DATED HISTORY

The Scalar Shadow of Co-Emergent Geometry Clock Lag as the Minimal Readable Projection of a Relational Universe

April clock-lag edition of the scalar-shadow proposal. Its operational timing observable leaves microscopic generation of geometry open.

Manuscript · p. 1, operational reading

The Scalar Shadow of Co-Emergent Geometry

Evidence · Scalar source/window residual audit

The Scalar Shadow of Co-Emergent Geometry

Clock Lag as the Minimal Readable Projection of a Relational Universe

Joshua Farrow
Independent Research

April 2026

This paper is the interpretive companion to the scalar-timing program. Its purpose is not to replace the technical closure theory, but to prevent the phrase "the clock before gravity" from being misread as a literal temporal claim. The central distinction is between chronological emergence and operational readability: a full relational structure may cohere as one object of law, while a finite observer recovers it through partial projections.

Abstract

This paper reformulates scalar timing geometry around a distinction between temporal genesis and operational readability. If spacetime, matter, clocks, and gravitational behavior emerge from a deeper relational substrate, then it is misleading to picture them assembling in a sequence of events inside time. The stronger and safer claim is one of co-emergence with asymmetric readability: scalar, vector, gauge, tensor, topological, and record-forming sectors may be jointly implicated in a full relational structure, while finite observers recover only certain projections with minimal instruments.

We propose that the minimal clock-readable projection of such a structure is a scalar timing channel. A local clock does not receive the whole substrate; it integrates a reduced scalar load. The effective clock rate is modeled by

$$\omega_{\text{eff}} = \frac{\omega}{1 + \alpha\Lambda},$$

where Λ is a coarse-grained scalar load and α is a clock susceptibility. This does not assert that scalar timing is the foundation of gravity, nor that gravity appears later. Rather, scalar timing is the lowest-order shadow cast by a richer co-emergent structure when that structure is interrogated by a local clock.

The central claim is therefore not sequential emergence but projected observability. A relational substrate may admit an effective weighted graph, a graph Laplacian, a scalar load, and richer reconstructed sectors. The scalar branch becomes gravity-like only if the same operator that governs scalar response also yields an effective dimension near three, producing a $1/r$ Green-response envelope. The framework is not a completed theory of gravity. It is a disciplined interpretation of what the scalar timing program would mean if its numerical, dynamical, and experimental closure tests succeed.

Contents

1 The danger of explanatory order **2**

2 Genesis versus readability **2**

2.1 What co-emergence does and does not mean 3

3 Why scalar timing is the simplest readable projection **3**

4 Relational substrate and projected sectors **4**

5 Postulates of co-emergent scalar timing geometry **4**

6 The clock as a projection device **5**

7 Scalar load from an effective graph **5**

8 Effective dimension from the same operator **6**

9 The 3D branch as a readability condition **7**

10 Gravity as richer reconstruction, not later creation **7**

11 Mass, magnetism, and records **7**
11.1 Mass-like persistence 7
11.2 Gauge-like circulation 8
11.3 Tensor gravity 8
11.4 Classical records 8

12 The readability ladder **8**

13 Internal loads and external observables **8**

14 The severe closure criterion **9**

15 Experimental posture **10**

16 Relation to existing ideas **10**

17 Limits **10**

18 Conclusion: the scalar face of a simultaneous world **11**

1. The danger of explanatory order

When a theory tries to explain time, it must be careful not to smuggle time into the explanation.

It is tempting to say that relational updating comes first, then scalar load, then clock lag, then gravity. As a map of conceptual dependence, this can be useful. As a literal chronology, it is incoherent. If time itself is emergent, then "first" cannot mean "earlier in time" at the deepest level. A pre-geometric substrate does not wait, then make clocks, then wait again, then make gravity. Waiting is already a temporal concept.

The careful claim is different:

> **The relational universe may cohere as one structure of law, but finite instruments do not read it all at once.**

A clock does not measure the whole substrate. A local observer does not directly receive the full tensor, gauge, topological, and informational structure of the world. They receive a reduced set of stable observables: ticks, phases, delays, correlations, accelerations, and records.

Among these reduced observables, scalar timing is the simplest. This is not the claim that clock lag is physically older than gravity. It is the claim that clock lag is operationally prior: the lowest-order projection through which a richer co-emergent geometry becomes measurable.

A chord is not assembled note by note, yet an instrument may detect the bass first. White light is not born color by color, yet a prism separates it into components. A relational universe need not build scalar timing before gravity. Rather, scalar timing may be the component revealed when the full structure is projected through the measurement basis of a local clock.

The earlier slogan, "the clock before gravity," should therefore be sharpened:

> **The clock is not before gravity in time. The clock is the scalar face of co-emergent geometry.**

2. Genesis versus readability

The main conceptual correction is the distinction between *genetic order* and *readability order*.

A genetic order says

$$A \to B \to C,$$

as though A happens, then B, then C.

A readability order says

$$\mathcal{R}_{\text{full}} \longrightarrow \Pi_{\text{obs}}(\mathcal{R}_{\text{full}}),$$

where $\mathcal{R}_{\text{full}}$ is the full relational structure and Π_{obs} is the projection imposed by finite instruments, finite resolution, coarse graining, and stable records.

In this second sense, scalar timing can be "first" without being temporally first. It is first because it requires the least reconstructed structure. A scalar clock-rate shift requires only a local load and a clock response. A full tensor theory of gravity requires much more: rods, clocks, free-fall behavior, universal coupling, Lorentz-compatible propagation, stress-energy response, gauge redundancy or equivalent constraints, and a spin-2-like sector.

Thus the hierarchy is not

clock lag, then gravity.

It is

$$\mathcal{R}_{\text{full}} \longrightarrow \begin{cases} \text{scalar timing projection,} \\ \text{vector/gauge projection,} \\ \text{mass-like persistence,} \\ \text{tensