controlled resonators [6,7]. A separate analysis emphasizes that a single-graviton-compatible signal does not automatically exclude every classical-wave explanation [5]. These are important developments, but proposals and theoretical feasibility analyses are not measurements of a graviton, and none has established QGC’s five-state structure.

A second route tests whether gravity can mediate entanglement between quantum matter systems. Proposals by Bose and collaborators and by Marletto and Vedral argue that entanglement under carefully justified assumptions can witness quantum features of the mediator [8,9]. Such a result would be important evidence about gravity’s quantum character, but it would not by itself demonstrate a fundamental five-level graviton qdit or establish that individual gravitons were detected.

NON-NEGOTIABLE DISTINCTION

(i) observed classical gravitational waves, (ii) evidence that gravity has quantum features, (iii) detection or inference of single-quantum exchange, and (iv) evidence for a five-state QGC register are four different evidential milestones.

4. The five-state qdit hypothesis

QGC adopts a five-dimensional complex Hilbert space as its working register: $\mathbb{H}_g \equiv \mathbb{C}^5$. Its computational basis is $|0\rangle, |1\rangle, |2\rangle, |3\rangle, |4\rangle$. A normalized pure state is $|\psi_g\rangle = \sum_{j=0}^4 a_j |j\rangle$, with $\sum_j |a_j|^2 = 1$. A general state, including classical uncertainty or entanglement with unobserved degrees of freedom, is a density operator ρ_g satisfying $\text{Tr} \rho_g = 1$ and $\rho_g \geq 0$.

$$|\psi_g\rangle = a_0|0\rangle + a_1|1\rangle + a_2|2\rangle + a_3|3\rangle + a_4|4\rangle, \quad \sum_j |a_j|^2 = 1$$

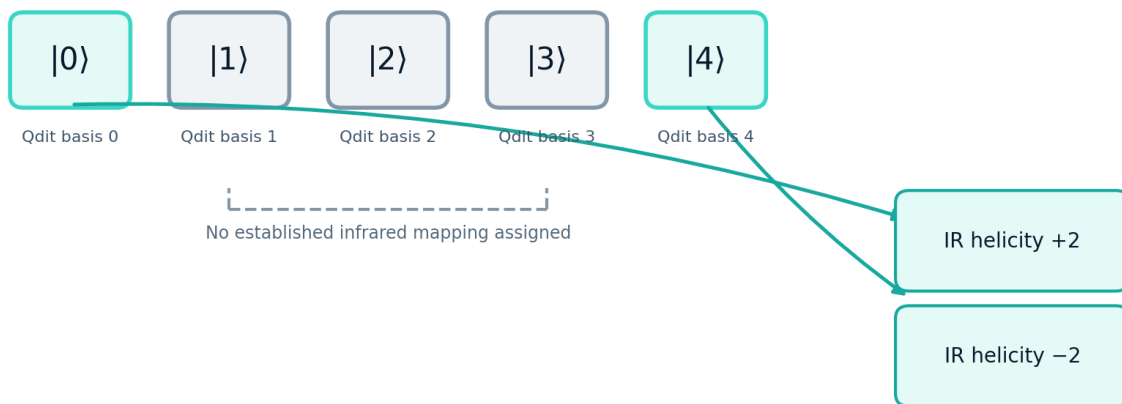
The basis labels are computational labels until a model assigns them physical meaning. Two candidate readings must remain distinct:

- **Massive-spin-2 reading:** identify the five labels with the conventional spin projections $m = -2, -1, 0, +1, +2$. This is familiar representation theory, but it requires a consistent massive-spin-2 dynamics and does not automatically recover ordinary massless gravity.
- **Internal-register reading:** treat $\mathbb{C}^5$ as a proposed microscopic internal state space while the observable low-energy massless gravitational field has only helicities ± 2 . This preserves the two-helicity infrared requirement, but the meaning and fate of the other three directions must be derived through constraints, transition rules, decoupling, or a physical internal mechanism.

For this manuscript, the *software model* uses the internal-register reading as its default and keeps the physical interpretation configurable. It does *not* assert that the three non-infrared directions are real hidden polarizations. It also does not introduce extra spatial dimensions. If a future derivation selects the massive-spin-2 reading, that is a model change with new consistency burdens, not a harmless relabelling.

FIVE-STATE REGISTER $\neq$ FIVE MASSLESS HELICITIES

QGC uses a five-level computational space as a hypothesis; the physical map is an open derivation.



Possible bookkeeping choice: map two designated register directions to the two massless helicities. That map is a conjecture until it follows from a Lorentz-consistent model; the other three levels must be explained.

Figure 2. The five-dimensional register and the two-helicity infrared target are distinct spaces. The drawn two-state mapping is an illustration of a possible bookkeeping choice, not a derived physical projection.

4.1 What “two states relate to classical spacetime” can mean

The project’s intuition that two directions of the register should relate to the familiar classical gravitational sector can be formalized as a proposed infrared map. One illustrative basis choice would nominate two orthogonal register directions and associate them with $|h+\rangle$ and $|h-\rangle$, while the remaining three directions do not appear as additional long-range massless polarizations. This is a useful design hypothesis, not a result. A physically legitimate map must specify the allowed states, transition amplitudes, conservation laws, gauge behavior, and any leakage probability. It cannot simply erase three components whenever they are inconvenient.

Candidate interface: $\mathcal{E}IR : \text{states on } \mathcal{H}_5 \rightarrow \text{observables in } \mathcal{H}_{\text{massless-spin-2}}$ (to be derived)

The interface may be a low-energy effective channel rather than a literal projection. If part of a state is lost to unobserved sectors, the full description must include that loss channel so that probabilities remain normalized. If the map is an isometry on an allowed two-dimensional code subspace, the allowed subspace and the reason it is selected must follow from the physical dynamics.

5. Dimensional discipline and the 1 + 24 algebra

Removing extra spatial dimensions is a substantive simplification of the present QGC architecture. Spacetime coordinates remain x_μ with $\mu = 0, 1, 2, 3$. An internal state-space dimension is a different mathematical quantity from a coordinate dimension. A five-dimensional complex Hilbert space does not mean five spacetime dimensions; a 25-dimensional operator space does not mean 25 particles; and 24 traceless generators do not establish 24 additional fields.

$\dim_{\mathbb{C}} \text{End}(\mathbb{C}^5) = 5^2 = 25$; $\dim_{\mathbb{R}} \text{Herm}(\mathbb{C}^5) = 25 = 1 \text{ identity} + 24 \text{ traceless generators}$

The traceless Hermitian generators can be chosen as a basis for the Lie algebra $\mathfrak{su}(5)$, with a conventional normalization such as $\text{Tr}(TA \cdot TB) = \frac{1}{2}\delta_{AB}$. A density matrix can then be expanded as $\rho = I_5/5 + \sum A = 1^{24} r_A T_A$, subject to positivity constraints. The 24 real coefficients r_A are not 24 independent classical bits and are not a list of observed physical excitations. A genuine $SU(5)$ gauge theory would require gauge fields, transformation rules, representations, symmetry breaking, and phenomenological consequences; it does not follow from the algebra of one qdit.

The earlier higher-dimensional calculations—compactification, Kaluza–Klein masses, a 28D arena, and a 24D compact sector—do not carry over as evidence to this 3+1D model. Their useful methodological lessons remain: define actions, check dimensions, derive spectra, and calculate observables. Their assumed geometric construction is removed. Any new structure must be justified by a specific consistency obstruction and shown to resolve it.

6. Mathematical substrate

6.1 State spaces and composition

A single Q5 register has $\mathcal{H}_5 \cong \mathbb{C}^5$. For N distinguishable registers, QGC uses the tensor product $\mathcal{H}^N = (\mathbb{C}^5)^{\otimes N}$ with dimension 5^N . A computational-basis string such as $|0241\rangle$ labels one basis vector of a four-register space; it is not a complete state unless the state is known to be exactly that basis vector.

$|\psi\rangle = \sum_{x \in \{0, \dots, 4\}^N} c_x |x\rangle$, $\sum_x |c_x|^2 = 1$

The complete pure state contains up to 5^N complex amplitudes before normalization and global-phase redundancies. This exponential scaling is both the expressive power and the cost of exact state-vector simulation. The reference simulator is for small circuits and mathematical tests, not for brute-force simulation of macroscopic spacetime.

6.2 Density operators and observables

$\rho = |\psi\rangle\langle\psi|$ for a pure state; $\rho = \sum_a p_a |\psi_a\rangle\langle\psi_a|$ for a mixture

For an observable A , the predicted expectation is $\langle A \rangle = \text{Tr}(\rho A)$. Measurement outcomes obey the Born rule. In a projective measurement with projectors P_k , $p(k) = \text{Tr}(\rho P_k)$; for a generalized measurement with POVM elements E_k , $p(k) = \text{Tr}(\rho E_k)$,

with $E_k \geq 0$ and $\sum_k E_k = I$. Outcomes are not the amplitudes themselves; they are samples drawn according to the measurement statistics.

6.3 Unitary operations and quantum channels

$$\rho \mapsto U\rho U^\dagger, \quad U^\dagger U = I; \quad \rho \mapsto \mathcal{E}(\rho) = \sum_a K_a \rho K_a^\dagger, \quad \sum_a K_a^\dagger K_a = I$$

Closed-system dynamics are unitary. An accessible subsystem interacting with an ignored environment is generally described by a completely positive trace-preserving (CPTP) map. Unitary gates, measurement, and noise must not be blended into one informal “state change”: they have different semantics and different conservation/accounting requirements.

6.4 State-space capacity is not classical information

$\log_2 5 \approx 2.322$ is the logarithm of the five-dimensional register’s Hilbert-space dimension, expressed in qubit units. It is not a promise that one Q5 register returns 2.322 readable classical bits, nor that five amplitudes can be directly inspected in one shot. Output access is limited by measurement and must be estimated from repeated experiments.

PART II — COMPUTATIONAL ARCHITECTURE

7. Registers, operators, and state composition

7.1 Generalized Pauli operators

Let $\omega = \exp(2\pi i/5)$. The generalized shift X_5 and clock Z_5 operators act on the computational basis as follows:

$$X_5|j\rangle = |j+1 \bmod 5\rangle; \quad Z_5|j\rangle = \omega^j|j\rangle; \quad Z_5X_5 = \omega X_5Z_5$$

The five-point quantum Fourier transform is $F_5|j\rangle = (1/\sqrt{5})\sum_{k=0}^4 \omega^{jk}|k\rangle$, and $F_5^\dagger$ reverses it. These are standard finite-dimensional quantum-information constructions. They are QGC's computational instruction set by design, not experimentally identified graviton operations.

$$F_5[k,j] = \omega^{kj} / \sqrt{5}, \quad F_5^\dagger F_5 = I_5$$

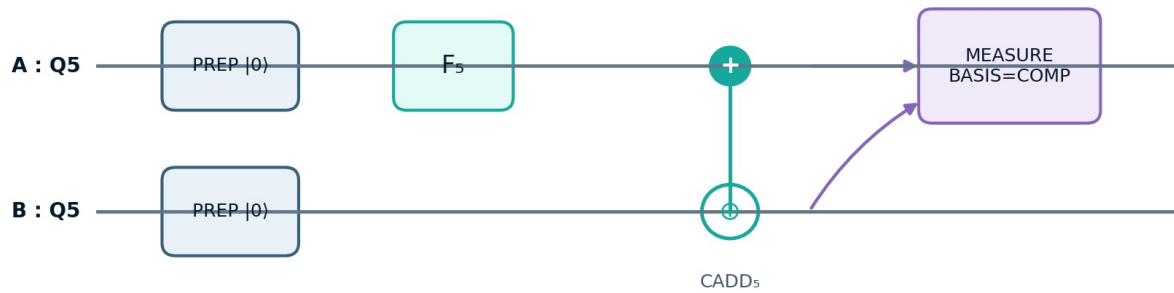
7.2 Controlled interactions

The generalized controlled-add operation is defined by $CADD_5|a,b\rangle = |a,b+a \bmod 5\rangle$. Its inverse subtracts the control value modulo five. A controlled phase gate is $CPHASE_5(\varphi)|a,b\rangle = \exp(i\varphi ab)|a,b\rangle$. Both are unitary for real φ . A controlled-add gate applied after F_5 creates a maximally entangled pair from $|0,0\rangle$.

$$|\Phi_5\rangle = (1/\sqrt{5}) \sum_{j=0}^4 |j,j\rangle; \quad \rho_A = \rho_B = I_5/5$$

The entropy of either reduced register in this ideal state is $\log_2 5$ bits (or $\ln 5$ nats). This is entanglement entropy, not accessible classical capacity without specifying a communication task and measurement protocol.

QCL-1.0 EXAMPLE: PREPARE A FIVE-LEVEL ENTANGLED PAIR



Output state: $|\Phi_5\rangle = (1/\sqrt{5}) \sum_{j=0}^4 |j,j\rangle$. Correlated outcomes do not, by themselves, prove entanglement.

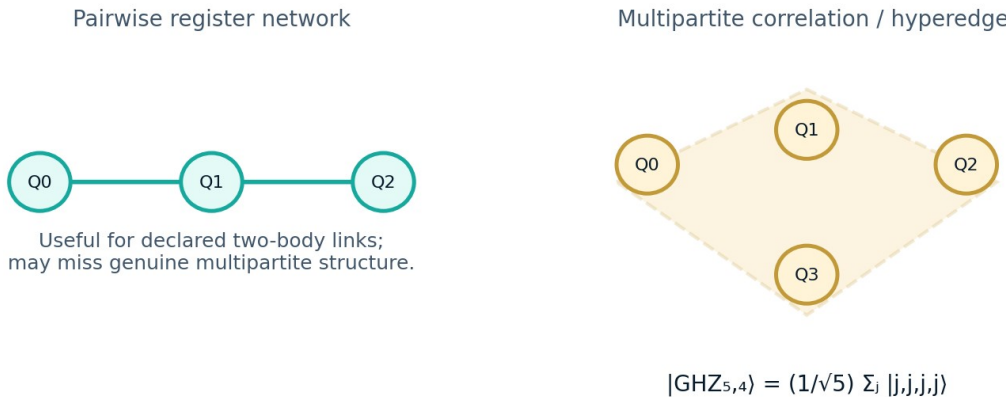
Figure 3. A two-register QCL circuit. F_5 creates a uniform superposition on A; $CADD_5$ correlates the target B with its control. The joint state is entangled even though every single-shot measurement returns only one pair of labels.

7.3 Multipartite assemblies and hypergraphs

An assembly is not just a row of independent qdits. Its state may contain two-body, multipartite, and long-range correlations. A graph $\mathcal{G} = (V,E)$ is useful when E explicitly labels modeled pairwise couplings or entanglement links, but pairwise graphs do not generally characterize all multipartite correlations. A hypergraph or tensor-network representation may be more appropriate when a joint operation couples three or more registers.

$$|\text{GHZ}_5, N\rangle = (1/\sqrt{5}) \sum_{j=0}^4 |j\rangle \otimes N$$

ASSEMBLIES: GRAPH EDGES ARE NOT THE WHOLE STORY



Entanglement is a property of the joint state relative to a partition—not a synonym for matching readouts.

Figure 4. A pairwise network and a multipartite hyperedge are different organizational tools. The actual entanglement structure is determined by the joint quantum state and the chosen partition.

7.4 Entanglement verification

Correlated outcomes are not enough. The separable state $\rho_{\text{sep}} = (1/5) \sum_j |j,j\rangle\langle j,j|$ produces perfectly matching computational-basis labels, yet it is a classical mixture of product states and is not the pure maximally entangled state $|\Phi_5\rangle$. Distinguishing them requires measurements in additional bases, state tomography where feasible, an entanglement witness, or a model-specific bound that separable states cannot violate. Witnesses are sufficient evidence when they violate the bound; a witness that fails to detect entanglement does not prove the state separable.

For a bipartite density operator, the partial transpose and negativity can provide useful diagnostics. In local dimension above two, the positive-partial-transpose condition is not a universal test of separability; therefore the program must not treat one convenient diagnostic as a complete characterization. Multipartite states require explicit partitions and witness choices.

8. Dynamics and the physical interface

8.1 Abstract dynamics

For a known Hamiltonian $H(t)$, the closed-system propagator over an interval is

$$U(t_1, t_0) = \mathcal{T} \exp\left[-(i/\hbar) \int_{t_0}^{t_1} H(t) dt\right]$$

A finite-dimensional circuit uses a matrix U ; a field-theoretic model begins with an action or Hamiltonian and derives the relevant U within an approximation regime. The word “gate” is acceptable as software shorthand only after the physical interaction has determined the transformation. A desired unitary cannot be assumed available in nature merely because it is easy to write in QCL.

8.2 Established gravitational interaction scaffold

For a linearized gravitational perturbation coupled to a conserved matter stress-energy tensor, a common natural-unit convention is

$$\mathcal{L}_{\text{int}} = -(\kappa/2) h_{\mu\nu} T_{\mu\nu}, \quad \kappa = \sqrt{32\pi G} \quad (\hbar = c = 1 \text{ convention})$$

This is an established perturbative coupling scaffold. It is not a complete QGC action. A physical implementation must state how the tensor field $h_{\mu\nu}$ relates to the Q5 register, how constraints and gauge redundancy are respected, how the matter source is represented, and how the operator is normalized. If the register is internal rather than a polarization basis, the coupling to the internal operators must be derived without violating Lorentz covariance or the observed low-energy limit.

8.3 Candidate qdit–matter coupling

As a bookkeeping ansatz, one may write an interaction of the form $H_{gm} = \sum_A g_A G_A \otimes O_A$, where G_A are operators on the five-level register and O_A are operators on matter, geometry, or a probe. This notation only says how a finite-dimensional subsystem might couple to something else. It does not define the O_A , their spacetime transformation properties, their dimensions, or the coefficients g_A . Those definitions must come from a covariant action or an explicit microscopic model. The 24-generator algebra does not provide 24 physical fields by itself.

A complete physical adapter must supply at least: (i) the register-to-field map; (ii) the admissible state constraints; (iii) the covariant interaction and its domain of validity; (iv) the conservation laws; (v) an approximation yielding a computable propagator; and (vi) a detector model connecting predicted observables to data. QCL’s `MODEL\_BIND` opcode is a reference to that bundle, not a substitute for it.

8.4 The computational-geometric interpretation

The TOE interpretation treats graviton-sector state changes as candidate primitives in the construction of relational geometry. In abstract notation, one would need a coarse-graining map $\mathcal{F}$ such that register states, correlations, and dynamics yield an effective metric, connection, curvature, or equivalent relational description: $g_{\mu\nu}^{\text{eff}} = \mathcal{F}[\rho, \text{correlations, state transitions}]$. The map must be invariant under the relevant coordinate/gauge redundancies and recover Einstein dynamics at scales where General Relativity is verified. Without this map, “the qdit writes geometry” remains a useful intuition rather than a calculable physical statement.

8.5 Phase, holonomy, and transition cost

Earlier QGC/TOE work used a combined amplitude-and-phase motif: a transition may have an attenuation or cost factor and a geometric phase. That useful motif can be retained in 3+1D without reintroducing compact spatial dimensions, but its interpretation must change: a transition is between specified internal states or geometric configurations, not automatically a transition along a hidden coordinate.

$$W_{\alpha \rightarrow \beta} = A_{\alpha\beta} \mathcal{P} \exp(i \int \gamma \mathcal{A}) U_{\text{qdit}}(\alpha \rightarrow \beta)$$

Here $A_{\alpha\beta}$ is an amplitude or loss factor, the path-ordered exponential is a candidate holonomy, and U_{qdit} is the internal state transformation. This is an ansatz. If $|A_{\alpha\beta}| < 1$, W alone is not a unitary operation on the modeled subsystem; the lost probability must be assigned to additional outcomes or an environment channel so total probability is conserved. A phase of π is operationally meaningful only when defined relative to a phase reference; a global phase applied to an entire isolated state is unobservable. Neither π nor a visually elegant closure argument is evidence unless a derived invariant and a measurable consequence follow.

9. Entanglement and assemblies

9.1 What entanglement means in QGC

QGC should reserve the word entanglement for a property of a joint quantum state that cannot be represented as a convex mixture of product states across a specified bipartition. In a pure bipartite state, entanglement is equivalent to nontrivial Schmidt rank; for mixed states, the test is more involved. An interaction may create entanglement, while subsequent noise or coupling to an environment can reduce it. A graph edge is a model record of a chosen coupling or inferred relation; it is not a substitute for the state-level definition.

9.2 Three distinct gravitational entanglement questions

Question	Systems involved	What a positive result would mean	What it would not prove
Q1. Graviton–graviton entanglement	Two or more quantized gravitational excitations.	Nonseparable joint state of gravitational modes, if the modes are operationally defined.	A specific Q5 state basis without a model-to-measurement map.
Q2. Gravity-mediated matter entanglement	Two quantum matter probes interacting gravitationally.	Under the proposal’s assumptions and controls, evidence that the mediator supports quantum features [8,9].	Direct detection of a graviton, or the five-state QGC hypothesis by itself.
Q3. Entanglement–geometry relation	Quantum subsystems and an effective geometric description.	A derived relation between correlations and geometric observables in a specified theory.	A universal “entanglement makes wormholes” rule.

9.3 The no-magic rule for spacetime shortcuts

Entanglement does not permit controllable superluminal signalling by itself. Nor does a maximally entangled pair constitute a tunnel, wormhole, or transport device. A wormhole interpretation would require an actual four-dimensional spacetime solution, a throat supported by consistent stress-energy, stability and causal analysis, and an input–output channel with calculated capacity, losses, and backreaction. QGC may describe such a channel if one is derived, but the qdit language does not supply the geometry for free.

10. QCL-1.0: Quantum Computational Language

QCL-1.0 is a proposed domain-specific language for declaring Q5 registers, composing gates, evolving through a named model, applying noise, measuring, and estimating parameters. Its syntax is inspired by assembly language because the goal is to express operations on assemblies of qdits clearly. The names and opcode identifiers below are provisional semantics, not an industry standard, hardware instruction encoding, or claim that physical graviton gates are currently available.

10.1 Design principles

- Every register has a declared dimension and basis convention.
- Every unitary operation has a defined matrix or basis action and a unitary validation test.
- Every nonunitary operation names a measurement or channel, including the basis and environment assumptions.
- Every physical interaction binds to an explicit model and records its assumptions; no implicit “gravity gate” is allowed.
- Every measurement is followed by a record format, calibration model, estimator, uncertainty, and null comparison.
- Every run logs version, parameters, initial state, random seed, noise model, and measurement settings.

10.2 Minimal grammar

```

PROGRAM <name> VERSION "1.0"
REGISTER <name> : Q5 [COUNT=<N>]
PREP <register> = BASIS(<digits>)
PREP <register> = STATE(<normalized amplitudes>)
GATE F5 <qdit> [INVERSE]
GATE X5 <qdit> [POWER=<integer>]
GATE Z5 <qdit> [POWER=<integer>]
GATE PHASE5 <qdit> THETA=<real>
GATE CADD5 <control> -> <target> [POWER=<integer>]
GATE CPHASE5 <control>,<target> THETA=<real>
EVOLVE <registers> MODEL=<model-id> DT=<time>
CHANNEL DEPHASE <qdit> COHERENCE_KEEP=<eta> BASIS=COMP
MEASURE <qdit> BASIS=<basis> INTO <classical-variable>
REPEAT SHOTS=<integer>
ESTIMATE MLE <parameter> FROM <counts> MODEL=<likelihood-id>
ASSERT NORM <register>
ASSERT UNITARY <matrix-or-gate>
REPORT <run-id>
END

```

In QCL examples, `Q5` is the register type; `[0..4]` are basis labels; `A[0]` denotes the first qdit in register A; and `->` marks control-to-target direction for a controlled operation. Numerical time `DT` is meaningful only when `MODEL` defines units and a Hamiltonian. A program that omits those definitions is an abstract circuit, not a physical graviton simulation.

10.3 Core type system

Type	Meaning	Invariants / notes
Q5	One five-level quantum register.	State dimension 5; normalized positive state representation.
Q5[N]	Register array containing N Q5 subsystems.	Joint dimension 5^N ; register ordering must be explicit.
QSTATE	Pure state vector of declared dimension.	$\sum c_i ^2 = 1$; global phase is physically redundant.
QDENS	Density matrix.	Hermitian, positive semidefinite, unit trace.
QGATE	Unitary map.	$U^\dagger U = I$; input and output dimensions match.
QCHANNEL	Completely positive trace-preserving map.	Kraus completeness $\sum K^\dagger K = I$ or equivalent proof.
COUT	Classical output record.	Counts/timestamps/labels; must include calibration and provenance.
MODELREF	Named physical or toy model.	Defines action/Hamiltonian, parameters, units, approximations, and scope.

10.4 Program execution semantics

A QCL execution is the following ordered composition: initialize the declared quantum state; apply gates in program order; apply a model-derived propagator when requested; apply channel/noise instructions at their specified locations; sample measurements with the Born rule; collect classical records over repeated shots; estimate requested parameters; compute uncertainty and checks; emit a report. Changing gate order generally changes the state because quantum operations need not commute. Reset is physically nonunitary and must be treated as a preparation operation with an environment, not as a free reversible gate.

If a model includes classical controls conditioned on prior measurement, the run is a hybrid quantum–classical process. Branching rules need explicit conditions and logs. If a register is discarded, partial trace is an explicit operation; it may remove accessible coherence while leaving correlations in the discarded sector. This is crucial for correct interpretation of decoherence.

11. Opcode specification

QCL opcodes are assigned stable mnemonic identifiers and grouped by function. The hexadecimal IDs are semantic identifiers for specification and logs, not binary machine code. A backend must declare which opcodes it implements. The supplied Python backend implements the basic single-qdit gates, CADD_5 , CPHASE_5 , basis preparation, projective measurement, and one trajectory realization of a simple dephasing channel. The full physical/model-validation opcodes are specified as interface obligations, not falsely advertised as implemented.

ID	Opcode	Signature / meaning	Implementation status
0x00	NOP	No operation; useful for alignment/debugging.	Specified; trivial.
0x01	DECLARE.Q5	Create a dimension-5 register; record ordering.	Specified; Python class.
0x02	PREP.BASIS	Initialize a product computational-basis state.	Implemented.
0x03	PREP.STATE	Initialize an arbitrary normalized vector.	Implemented for full register.
0x10	GATE.F5	Apply F_5 ; optional inverse $F_5^\dagger$.	Implemented.
0x11	GATE.X5	Apply generalized shift X_5^p .	Implemented.
0x12	GATE.Z5	Apply generalized clock Z_5^p .	Implemented.
0x13	GATE.PHASE5	Apply $\text{diag}(e^{i\theta_j})$ to one qdit.	Implemented.

ID	Opcode	Signature / meaning	Implementation status
0x14	GATE.CADD5	Map $ a,b\rangle$ to $ a,b+a \bmod 5\rangle$.	Implemented.
0x15	GATE.CPHASE5	Apply $\exp(i\theta ab)$ to basis $ a,b\rangle$.	Implemented.
0x16	GATE.UNITARY	Apply a user-supplied dimension-matched unitary.	Implemented for full register / local gate.
0x20	EVOLVE.MODEL	U = time-ordered exponential of model Hamiltonian.	Specified; physical model backend open.
0x21	MODEL.BIND	Bind parameters, units, action/Hamiltonian, and approximations.	Interface specified; adapter not supplied.
0x22	CHANNEL.CPTP	Apply Kraus or equivalent open-system map.	Language-level specification.
0x23	CHANNEL.DEPHASE	Apply dephasing in a named basis.	Single-qdit stochastic trajectory implemented.
0x24	CHANNEL.LEAKAGE	Model transition outside computational subspace.	Specified; backend needed.
0x30	MEAS.COMP	Projective measurement in computational basis.	Implemented.
0x31	MEAS.BASIS	Projective measurement in user-specified orthonormal basis.	Implemented for single qdit.
0x32	MEAS.POVM	General positive-operator-valued measurement.	Specified; backend needed.
0x33	SHOTS.RUN	Repeat a declared experiment with reset/preparation.	Demonstrated by helper functions.
0x40	TRACE.OUT	Trace out an unobserved subsystem.	Implemented for pure-state input via reduced density matrix.
0x41	ESTIMATE.MLE	Maximum-likelihood parameter estimate.	Phase demo implemented on a grid.
0x42	ESTIMATE.FISHER	Compute classical Fisher information and bounds.	Specified; application code needed per model.
0x43	WITNESS.ENT	Evaluate a named entanglement witness across a declared partition.	Bipartite negativity helper implemented; broader witness library remains open.
0x50	ASSERT.NORM	Check state normalization.	Implemented.
0x51	ASSERT.UNITARY	Check $U^\dagger U = I$ within tolerance.	Implemented internally.
0x52	ASSERT.TRACE	Check density matrix trace and positivity.	Specified; density backend needed.
0x53	ASSERT.COVARANCE	Test declared covariance/constraint identities.	Specification target; physics backend needed.
0x60	OBSERVE.GRAVITY	Convert model observables into detector-facing predictions.	Physical adapter required.
0x61	CALIBRATE.DETECTOR	Apply response function, offsets, noise, and timestamping.	Instrument-specific backend required.
0x62	COMPARE.BASELINE	Compare with GR/QFT or another named baseline.	Statistical-analysis layer required.
0x70	REPORT.RUN	Export configuration, results, uncertainties, null tests.	Partially represented in helper output.
0x7F	HALT	Terminate after consistency checks and report.	Specified.

11.1 Error semantics

A compliant backend must stop or return an explicit error if a register index is out of range, a unitary has the wrong dimension or fails the unitary check, a state has zero/nonfinite norm, a channel violates trace-preserving conditions, a measurement basis is not orthonormal, or a physical model omits required units and model identifiers. It must not silently renormalize a malformed probability distribution without logging the correction. Recovery is allowed only where specified—for example, normalizing a user-supplied nonzero state vector may be a declared convenience operation, but the report must say that normalization occurred.

12. Worked QCL programs

12.1 Bell-like entangled pair

```
PROGRAM BELLS VERSION "1.0"
REGISTER R : Q5[COUNT=2]
PREP R = BASIS(0,0)
GATE F5 R[0]
GATE CADD5 R[0] -> R[1]
ASSERT NORM R
MEASURE R[0] BASIS=COMP INTO a
MEASURE R[1] BASIS=COMP INTO b
REPEAT SHOTS=10000
REPORT bells_run
END
```

The ideal joint state is $|\Phi_5\rangle = (1/\sqrt{5})\sum_j |j,j\rangle$. If both registers are measured in the computational basis, ideal outcomes match and each of the five values has probability 1/5. That alone does not distinguish $|\Phi_5\rangle$ from the separable mixture discussed above. A full entanglement claim needs noncommuting measurement settings, a witness, or tomography with stated assumptions.

12.2 Multipartite GHZ-like state

```
PROGRAM GHZ5 VERSION "1.0"
REGISTER G : Q5[COUNT=4]
PREP G = BASIS(0,0,0,0)
GATE F5 G[0]
GATE CADD5 G[0] -> G[1]
GATE CADD5 G[1] -> G[2]
GATE CADD5 G[2] -> G[3]
ASSERT NORM G
MEASURE G BASIS=COMP INTO record
REPEAT SHOTS=50000
REPORT ghz5_run
END
```

This sequence produces $(1/\sqrt{5})\sum_j |j,j,j\rangle$ because each control digit carries the same value j forward to the next target. It is a computational demonstration of multipartite entanglement, not a claim about natural graviton assemblies. For large N , direct state-vector simulation becomes exponentially expensive; tensor-network, stabilizer-like, variational, or other specialized methods would be needed when their assumptions apply.

12.3 Simple phase sensor

```
PROGRAM PHASE5 VERSION "1.0"
REGISTER S : Q5
PREP S = BASIS(0)
GATE F5 S[0]
GATE PHASE5 S[0] THETA=theta
GATE F5 S[0] INVERSE
MEASURE S[0] BASIS=COMP INTO k
REPEAT SHOTS=M
ESTIMATE MLE theta FROM k MODEL=PHASE5_LIKELIHOOD
REPORT phase5_run
END
```

The phase likelihood is defined by $P(k|\theta) = (1/25)|\sum_j e^{ij\theta} \omega^{-kj}|^2$. Repeated outcomes yield counts n_k ; the likelihood is proportional to $\prod_k P(k|\theta)^{n_k}$. A grid-based maximum-likelihood estimate is simple but not always optimal. Periodicity, poor operating points, phase ambiguities, drift, detector response, and model misspecification must all be accounted for. A Q5 phase sensor is a valid abstract metrology example; it becomes a gravitational sensor only after θ is explicitly linked to a physical gravitational interaction and calibrated observable.

13. Geometry, I-field, dark sector, and transport modules

The gravitational qdit should remain a well-defined core register while ambitious TOE extensions are exposed as optional modules. An extensible framework is valuable precisely because it permits a module to fail without rewriting the register algebra or changing the evidence labels.

13.1 The epistemic I-field module

The current 3+1D I-field manuscript treats $\mathcal{I}(x)$ as a candidate scalar field and gives it a canonical four-dimensional starting action, for example $\mathcal{A} = -\frac{1}{2}\partial_\mu \mathcal{I} \partial^\mu \mathcal{I} - V(\mathcal{I})$, with optional couplings specified separately. For a canonically normalized scalar in four spacetime dimensions, $[\mathcal{I}] = 1$ in mass units. The field remains a hypothesis; a canonical scalar action proves mathematical consistency of that model class, not the field's existence.

A coupling between $\mathcal{I}$ and the Q5 sector requires an explicitly defined covariant operator $\mathcal{O}_g$, with symmetry properties and scaling dimensions. If $[\mathcal{O}_g] = d$, then a term $g\mathcal{I}\mathcal{O}_g$ in a four-dimensional Lagrangian has $[g] = 3 - d$. The model must then calculate renormalization, stress-energy, backreaction, stability, and at least one distinctive prediction. Correlation is not automatically a local source term; mutual information or a correlation proxy must not be inserted into a field equation without a defined, covariant, regulator-controlled functional.

13.2 Dark matter and dark energy as conditional branches

The revised dark-sector direction asks whether a stable, nonrelativistic state of the 3+1D gravitational/relational sector could behave like cold dark matter, and whether a well-defined scalar or collective response could contribute dark-energy-like behavior. These are hypotheses, not established outputs of QGC. A massive spin-2 candidate needs a healthy helicity-zero sector, acceptable nonlinear completion, no pathological ghost within its domain, the right relic abundance and longevity, and consistency with clustering, cosmic microwave background, structure formation, and lensing [3,4,19].

A homogeneous scalar can have an equation of state near -1 when potential energy dominates kinetic energy, but that does not solve the cosmological-constant problem or establish a link to the qdit. The same parameter set must satisfy the expansion history and perturbation data. Dark-matter and dark-energy branches must not be counted twice, and energy exchange must be derived from a covariant interaction rather than chosen solely to improve a fit.

13.3 Lensing and black-hole ringdown

Gravitational lensing and black-hole ringdown are already described by General Relativity. QGC earns a role here only if its derived mapping predicts a quantified deviation—such as an altered phase, polarization response, dispersion relation, correlation function, or ringdown mode—with a clear operating regime and independent parameter constraints. Renaming a known lensing effect as a qdit readout is not a new prediction.

13.4 Wormholes as an optional channel model

A four-dimensional wormhole, if a consistent solution exists, could be described operationally as a physical channel between endpoint subsystems. That channel must specify the spacetime metric, throat support, energy conditions, stability, causal structure, backreaction, mode scattering, and quantum-channel map (transmission probability, fidelity, noise, and conserved charges). Entanglement does not establish a traversable wormhole. A `CHANNEL.WORMHOLE` module should not be installed in the core ISA unless a concrete solution and transfer operator have been derived [21].

13.5 The $3+\pi$ motif without extra spatial dimensions

The earlier “ $3 + \pi$ ” intuition can survive only as a candidate relation between three spatial coordinates and a phase/holonomy in the register's internal state space—not as evidence for a fourth, fifth, or 28th spatial coordinate. The value π appears naturally in phase factors, rotations, and closure operations, but it is not a new physical dimension. A phase gate is mathematically exact; a claim that a physical geometric transition produces that phase must provide the dynamics and an observable consequence.

PART III — OPEN SYSTEMS AND CLASSICAL SIGNAL EXTRACTION

14. Decoherence and noise

14.1 Coherence in a Q5 register

For a pure Q5 state $|\psi\rangle = \sum_j c_j |j\rangle$, the density matrix has components $\rho_{jk} = c_j c_k^*$. The diagonal entries are basis populations; off-diagonal entries encode coherence relative to that basis. Coherence is basis-dependent. A statement that a register “has lost coherence” must identify the basis, observable, timescale, and interaction responsible for the loss.

$$\rho = \sum_{j,k} \rho_{jk} |j\rangle\langle k|; \quad \text{populations: } \rho_{jj}; \quad \text{coherences: } \rho_{jk} \ (j \neq k)$$

14.2 The environment and reduced state

Suppose the register interacts with an environment. A joint state may take the form $|\Psi\rangle_{SE} = \sum_j c_j |j\rangle |E_j\rangle$. Tracing over the environment gives

$$(\rho_S)_{jk} = c_j c_k^* \langle E_k | E_j \rangle$$

If the environment states associated with different j become nearly orthogonal, the register’s off-diagonal terms are suppressed and the reduced state approaches $\sum_j |c_j|^2 |j\rangle\langle j|$. The joint state may remain pure and information may remain in system–environment correlations; the local subsystem merely loses accessible interference. Decoherence is therefore not identical to a literal destruction of all information or to a conscious observer causing collapse. It is an open-system effect of physical interaction [10].

14.3 A standard dephasing model

A general Markovian open-system description may be written as a Lindblad master equation. With $\hbar$ restored, one conventional form is

$$d\rho/dt = -(i/\hbar)[H, \rho] + \sum_\mu \gamma_\mu (L_\mu \rho L_\mu^\dagger - \frac{1}{2}\{L_\mu^\dagger L_\mu, \rho\})$$

For pure dephasing in a computational basis, projectors $L_j = |j\rangle\langle j|$ provide a simple illustrative choice, with rates arranged so that off-diagonal elements decay as $\rho_{jk}(t) \approx \rho_{jk}(0)e^{-(\Gamma)_{jk} t}$. This is a phenomenological model until the Lindblad operators and rates are derived from a specified environment. Gravitational decoherence, laboratory decoherence, thermal noise, vibration, electromagnetic contamination, and detector backaction are not interchangeable explanations.

14.4 The QCL dephasing channel

The reference instruction ``CHANNEL DEPHASE q COHERENCE_KEEP= $\eta$  BASIS=COMP`` implements a simple trajectory ensemble corresponding to $\mathcal{D}_\eta(\rho) = \eta\rho + (1-\eta)\Delta_q(\rho)$, where Δ_q removes off-diagonal components for the selected qdit in the computational basis. With probability η , the trajectory leaves the state untouched; otherwise, it performs and discards the outcome of a computational-basis measurement. Averaging many trajectories reproduces the channel. This simple model is a simulation convenience; it does not claim that actual graviton decoherence has this form.

$$\mathcal{D}_\eta(\rho) = \eta\rho + (1-\eta) \sum_j P_j \rho P_j, \quad P_j = |j\rangle\langle j|$$

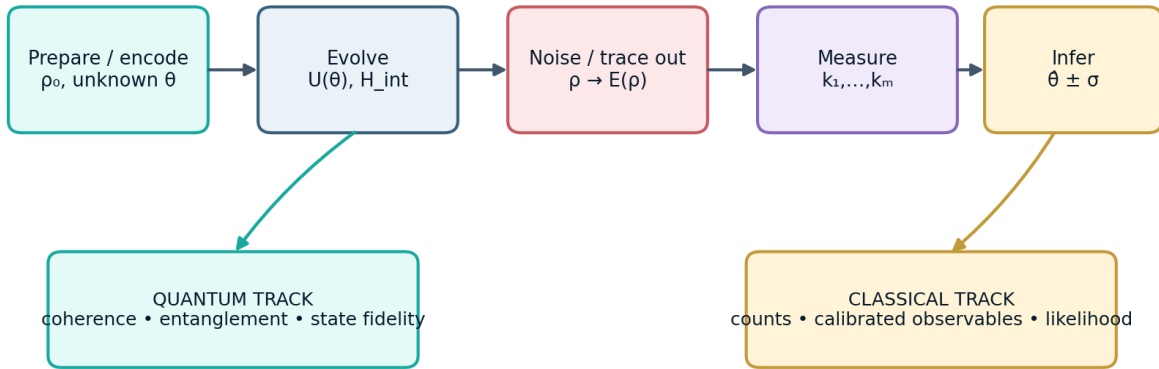
14.5 Coherence, entanglement, and signal must be tracked separately

A system can retain classical signal information after quantum coherence is suppressed; conversely, a coherent state may carry little information about the parameter being estimated if the chosen measurement is insensitive to it. Entanglement can be degraded without erasing all correlations, and some correlation can persist in a separable mixture. A QGC report should

therefore track at least three separate quantities: a basis-specific coherence diagnostic, an entanglement diagnostic for declared partitions, and information about the target parameter in the measurement distribution.

In the Bell-like example, ideal $|\Phi_5\rangle$ can undergo complete dephasing in the joint computational pointer basis to yield $\rho = (1/5)\sum_j |j,j\rangle\langle j,j|$. Both states give identical same-basis matching probabilities, but the latter is separable. The lesson is severe and practical: same-basis correlation alone is not an entanglement witness.

FROM QUANTUM EVOLUTION TO A CLASSICAL ESTIMATE



Decoherence changes accessible coherence; measurement creates a record; inference turns repeated records into an estimate.

These are related steps—not synonyms. A classical-looking record is not, by itself, evidence for graviton quantization.

Figure 5. Quantum evolution, open-system loss, measurement, and classical inference are distinct steps in a defensible signal pipeline.

15. Measurement and classical signal extraction

15.1 The three-stage separation

QGC separates **decoherence**, **measurement**, and **inference**. Decoherence changes which coherences remain accessible in a subsystem. Measurement produces an outcome according to a specified POVM or projective basis. Inference converts repeated outcomes and calibration data into an estimate of a parameter, model comparison, or decision. None is a synonym for the other two.

- **Quantum dynamics:** prepare a state, couple it to the target physical interaction, and model noise and backaction.
- **Classical record:** collect outcome labels, times, detector channels, reference readings, and metadata across repeated trials.
- **Inference:** use a likelihood or estimator, propagate calibration uncertainty, report confidence or credible intervals, and test alternative models.

15.2 A worked phase-encoding example

Use the state $|+\rangle = (1/\sqrt{5})\sum_j |j\rangle$, encode a phase θ by $U_\theta = \text{diag}(1, e^{i\theta}, e^{i2\theta}, e^{i3\theta}, e^{i4\theta})$, apply $F_5^\dagger$, and measure in the computational basis. The measurement probabilities are

$$P(k|\theta) = (1/25) |\sum_{j=0}^4 \exp(ij\theta) \omega^{(-kj)}|^2, \quad \omega = \exp(2\pi i/5)$$

After M independent repetitions, let n_k be the number of outcomes k . The observed frequencies are $\hat{p}_k = n_k/M$. Under the stated model, a maximum-likelihood estimate is

$$\hat{\theta} = \arg\max_{\theta} \sum_k n_k \log P(k|\theta)$$

The likelihood must use the real device’s response model once calibrated. The simple analytic expression applies only to the ideal phase-circuit assumptions above. θ is periodic; parameter aliasing, unidentifiable operating points, and finite-shot effects must be addressed explicitly. A numerical maximum on a grid is a demonstration, not a universal optimal estimator.

15.3 Fisher information and uncertainty

For a discrete measurement distribution $P(k|\theta)$, the classical Fisher information is

$$\mathcal{F}(\theta) = \sum_k P(k|\theta) \left[\frac{\partial \log P(k|\theta)}{\partial \theta} \right]^2$$

For M independent identically prepared trials and a regular, locally identifiable model, an unbiased estimator satisfies the Cramér–Rao bound $\text{Var}(\hat{\theta}) \geq 1/[M\mathcal{F}(\theta)]$. The conditions matter: the bound is local, assumes the probability model is correct, and does not excuse calibration error or model selection uncertainty. A QGC advantage must be demonstrated against a clearly defined reference protocol with equal resources and realistic noise; entangling registers does not automatically improve sensitivity.

15.4 What the classical signal means physically

A detector’s phase shift, transition count, frequency shift, timing residual, polarization response, or cross-correlation may be a classical signal extracted from a quantum system. It is not automatically a graviton count. A sensor can respond to curvature or a classical gravitational wave without demonstrating that the gravitational field is quantized. The physical model must connect a defined gravitational input to the quantum Hamiltonian and then calculate a readout distribution that discriminates the QGC proposal from conventional alternatives.

15.5 Calibration and controls

A minimally acceptable measurement campaign should include state-preparation calibration; gate calibration; background and environmental noise characterization; detector response and timing calibration; reference runs with the target interaction turned off or reversed where feasible; injected known signals; blind or randomized analysis windows where appropriate; explicit uncertainty budgets; and a predeclared comparison model. Corrections inferred after seeing the target data must be logged to avoid silently tuning the hypothesis to the result.

16. Metrology, error control, and reproducibility

16.1 Error taxonomy

Error type	QGC manifestation	Required response
Coherent control error	Wrong gate angle, wrong F_5 phase, systematic drift.	Calibrate gate matrices; track drift; validate against known circuits.
Incoherent noise	Dephasing, depolarization, thermal transitions.	Fit a specified channel; repeat measurements; report uncertainty.
Leakage	State exits the five-level computational subspace in a physical realization.	Add leakage levels/outcomes or derive a controlled effective channel; never renormalize silently.
Correlated noise	Several registers interact with the same environment.	Model joint channels; test whether independent-noise assumptions fail.
Readout error	Digit labels are misidentified or biased.	Measure the confusion matrix and include it in likelihoods.
Model error	The assumed Hamiltonian or signal law is wrong.	Compare alternative models; conduct posterior/predictive checks.
Analysis error	Selection effects, multiple testing, post-hoc tuning.	Pre-register primary endpoints; keep a complete analysis log.

16.2 Error correction is not a magic property of $d = 5$

Five-level qudits can support quantum error-correction codes, but no code follows merely from choosing five levels. A code must specify its logical subspace, correctable error set, syndrome measurements, recovery operations, and resource cost. The usual prime-dimensional generalized Pauli structure can be useful because 5 is prime, but a physical QGC code must also consider leakage, correlated gravitational coupling, and the difficulty of reading out the proposed register. Do not claim robustness before a code and its noise assumptions are defined.

16.3 Reproducibility record

Every QGC run should record: language version; simulator/backend version; register order; initial state and normalization; all gate matrices or gate parameters; the bound model and its hash/version; physical units; integration method and tolerance; channel parameters; random seeds; measurement bases; shot counts; calibration version; estimation method; uncertainty intervals; excluded data and reasons; and comparisons with baseline predictions. A report should distinguish simulated, analytically computed, and experimentally measured data with separate labels.

16.4 Thermodynamic guardrail

Landauer's bound $E \geq kBT \ln 2$ concerns the minimum heat dissipated in an idealized logically irreversible erasure of one bit at temperature T [13]. It is not the amount of energy contained in a stored bit, nor does it convert a state count into a free-energy estimate. Any energy density or stress-energy attributed to the graviton qdit or the I-field must be derived from a normalized physical action and the corresponding stress-energy tensor.

17. Reference simulator and execution semantics

17.1 What the included source does

The companion `Quantum_Graviton_Computing_reference.py` is a small NumPy backend for the abstract Q5 register. It implements N-register state vectors, basis initialization, normalized input states, F_5 and $F_5^\dagger$, X_5 , Z_5 , phase ramps, $CADD_5$, $CPHASE_5$, arbitrary full-register unitaries, projective measurement, stochastic dephasing trajectories, full and reduced density matrices, partial transpose, bipartite negativity, and a grid-based phase likelihood. It also includes a minimal executable interpreter for the supported QCL-1.0 subset: declarations, basis preparation, gate sequences, measurements, repeated shots, simple phase MLE, and reports. Its self-test exercises both the underlying simulator and QCL source execution.

17.2 What it does not do

The source is not a relativistic field solver and does not implement a graviton field, a metric, Einstein equations, a covariant Q5 interaction, a massive spin-2 action, detector hardware, general Kraus-channel evolution, full state tomography, or a complete entanglement-witness library. The interpreter accepts a deliberately documented subset of QCL and raises errors for unsupported statements; it is not a full optimizing compiler. The language specification describes interfaces for further modules, but the reference source does not pretend they are already solved. This line between executable code and unimplemented physics is deliberate.

17.3 Run and verify

```
python -m pip install numpy
python Quantum_Graviton_Computing_reference.py
```

```
# Expected first line:
# QGC reference simulator self-test: PASS
```

The self-test verifies gate unitarity, the Bell-like state's diagonal joint support and maximally mixed one-qdit reduction, a positive bipartite negativity value, GHZ-state support, normalized phase probabilities, and execution of Bell-like and phase-sensing QCL source programs. The phase demo generates a synthetic dataset and estimates θ from the stated model. These tests verify abstract software semantics under declared assumptions; they do not validate any physical gravitational premise.

PART IV — PHYSICS PROGRAM

18. Observable predictions

A QGC physical claim needs a map from a parameterized model to an observable distribution. It is insufficient to say that the system “computes geometry” or that an internal state “contains dark information.” A prediction should identify the observable, the control parameters, the baseline, the magnitude and sign of the deviation, the uncertainty, and the regime where the approximation is valid.

18.1 Prediction classes

Class	Possible observable	Minimum requirement
Register-specific	Transition probability or coherence between nominated Q5 basis directions.	Derived preparation/interaction/readout map and reason those basis directions are physical.
Quantum-gravity interface	Matter–matter entanglement, phase, or noise caused by gravitational interaction.	An interaction model and controls that exclude nongravitational coupling and common causes.
Gravitational-wave sector	Dispersion, polarization, phase, waveform, or ringdown deviation.	Covariant derivation and comparison with existing bounds.
Cosmological/dark sector	Abundance, clustering, lensing, expansion history, perturbations.	Relic-production mechanism, stability, shared parameters, joint fit.
I-field response	A new scalar-mediated effect, correlation response, or cosmological signature.	Normalized action, coupling, renormalization, conservation, and a distinctive null-testable prediction.
Transport/wormhole	Endpoint channel capacity/fidelity or travel-time relation for a solved geometry.	Actual spacetime solution, support, stability, causal structure, and channel map.

18.2 The minimum mathematical-to-physical bridge

For each proposed prediction, publish the bridge in the following order:

- **Microscopic definition:** identify the state variables, observables, Hilbert spaces, and symmetries.
- **Dynamics:** write the action or Hamiltonian, constraints, parameters, and valid approximation.
- **Evolution:** compute U or a CPTP map for a stated experiment or cosmological setup.
- **Measurement:** derive $P(\text{data}|\text{parameters}, \text{model})$, including detector response and noise.
- **Comparison:** fit or predict under QGC and the baseline with common data, assumptions, and uncertainty accounting.
- **Failure test:** state what observed pattern or parameter bound would exclude the model.

18.3 A single “smoking gun” must be specific

A result is not a smoking gun because it is surprising, elegant, or compatible with the framework. It becomes discriminating evidence only if the prediction was specified independently, the alternative models do not predict the same observation within uncertainty, systematic explanations are controlled, and the result is replicated or otherwise independently validated. A new qdit parameter that can be redefined after the measurement is not a falsifiable signature.

19. Experimental pathways

19.1 Path A: validate abstract QCL

Start with simulator benchmarks and independent implementations of the five-dimensional gates. Validate matrix conventions, tensor ordering, measurement sampling, channel statistics, and estimator calibration. Reproduce analytical

probabilities, and compare Monte Carlo results to exact distributions. This work is inexpensive and useful, but it validates the computational model only.

19.2 Path B: use controllable non-gravitational qdits as testbeds

A laboratory quantum platform that supports five-level systems could test QCL circuits, state preparation, Fourier transforms, entanglement witnesses, noise models, and classical readout. Such a platform would demonstrate that the algorithmic specification is coherent and may reveal which operations are robust. It would not show that gravitons themselves are five-level qdits. Any analogy must be labelled clearly.

19.3 Path C: test quantum features of gravity

Gravity-mediated entanglement proposals use quantum matter prepared in spatial superpositions and seek entanglement that cannot be explained by specified local-classical mediator models under stated assumptions [8,9]. These experiments involve demanding isolation, magnetic/electromagnetic control, phase readout, and carefully justified assumptions. A positive outcome could support quantum features of gravity; it would not automatically validate the Q5 internal register.

19.4 Path D: single-graviton sensing proposals

Recent work proposes detecting signatures of single-graviton exchange through stimulated absorption or emission in quantum acoustic resonators and continuous measurement of energy eigenstates [6,7]. An independent analysis cautions that sensitivity to a one-quantum-compatible signal should not be conflated with an unambiguous demonstration of the full quantum nature of gravitational radiation [5]. If these experimental pathways mature, QGC's distinctive task would still be to predict something about the five-state register beyond the generic quantum-gravity signature.

19.5 Path E: qdit-specific discriminating experiment

A genuine QGC experiment must go further than observing discrete energy exchange. It must identify a state-dependent transition, selection rule, correlation pattern, polarization relation, or phase law that follows from a five-state register but not from conventional two-helicity linearized gravity, known massive-spin-2 alternatives, instrumental artifacts, or a classical-wave model. The observable and its scaling must be calculated before the result is inspected. If the qdit map never yields such a difference, then QGC remains a useful abstract quantum language but does not yet add new physical content.

19.6 Path F: gravitational-wave and cosmological data

The existing gravitational-wave and cosmological data are not blank canvases. A model must be tested against observed waveforms, propagation constraints, lensing, matter clustering, cosmic microwave background, and expansion history. A fit that adds flexible qdit or I-field terms without improving predictive performance may be overparameterization rather than discovery. The comparator must include uncertainty and complexity penalties; null results and excluded regions are outputs, not inconveniences.

20. Consistency, failure modes, and falsification

20.1 Mathematical failure conditions

- A claimed gate is nonunitary but is not labelled as a measurement or channel.
- A density operator is not Hermitian, positive semidefinite, or trace one.
- The tensor-product ordering is ambiguous or changes between examples.
- Probabilities fail to sum to one, or an estimator uses a likelihood inconsistent with the circuit.
- A “24-state” or “24-dimensional” statement confuses operator-algebra dimension with physical spatial or field degrees of freedom.

20.2 Physical failure conditions

- The five-state register cannot be embedded in a Lorentz-consistent model or violates the gauge/constraint structure of massless spin-2 gravity.
- The theory adds unobserved long-range polarizations or a massive spin-2 sector inconsistent with known constraints.
- The microscopic dynamics fail to recover General Relativity’s successful weak-field, Newtonian, gravitational-wave, or strong-field limits.
- The proposed interaction violates energy-momentum conservation or uses a non-covariant source without explanation.
- The model has ghosts, pathological instabilities, negative-norm states, or uncontrolled high-energy behavior in its claimed domain.
- The Q5-to-observable map cannot be calculated, or the extra states have no defined operational consequence yet are used to explain anything after the fact.

20.3 Empirical failure conditions

- A predicted signal is absent at a sensitivity that excludes the model’s allowed parameter range.
- A purported QGC-specific signature is equally predicted by the standard baseline or a simpler alternative.
- The model fits one dataset but fails lensing, structure formation, or independent constraints using the same parameters.
- The result requires post-hoc retuning without an independent validation dataset.
- An uncertainty budget leaves a systematic explanation unresolved at the size of the claimed effect.

20.4 Adversarial decision ledger

Question	Current status	Next decisive action
Is $\mathbb{H}_5$ mathematically well-defined?	Yes, as a finite-dimensional quantum register.	Keep implementation tests and conventions fixed.
Does a massless 4D graviton have five helicities?	No; the conventional massless spin-2 baseline has two helicities.	Do not describe Q5 as five massless polarization states.
Can massive spin-2 have five physical polarizations?	Yes, in the conventional representation; dynamical consistency remains model-dependent.	If used physically, specify action, constraints, mass regime, and stability.
Is Q5 a proven intrinsic graviton register?	No. It is the QGC/TOE working hypothesis.	Derive the state-to-field map and distinctive observable.
Are there 24 extra spatial dimensions or 24 new fields?	Not implied by the Q5 operator algebra; the current model uses 3+1D.	Keep algebraic and geometric dimensions separate.
Has single-graviton exchange been experimentally established?	Not at manuscript preparation; proposals and feasibility studies exist.	Follow empirical literature and distinguish proposals from observed results.
Does decoherence itself yield a classical signal?	No; signal extraction requires a measurement and an inference model.	Report channel, POVM, counts, estimator, uncertainty, and controls.
Does QGC presently predict a unique measurable deviation?	Not yet from the materials consolidated here.	Derive and preregister one quantitative discriminator.

21. A-to-Z implementation roadmap

The practical roadmap is staged to avoid treating a promising software layer as a completed physical theory.

Gate	Deliverable	Pass criterion	Failure consequence
0. Freeze conventions	QCL version, basis ordering, units, operator definitions.	Independent implementation gives identical distributions.	Fix specification before adding more features.
1. Verify simulator	Unitary, normalization, Bell/GHZ, measurement, dephasing, phase estimation tests.	Exact analytic tests and reproducible Monte Carlo agreement.	No physics claims until code is repaired.
2. Add density matrices	CPTP channels, partial trace, tomography, witnesses.	Trace, positivity, and channel-completeness tests pass.	Open-system conclusions remain illustrative only.

Gate	Deliverable	Pass criterion	Failure consequence
3. Specify physical hypothesis	Choose internal-register vs massive-spin-2 reading.	One interpretation with explicit variables and symmetries.	Do not combine incompatible readings ad hoc.
4. Derive dynamics	Action/Hamiltonian, interaction, constraints, normalization.	Covariance, conservation, unitarity/stability shown in domain.	Q5 remains an abstract register.
5. Derive IR limit	Map Q5 to two-helicity massless gravitational sector.	Recovers GR and existing limits quantitatively.	Physical qdit interpretation fails or must be revised.
6. Produce prediction	Observable $P(\text{data} \theta, \text{QGC})$ and baseline distribution.	Finite parameter set, calculable deviation, published null target.	No distinctive physical content yet.
7. Validate with data	Calibration, systematics, baseline comparison, uncertainty.	Independent evidence with controlled alternatives.	Constrain or falsify the chosen model.

21.1 A minimum credible next paper

The highest-value next technical deliverable is not another broad ontology chapter. It is a short, reproducible paper that picks one concrete physical embedding—most conservatively, an effective Q5 register coupled to a controllable quantum probe—derives a Hamiltonian from a stated action, computes a readout distribution and noise budget, and demonstrates one observable difference from the simplest baseline. If no such difference can be derived, that negative result is useful: the computational framework may remain a language, while the physical claim remains underdetermined.

21.2 Reproducibility and external review

Before public claims, ask an independent quantum-information researcher to audit QCL semantics and state-vector code, a field theorist to audit the spin-2 representation and physical map, and an experimentalist/statistician to audit the proposed observable and null tests. Publish the equations, source, parameters, data-generation scripts, and negative results. A framework that survives hostile replication is stronger than a framework protected by ambiguity.

22. Conclusions and decision ledger

QGC now has a coherent abstract computational specification: a five-level register, multi-register composition, generalized Pauli and Fourier operations, entangling gates, open-system semantics, measurement, inference, source code, and validation rules. This is a real step forward because it turns the phrase “graviton computing” into a system that can be written down, executed, unit-tested, and criticized.

The central physical conjecture remains bold: a five-state degree of freedom associated with the gravitational sector may function as a computational primitive, with two directions connected to the observed massless spin-2 infrared behavior. Standard physics does not establish this mapping. A massive spin-2 field’s five polarization states are not identical by default to an internal Q5 register, and neither is identical to the two helicities of the massless field. The current model stays in 3+1D and does not use extra spatial dimensions as a rescue mechanism.

Entanglement, decoherence, and classical readout are not decorative footnotes; they are the operational core. Entanglement belongs to the joint state, decoherence to open-system dynamics and accessible coherence, measurement to outcome probabilities, and inference to the conversion of outcomes into parameter estimates with uncertainty. None of these steps alone proves graviton quantization, the five-state hypothesis, an I-field, dark-sector unification, or a traversable wormhole.

The next physical advance must be a derivation: specify the Q5-to-field map, write the dynamics, recover known gravity, calculate a discriminator, and state what would falsify it. Until then, the software is a testable computational framework and the five-state gravitational interpretation is a hypothesis. The distinction is not a retreat; it is the way the framework stays open to correction.

FINAL OPERATING PRINCIPLE

A qdit is not a graviton because we named it one. A phase is not geometry because it looks elegant. Correlation is not entanglement until the state is tested. A fit is not an explanation until alternatives are beaten. No sacred variables. Reality wins.

APPENDIX A — Opcode reference and core equations

A.1 Core algebra at a glance

Object	Definition	Role
Single register	$\mathbb{X}_5 \cong \mathbb{C}^5$	Local computational state space.
N-register space	$\mathbb{X}N = (\mathbb{C}_5^{\otimes})^{\otimes}N$; $\dim \mathbb{X}N = 5^N$	Assemblies and their correlations.
Shift	$X_5 j\rangle = j+1 \bmod 5\rangle$	Generalized Pauli gate.
Clock	$Z_5 j\rangle = \omega^j j\rangle$; $ZX = \omega XZ$	Relative phase gate.
Fourier	$F_5[k,j] = \omega^{kj}/\sqrt{5}$	Basis change / equal superposition.
Controlled add	$CADD_5 a,b\rangle = a,b+a \bmod 5\rangle$	Canonical two-register entangler.
Controlled phase	$CPHASE_5(\varphi) a,b\rangle = e^{i\varphi ab} a,b\rangle$	Conditional phase.
Unitary evolution	$U = \mathcal{T} \exp[-(i/\hbar)\int H dt]$	Closed-system dynamics.
Quantum channel	$\mathcal{E}(\rho) = \Sigma K \rho K^\dagger$; $\Sigma K^\dagger K = I$	Open-system evolution.
Projective readout	$p(k) = \text{Tr}(\rho P_k)$	Outcome probability.
Fisher information	$\mathcal{F} = \Sigma (\partial \theta P_k)^2 / P_k$	Local information about θ in measurement data.

A.2 Standard QCL example suite

The following examples are included as small conformance fixtures: INIT-ZERO, X5-ROUNDTRIP (apply X then X⁴), F5-ROUNDTRIP (F then F[†]), BELL5-CADD, GHZ5-FOUR, MEASUREMENT-BORN, DEPHASE-ENSEMBLE, PHASE5-LIKELIHOOD, and NORM-ASSERT. An implementation should publish expected exact probabilities where practical and statistical acceptance bounds for Monte Carlo results.

APPENDIX B — Complete reference source

The complete source below is also supplied as the companion file `Quantum\_Graviton\_Computing\_reference.py`. It is an abstract finite-dimensional simulator. It is not a physical graviton simulator.

```
"""QGC-1 reference simulator: abstract five-level (qudit) quantum circuits.

This is a pedagogical state-vector simulator for the mathematical QGC register model.
It is NOT a simulator of quantum gravity, relativistic spin-2 fields, or real gravitons.
Requires Python 3.10+ and NumPy. No external quantum SDK is required.

Convention: computational basis digits are 0..4; a register of n qudits is ordered
left-to-right as q[0], ..., q[n-1], and a controlled-add gate maps
|a,b> -> |a, b+a mod 5> (control first, target second).
"""
from __future__ import annotations

from dataclasses import dataclass
from typing import Iterable, Sequence
import re
import numpy as np

D = 5
OMEGA = np.exp(2j * np.pi / D)

def fourier5(inverse: bool = False) -> np.ndarray:
    """Return the 5-point quantum Fourier transform or its adjoint."""
    j = np.arange(D)
    sign = -1 if inverse else 1
    return (OMEGA ** (sign * np.outer(j, j))) / np.sqrt(D)

def shift5(power: int = 1) -> np.ndarray:
    """Generalized Pauli X: X|j> = |j+power mod 5>."""
    u = np.zeros((D, D), dtype=complex)
    for j in range(D):
        u[(j + power) % D, j] = 1.0
    return u

def clock5(power: int = 1) -> np.ndarray:
    """Generalized Pauli Z: Z|j> = omega**j |j>."""
    return np.diag([OMEGA ** (power * j) for j in range(D)]).astype(complex)

def phase_ramp5(theta: float) -> np.ndarray:
    """Encode a dimensionless phase theta as |j> -> exp(i*j*theta)|j>."""
    return np.diag(np.exp(1j * theta * np.arange(D))).astype(complex)

def _check_unitary(u: np.ndarray, tol: float = 1e-10) -> None:
    if u.ndim != 2 or u.shape[0] != u.shape[1]:
        raise ValueError("Gate must be a square matrix")
    ident = np.eye(u.shape[0], dtype=complex)
    if not np.allclose(u.conj().T @ u, ident, atol=tol):
        raise ValueError("Gate is not unitary within tolerance")

@dataclass
class QGCRegister:
    """Pure-state register of n five-level qudits, with stochastic measurement."""
    n: int
    seed: int | None = None

    def __post_init__(self) -> None:
        if not isinstance(self.n, int) or self.n < 1:
            raise ValueError("n must be a positive integer")
        self.dim = D ** self.n
        self.rng = np.random.default_rng(self.seed)
        self.psi = np.zeros(self.dim, dtype=complex)
        self.psi[0] = 1.0

    def _check_q(self, q: int) -> None:
        if not isinstance(q, int) or not (0 <= q < self.n):
            raise IndexError(f"qudit index must be in 0..{self.n-1}")
```

```

def reset_basis(self, digits: Sequence[int] | None = None) -> None:
    """Reset to a computational basis state; digits default to all zero."""
    if digits is None:
        digits = [0] * self.n
    if len(digits) != self.n or any((not isinstance(x, int)) or x not in range(D) for x in digits):
        raise ValueError(f"digits must be {self.n} integers in 0..{D}")
    idx = int(np.ravel_multi_index(tuple(digits), (D,) * self.n))
    self.psi[:] = 0.0
    self.psi[idx] = 1.0

def set_state(self, amplitudes: Sequence[complex]) -> None:
    """Set a normalized full-register state vector."""
    a = np.asarray(amplitudes, dtype=complex).reshape(-1)
    if a.size != self.dim:
        raise ValueError(f"state vector length must be {self.dim}")
    norm = np.linalg.norm(a)
    if not np.isfinite(norm) or norm <= 0:
        raise ValueError("state must have finite nonzero norm")
    self.psi = a / norm

def assert_norm(self, tol: float = 1e-10) -> None:
    norm2 = float(np.vdot(self.psi, self.psi).real)
    if not np.isclose(norm2, 1.0, atol=tol):
        raise AssertionError(f"state norm squared is {norm2}, not 1")

def probabilities(self) -> np.ndarray:
    """Return full computational-basis outcome probabilities."""
    p = np.abs(self.psi) ** 2
    return p / p.sum()

def apply_local(self, u: np.ndarray, q: int, check_unitary: bool = True) -> None:
    """Apply a 5x5 gate to one qdit using tensor-axis contraction."""
    self._check_q(q)
    u = np.asarray(u, dtype=complex)
    if u.shape != (D, D):
        raise ValueError("single-qdit gate must be 5x5")
    if check_unitary:
        _check_unitary(u)
    tensor = self.psi.reshape((D,) * self.n)
    tensor = np.moveaxis(tensor, q, 0)
    tensor = (u @ tensor.reshape(D, -1)).reshape((D,) * self.n)
    tensor = np.moveaxis(tensor, 0, q)
    self.psi = tensor.reshape(-1)

def f5(self, q: int, inverse: bool = False) -> None:
    self.apply_local(fourier5(inverse=inverse), q)

def x5(self, q: int, power: int = 1) -> None:
    self.apply_local(shift5(power), q)

def z5(self, q: int, power: int = 1) -> None:
    self.apply_local(clock5(power), q)

def phase_ramp(self, q: int, theta: float) -> None:
    self.apply_local(phase_ramp5(theta), q)

def cadd5(self, control: int, target: int, power: int = 1) -> None:
    """Apply SUM_5^power: |a,b> -> |a,b+power*a mod 5>."""
    self._check_q(control)
    self._check_q(target)
    if control == target:
        raise ValueError("control and target must be different qdits")
    src_tensor = self.psi.reshape((D,) * self.n)
    dst = np.zeros_like(src_tensor)
    # Iterate over the 5**n basis entries. This is clear and adequate for small demos.
    for idx in np.ndindex((D,) * self.n):
        out_idx = list(idx)
        out_idx[target] = (idx[target] + power * idx[control]) % D
        dst[tuple(out_idx)] = src_tensor[idx]
    self.psi = dst.reshape(-1)

def cphase5(self, control: int, target: int, theta: float = 2 * np.pi / D) -> None:
    """Apply diagonal controlled phase exp(i*theta*a*b)."""
    self._check_q(control)
    self._check_q(target)
    if control == target:
        raise ValueError("control and target must be different qdits")
    tensor = self.psi.reshape((D,) * self.n).copy()
    for idx in np.ndindex((D,) * self.n):
        tensor[idx] *= np.exp(1j * theta * idx[control] * idx[target])
    self.psi = tensor.reshape(-1)

def apply_full(self, u: np.ndarray, check_unitary: bool = True) -> None:

```

```

"""Apply a full-register unitary of dimension 5*n."""
u = np.asarray(u, dtype=complex)
if u.shape != (self.dim, self.dim):
    raise ValueError("full-register gate must be {self.dim}x{self.dim}")
if check_unitary:
    _check_unitary(u)
self.psi = u @ self.psi

def measure(self, q: int, basis: np.ndarray | None = None) -> int:
    """Measure one qdit; optionally measure in a basis whose columns are basis vectors.

    For basis B, computational measurement is performed after B†, so outcome k
    corresponds to projection onto column k of B. The conditional state is retained.
    """
    self._check_q(q)
    if basis is not None:
        basis = np.asarray(basis, dtype=complex)
        if basis.shape != (D, D):
            raise ValueError("measurement basis must be 5x5")
        _check_unitary(basis)
        self.apply_local(basis.conj().T, q)
    tensor = self.psi.reshape((D,) * self.n)
    other_axes = tuple(i for i in range(self.n) if i != q)
    probs = np.sum(np.abs(tensor) ** 2, axis=other_axes) if other_axes else np.abs(tensor) ** 2
    probs = np.asarray(probs, dtype=float)
    probs = np.maximum(probs, 0.0)
    probs /= probs.sum()
    outcome = int(self.rng.choice(D, p=probs))
    mask_shape = [1] * self.n
    mask_shape[q] = D
    mask = (np.arange(D) == outcome).reshape(mask_shape)
    tensor = np.where(mask, tensor, 0.0)
    norm = np.linalg.norm(tensor)
    if norm <= 0:
        raise RuntimeError("measurement selected a zero-probability branch")
    self.psi = (tensor / norm).reshape(-1)
    if basis is not None:
        self.apply_local(basis, q)
    return outcome

def dephase_trajectory(self, q: int, coherence_keep: float) -> int | None:
    """Apply the trajectory ensemble for rho -> eta*rho + (1-eta)*Delta_q(rho).

    With probability eta, do nothing; otherwise perform a computational-basis
    measurement and discard its outcome. Averaging many trajectories reproduces
    the stated single-qdit dephasing channel. This is a stochastic trajectory
    implementation, not a density-matrix solver.
    """
    self._check_q(q)
    if not (0.0 <= coherence_keep <= 1.0):
        raise ValueError("coherence_keep must be between 0 and 1")
    if self.rng.random() < coherence_keep:
        return None
    return self.measure(q)

def reduced_probabilities(self, q: int) -> np.ndarray:
    """Return diagonal probabilities for a chosen qdit, ignoring other registers."""
    self._check_q(q)
    tensor = self.psi.reshape((D,) * self.n)
    other_axes = tuple(i for i in range(self.n) if i != q)
    p = np.sum(np.abs(tensor) ** 2, axis=other_axes) if other_axes else np.abs(tensor) ** 2
    p = np.asarray(p, dtype=float)
    return p / p.sum()

def density_matrix(self) -> np.ndarray:
    """Return the full pure-state density operator |psi><psi|. """
    return np.outer(self.psi, self.psi.conj())

def reduced_density_matrix(self, keep: Sequence[int]) -> np.ndarray:
    """Partial-trace all but the listed qdits (indices must be sorted). """
    keep = tuple(keep)
    if len(set(keep)) != len(keep) or any(not isinstance(q, int) or q not in range(self.n) for q in keep):
        raise ValueError("keep must contain unique valid qdit indices")
    if tuple(sorted(keep)) != keep:
        raise ValueError("keep indices must be in ascending register order")
    tensor = self.density_matrix().reshape((D,) * (2 * self.n))
    current_n = self.n
    for q in reversed([i for i in range(self.n) if i not in keep]):
        tensor = np.trace(tensor, axis1=q, axis2=q + current_n)
        current_n -= 1
    d_keep = D ** len(keep)
    reduced = np.asarray(tensor).reshape((d_keep, d_keep))
    if not np.allclose(reduced, reduced.conj().T, atol=1e-10):
        raise AssertionError("partial trace produced a non-Hermitian state")
    if not np.isclose(np.trace(reduced), 1.0, atol=1e-10):
        raise AssertionError("reduced density matrix does not have unit trace")
    return reduced

```

```

def prepare_ghz5(self) -> None:
    """Prepare |GHZ_5,n> = (1/sqrt(5))*sum_j |j>***tensor n."""
    self.psi[:] = 0.0
    for j in range(D):
        idx = int(np.ravel_multi_index((j,) * self.n, (D,) * self.n))
        self.psi[idx] = 1.0 / np.sqrt(D)

def partial_transpose(rho: np.ndarray, dims: Sequence[int], subsystems: Sequence[int]) -> np.ndarray:
    """Partial transpose a density matrix on the requested subsystem indices."""
    dims = tuple(int(d) for d in dims)
    subsystems = tuple(subsystems)
    if not dims or any(d < 1 for d in dims):
        raise ValueError("dims must be a nonempty sequence of positive integers")
    if len(set(subsystems)) != len(subsystems) or any(not isinstance(i, int) or i not in range(len(dims)) for i in subsystems):
        raise ValueError("subsystems must be unique valid subsystem indices")
    total = int(np.prod(dims))
    rho = np.asarray(rho, dtype=complex)
    if rho.shape != (total, total):
        raise ValueError("density matrix shape does not match subsystem dimensions")
    tensor = rho.reshape(dims + dims)
    axes = list(range(2 * len(dims)))
    for i in subsystems:
        axes[i], axes[i + len(dims)] = axes[i + len(dims)], axes[i]
    return tensor.transpose(axes).reshape((total, total))

def entanglement_negativity(reg: QGCRegister, subsystem_a: Sequence[int]) -> float:
    """Compute bipartite negativity from a pure-register density matrix.

    Positive negativity witnesses entanglement across the declared partition;
    zero does not prove separability for every mixed-state/high-dimensional case.
    """
    transposed = partial_transpose(reg.density_matrix(), (D,) * reg.n, subsystem_a)
    eigvals = np.linalg.eigvalsh((transposed + transposed.conj().T) / 2)
    return float(np.sum(np.abs(eigvals[eigvals < 0.0])))

def bell5_state(seed: int | None = 7) -> QGCRegister:
    """Prepare |Phi_5> = sum_j |j,j>/sqrt(5) via F5 + CADD5."""
    reg = QGCRegister(2, seed=seed)
    reg.f5(0)
    reg.cadd5(0, 1)
    reg.assert_norm()
    return reg

def ghz5_state(n: int = 3, seed: int | None = 7) -> QGCRegister:
    """Prepare a 5-level GHZ state by the direct state-vector initializer."""
    reg = QGCRegister(n, seed=seed)
    reg.prepare_ghz5()
    reg.assert_norm()
    return reg

def phase_sensor_shots(theta: float, shots: int = 1000, seed: int = 7) -> np.ndarray:
    """Run the simple five-level phase experiment and return counts for outcomes 0..4."""
    if shots < 1:
        raise ValueError("shots must be >= 1")
    counts = np.zeros(D, dtype=int)
    rng = np.random.default_rng(seed)
    for _ in range(shots):
        reg = QGCRegister(1, seed=int(rng.integers(0, 2**32 - 1)))
        reg.f5(0)
        reg.phase_ramp(0, theta)
        reg.f5(0, inverse=True)
        counts[reg.measure(0)] += 1
    return counts

def phase_probabilities(theta: float) -> np.ndarray:
    """Analytic P(k|theta) after F5, phase encoding, and inverse F5."""
    j = np.arange(D)
    k = np.arange(D)
    amps = np.array([np.sum(np.exp(1j * j * theta) * (OMEGA ** (-ki * j))) / D for ki in k])
    p = np.abs(amps) ** 2
    return p / p.sum()

def maximum_likelihood_phase(counts: Sequence[int], grid_size: int = 4001) -> float:

```

```

"""Crude grid maximum-likelihood estimate on [-pi, pi); for demonstration only."""
counts = np.asarray(counts, dtype=int)
if counts.shape != (D,) or np.any(counts < 0) or counts.sum() == 0:
    raise ValueError("counts must contain five nonnegative integers with positive total")
grid = np.linspace(-np.pi, np.pi, grid_size, endpoint=False)
best_theta, best_loglike = 0.0, -np.inf
for theta in grid:
    p = np.maximum(phase_probabilities(float(theta)), 1e-15)
    loglike = float(np.dot(counts, np.log(p)))
    if loglike > best_loglike:
        best_theta, best_loglike = float(theta), loglike
return best_theta

# Minimal executable QCL-1.0 interpreter for the documented abstract subset.
# Inserted below QGCRegister and helpers so the same reference module executes examples.
@dataclass
class QCLRunResult:
    """Aggregated result from a minimal QCL-1.0 program run."""
    program: str
    shots: int
    measurement_counts: dict[str, dict[object, int]]
    joint_counts: dict[tuple[object, ...], int]
    estimates: dict[str, float]
    report_name: str | None = None

def _resolve_scalar(token: str, parameters: dict[str, float] | None = None) -> float:
    """Resolve a finite numeric literal or a declared scalar parameter."""
    token = token.strip()
    parameters = parameters or {}
    if token in parameters:
        value = float(parameters[token])
    else:
        value = float(token)
    if not np.isfinite(value):
        raise ValueError(f"parameter {token!r} must be finite")
    return value

def run_qcl(source: str, parameters: dict[str, float] | None = None,
            shots_override: int | None = None, seed: int = 7) -> QCLRunResult:
    """Execute the supported QCL-1.0 abstract subset and aggregate measurements.

    Supported statements: PROGRAM, REGISTER Q5, PREP BASIS, GATE F5/X5/Z5/
    PHASE5/CADD5/CPHASE5, ASSERT NORM, computational MEASURE, REPEAT SHOTS,
    ESTIMATE MLE for the PHASE5_LIKELIHOOD model, REPORT, END.

    This is an interpreter for finite-dimensional qdit circuits—not a physical
    gravity solver. Unsupported instructions fail explicitly instead of being
    silently ignored. Each shot receives a fresh register and RNG stream.
    """
    parameters = dict(parameters or {})
    lines = []
    for raw in source.splitlines():
        line = raw.strip()
        if not line or line.startswith("#") or line.startswith("//"):
            continue
        lines.append(line)
    if not lines:
        raise ValueError("QCL source is empty")

    program = "UNNAMED"
    shots = 1
    report_name = None
    registers: dict[str, int] = {}
    actions: list[tuple] = []
    measurements: list[tuple[str, str, int | None]] = []
    estimators: list[tuple[str, str, str]] = []

    for line in lines:
        m = re.fullmatch(r'PROGRAM\s+([A-Za-z_]\w*)\s+VERSION\s+["\']([^\']+)["\']', line, re.I)
        if m:
            program = m.group(1)
            continue
        m = re.fullmatch(r'REGISTER\s+([A-Za-z_]\w*)\s*\s*\s*Q5(?:\s*\s*\s*(\d+)\s*)?', line, re.I)
        if m:
            name, count = m.group(1), m.group(2)
            n = int(count) if count else 1
            if n < 1:
                raise ValueError(f"register {name} must have COUNT >= 1")
            if name in registers:
                raise ValueError(f"register {name} declared more than once")
            registers[name] = n
            continue

```

```

m = re.fullmatch(r'REPEAT\s+SHOTS\s*=\s*([A-Za-z_]\w*|\d+)', line, re.I)
if m:
    shots = int(parameters[m.group(1)]) if m.group(1) in parameters else int(m.group(1))
    continue
m = re.fullmatch(r'REPORT\s+([A-Za-z_]\w*)', line, re.I)
if m:
    report_name = m.group(1)
    continue
m = re.fullmatch(r'PREP\s+([A-Za-z_]\w*)\s*=\s*BASIS\s*\(((\^)*\))', line, re.I)
if m:
    name = m.group(1)
    if name not in registers:
        raise ValueError(f"register {name} must be declared before PREP")
    digits = [int(x.strip()) for x in m.group(2).split(',') if x.strip()]
    if len(digits) != registers[name]:
        raise ValueError(f"PREP BASIS for {name} needs {registers[name]} digits")
    if any(x not in range(D) for x in digits):
        raise ValueError("basis digits must be integers in 0..4")
    actions.append(("prep", name, digits))
    continue
m = re.fullmatch(r'GATE\s+F5\s+([A-Za-z_]\w*)\[(\d+)\](?:\s+(INVERSE))?', line, re.I)
if m:
    actions.append(("f5", m.group(1), int(m.group(2)), bool(m.group(3))))
    continue
m = re.fullmatch(r'GATE\s+(X5|Z5)\s+([A-Za-z_]\w*)\[(\d+)\](?:\s+POWER\s*=\s*(-?\d+))?', line, re.I)
if m:
    actions.append((m.group(1).lower(), m.group(2), int(m.group(3)), int(m.group(4) or 1)))
    continue
m = re.fullmatch(r'GATE\s+PHASE5\s+([A-Za-z_]\w*)\[(\d+)\]\s+THETA\s*=\s*([\w.+|-]+)', line, re.I)
if m:
    actions.append(("phase", m.group(1), int(m.group(2)), m.group(3)))
    continue
re.I) m = re.fullmatch(r'GATE\s+CADD5\s+([A-Za-z_]\w*)\[(\d+)\]\s*-\>\s*([A-Za-z_]\w*)\[(\d+)\](?:\s+POWER\s*=\s*(-?\d+))?', line,
if m:
    if m.group(1) != m.group(3):
        raise ValueError("minimal QCL runner currently requires CADD5 control/target in the same register")
    actions.append(("cadd", m.group(1), int(m.group(2)), int(m.group(4)), int(m.group(5) or 1)))
    continue
re.I) m = re.fullmatch(r'GATE\s+CPHASE5\s+([A-Za-z_]\w*)\[(\d+)\]\s*-\>\s*([A-Za-z_]\w*)\[(\d+)\]\s+THETA\s*=\s*([\w.+|-]+)', line,
if m:
    if m.group(1) != m.group(3):
        raise ValueError("minimal QCL runner currently requires CPHASE5 control/target in the same register")
    actions.append(("cphase", m.group(1), int(m.group(2)), int(m.group(4)), m.group(5)))
    continue
m = re.fullmatch(r'ASSERT\s+NORM\s+([A-Za-z_]\w*)', line, re.I)
if m:
    actions.append(("norm", m.group(1)))
    continue
m = re.fullmatch(r'MEASURE\s+([A-Za-z_]\w*)(?:\[(\d+)\])?\s+BASIS\s*=\s*COMP\s+INTO\s+([A-Za-z_]\w*)', line, re.I)
if m:
    register, q, alias = m.group(1), m.group(2), m.group(3)
    if register not in registers:
        raise ValueError(f"unknown register {register} in MEASURE")
    if q is not None:
        q = int(q)
        if q not in range(registers[register]):
            raise IndexError(f"qdit index {q} outside register {register}")
    measurements.append((alias, register, q))
    actions.append(("measure", alias, register, q))
    continue
m = re.fullmatch(r'ESTIMATE\s+MLE\s+([A-Za-z_]\w*)\s+FROM\s+([A-Za-z_]\w*)\s+MODEL\s*=\s*([A-Za-z_]\w*)', line, re.I)
if m:
    estimators.append((m.group(1), m.group(2), m.group(3).upper()))
    continue
if line.upper() in ("END", "NOP") or line.upper().startswith("#"):
    continue
raise ValueError(f"unsupported or malformed QCL statement: {line}")

if not registers:
    raise ValueError("QCL program must declare at least one register")
if shots_override is not None:
    shots = int(shots_override)
if shots < 1:
    raise ValueError("SHOTS must be >= 1")
if shots > 1_000_000:
    raise ValueError("SHOTS > 1,000,000 is disabled in the reference interpreter")

counts: dict[str, dict[object, int]] = {alias: {} for alias, _, _ in measurements}
joint_counts: dict[tuple[object, ...], int] = {}
estimates: dict[str, float] = {}
seed_rng = np.random.default_rng(seed)

# Only measurement instructions contribute result aliases; prepare/gate/assert
# operations are replayed each shot. This is the standard repeated-shot model.
for _shot in range(shots):
    regs = {name: QGCRRegister(n, seed=int(seed_rng.integers(0, 2**32 - 1)))
            for name, n in registers.items()}

```

```

shot_values: dict[str, object] = {}
for action in actions:
    op = action[0]
    if op == "prep":
        _, name, digits = action
        regs[name].reset_basis(digits)
    elif op == "f5":
        _, name, q, inverse = action
        regs[name].f5(q, inverse=inverse)
    elif op == "x5":
        _, name, q, power = action
        regs[name].x5(q, power=power)
    elif op == "z5":
        _, name, q, power = action
        regs[name].z5(q, power=power)
    elif op == "phase":
        _, name, q, token = action
        regs[name].phase_ramp(q, _resolve_scalar(token, parameters))
    elif op == "cadd":
        _, name, control, target, power = action
        regs[name].cadd5(control, target, power=power)
    elif op == "cphase":
        _, name, control, target, token = action
        regs[name].cphase5(control, target, theta=_resolve_scalar(token, parameters))
    elif op == "norm":
        regs[action[1]].assert_norm()
    elif op == "measure":
        _, alias, name, q = action
        reg = regs[name]
        if q is None:
            result: object = tuple(reg.measure(k) for k in range(reg.n))
        else:
            result = reg.measure(q)
        shot_values[alias] = result
    ordered = tuple(shot_values.get(alias) for alias, _, _ in measurements)
    joint_counts[ordered] = joint_counts.get(ordered, 0) + 1
for alias, value in shot_values.items():
    alias_counts = counts.setdefault(alias, {})
    alias_counts[value] = alias_counts.get(value, 0) + 1

for target, source, model in estimators:
    if source not in counts:
        raise ValueError(f"ESTIMATE source alias {source!r} is not measured")
    if model != "PHASE5_LIKELIHOOD":
        raise ValueError(f"unsupported estimator model: {model}")
    source_counts = counts[source]
    vec = np.array([source_counts.get(k, 0) for k in range(D)], dtype=int)
    estimates[target] = maximum_likelihood_phase(vec)

return QCLRunResult(program, shots, counts, joint_counts, estimates, report_name)

def _self_test() -> None:
    # Gate unitarity.
    for u in (fourier5(), shift5(), clock5(), phase_ramp5(0.37)):
        _check_unitary(u)
    # Bell-like entangled state has support only on |j,j> outcomes.
    bell = bell5_state()
    prob = bell.probabilities().reshape(D, D)
    assert np.allclose(np.diag(prob), np.full(D, 1 / D))
    assert np.allclose(prob - np.diag(np.diag(prob)), 0.0)
    # GHZ state has support only on |j,j,j>.
    ghz = ghz5_state(3)
    ghz.assert_norm()
    probs = ghz.probabilities().reshape(D, D, D)
    support = np.zeros_like(probs)
    for j in range(D):
        support[j, j, j] = 1 / D
    assert np.allclose(probs, support)
    # Phase probabilities normalize for multiple values.
    for theta in (-1.2, 0.0, 0.44, 2.3):
        assert np.isclose(phase_probabilities(theta).sum(), 1.0)
    reduced = bell.reduced_density_matrix([0])
    assert np.allclose(reduced, np.eye(D) / D)
    assert np.isclose(entanglement_negativity(bell, [0]), 2.0, atol=1e-10)
    bell_src = "\n".join([
        'PROGRAM BELL5 VERSION "1.0"', 'REGISTER R : Q5[COUNT=2]',
        'PREP R = BASIS(0,0)', 'GATE F5 R[0]', 'GATE CADD5 R[0] -> R[1]',
        'ASSERT NORM R', 'MEASURE R[0] BASIS=COMP INTO a',
        'MEASURE R[1] BASIS=COMP INTO b', 'REPEAT SHOTS=200', 'REPORT bell5_run', 'END'])
    qcl_bell = run_qcl(bell_src, seed=123)
    assert qcl_bell.shots == 200
    assert all(a == b for (a, b) in qcl_bell.joint_counts)
    phase_src = "\n".join([
        'PROGRAM PHASE5 VERSION "1.0"', 'REGISTER S : Q5', 'PREP S = BASIS(0)',
        'GATE F5 S[0]', 'GATE PHASE5 S[0] THETA=theta', 'GATE F5 S[0] INVERSE',
        'MEASURE S[0] BASIS=COMP INTO k', 'REPEAT SHOTS=1200',
        'ESTIMATE MLE theta FROM k MODEL=PHASE5_LIKELIHOOD', 'REPORT phase5_run', 'END'])

```

```
qcl_phase = run_qcl(phase_src, parameters={"theta": 0.44}, seed=123)
assert "theta" in qcl_phase.estimated and abs(qcl_phase.estimated["theta"] - 0.44) < 0.12
print("QGC reference simulator and QCL interpreter self-test: PASS")
print("Bell5 ideal joint probabilities (diagonal):", np.round(np.diag(prob), 3))
counts = phase_sensor_shots(theta=0.44, shots=3000, seed=123)
estimate = maximum_likelihood_phase(counts)
print("Phase demo counts:", counts.tolist())
print("True phase=0.44 rad; grid-MLE estimate=%.4f rad" % estimate)

if __name__ == "__main__":
    _self_test()
```

APPENDIX C — Additional QCL and analysis examples

C.1 A calibrated measurement record

```
RUN_METADATA {
  qcl_version: "1.0"
  backend: "QGCReferenceSimulator"
  model_id: "TOY_PHASE5_NOT_GRAVITY"
  register_order: [S[0]]
  initial_state: "F5|0>"
  signal_operator: "diag(exp(i*j*theta))"
  theta_units: "radian"
  measurement_basis: "computational_after_F5_dagger"
  shots: 10000
  noise_model: "none"
  random_seed: 20261024
  estimator: "grid maximum likelihood"
  output: {counts: [n0,n1,n2,n3,n4], theta_hat: ..., uncertainty: ...}
}
```

The metadata deliberately calls the model `TOY\_PHASE5\_NOT\_GRAVITY`. A physical run must replace the toy encoder with an explicitly derived gravitational interaction and include calibration, detector response, uncertainties, and a conventional comparator. The label prevents a successful toy circuit from being accidentally described as empirical support for the graviton hypothesis.

C.2 Density-matrix dephasing

$$\rho_{jk}(t) = \rho_{jk}(0)e^{(-\Gamma_{jk} t)}, \quad j \neq k; \quad \rho_{jj}(t) = \rho_{jj}(0) \text{ for pure dephasing}$$

This is an illustrative decay law. Real rates may depend on frequency, temperature, geometry, coupling, non-Markovian memory, and the pointer basis. If the environment cannot be approximated by a Markovian bath, the corresponding dynamics need not have a simple Lindblad form.

C.3 Entanglement witness reporting template

```
WITNESS_REPORT {
  state_model: <declared joint state or reconstructed density matrix>
  partition: A | B
  witness_operator: W
  separable_bound: w_sep
  observed_value: Tr(rho * W)
  uncertainty: sigma_w
  criterion: <predeclared inequality>
  controls: <readout calibration, drift, common-cause tests>
  conclusion: <witness violated / not violated / inconclusive>
}
```

The conclusion “witness not violated” must not be converted to “state is separable” unless the particular test is a necessary-and-sufficient criterion for the state family and assumptions in use.

C.4 Physical adapter contract

```
MODEL_BIND contract { # compact adapter interface
  model_id: unique and versioned; spacetime: 3+1D with signature
  variables: metric / perturbation / matter / Q5 registers declared
  action_Hamiltonian: specified with constraints, gauge, units
  normalization_and_parameters: declared ranges and approximation error
  evolution_map: derived unitary or CPTP channel
  observables: detector response/calibration; baseline: GR + matter model
  falsification_target: quantitative and predeclared }
```

APPENDIX D — Derivation notes and consistency identities

D.1 Normalization under gates

If U is unitary and $\langle \psi | \psi \rangle = 1$, then $\langle \psi | U^\dagger U | \psi \rangle = 1$. This is the mathematical basis for `ASSERT NORM` after a gate sequence. It is not a proof of physical unitarity for a model whose Hamiltonian or truncation has not been derived.

D.2 CADD₅ is unitary

The map $(a,b) \mapsto (a, b+a \bmod 5)$ is a bijection on the 25 basis pairs, with inverse $(a,b) \mapsto (a, b-a \bmod 5)$. It permutes an orthonormal basis, so its matrix is unitary. Reversibility at this abstract gate level must not be confused with the physical reversibility of a laboratory process that includes its environment.

D.3 Bell-like reduced state

$$|\Phi_5\rangle = (1/\sqrt{5}) \sum_j |j,j\rangle; \quad \rho_{AB} = |\Phi_5\rangle\langle\Phi_5|; \quad \text{Tr}_B \rho_{AB} = I_5/5$$

The reduced density matrix is maximally mixed, while the joint state is pure. This is the signature of entanglement for the ideal pure bipartite state. The separable mixture ρ_{sep} has the same computational-basis joint probabilities but does not have off-diagonal joint coherence; additional measurements distinguish them.

D.4 Measurement likelihood

For observed counts $n_0 \dots n_4$ from independent draws, the multinomial likelihood is $L(\theta) = M! / (\prod_k n_k!) \prod_k P(k|\theta)^{n_k}$. The factorial prefactor does not depend on θ , so maximizing the likelihood is equivalent to maximizing $\sum_k n_k \log P(k|\theta)$. An estimator must handle zero probabilities numerically and report multimodal or periodic solutions where present.

D.5 Gravitational limit obligations

- Recover Einstein's field equations or a specified effective-field-theory limit where General Relativity is tested.
- Recover the Newtonian potential for weak, slowly varying sources.
- Recover the two physical radiative modes of massless spin-2 gravity in the infrared.
- Preserve stress-energy conservation and the relevant gauge/constraint relations.
- Provide a controlled stability analysis and state the regime where the theory is valid.
- Calculate any qdit-specific deviation from the baseline with a finite set of parameters.

APPENDIX E — Glossary

Term	Operational meaning in this manuscript
QGC	Quantum Graviton Computing; proposed framework connecting five-level quantum registers to a gravitational-sector hypothesis.
QCL-1.0	Proposed instruction language with register, gate, channel, measurement, estimation, and validation operations.
Qdit	Quantum d-level register; here $d = 5$.
Q5	The five-level register type used by QCL.
Graviton	Hypothetical quantum of the gravitational field in perturbative quantized gravity; not experimentally confirmed as an individual particle at manuscript preparation.
Helicity	Spin projection along momentum for a massless representation; conventional massless spin-2 has helicities ± 2 .
Massive spin-2	A spin-2 representation with five physical polarizations in its standard massive description; consistent interactions require further conditions.
Entanglement	Nonseparability of a joint quantum state across a specified bipartition.
Coherence	Off-diagonal density-matrix structure relative to a specified basis.
Decoherence	Suppression of accessible interference due to interaction and correlation with unobserved degrees of freedom.
POVM	Positive-operator-valued measure; generalized measurement represented by positive effects that sum to identity.
CPTP channel	Completely positive trace-preserving map used to describe open-system evolution.
Q5 internal-register reading	Hypothesis that the five-dimensional state space is an internal microscopic register rather than five massless polarizations.
IR / infrared limit	Low-energy/long-wavelength regime that must recover known massless gravitational behavior.
$1 + 24$ algebra	One identity operator plus 24 traceless Hermitian generators for a five-level register; not a spatial-dimension count.
I-field	Candidate four-dimensional epistemic scalar $\mathcal{J}(x)$ in the TOE project; not established physics.
Reality veto	Rule that a model must be revised or rejected when calculations or evidence contradict it.

APPENDIX F — References and source trail

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Research-status note

This manuscript consolidates a research program and defines its computational specification. It is not peer-reviewed experimental evidence, and the QGC five-state graviton interpretation, the microscopic geometry map, the I-field connection, and the dark-sector/wormhole extensions remain conjectural. Literature references establish standard results or describe proposals; they do not validate QGC. The abstract simulator is released as reproducible supporting code with its physical limitations stated explicitly.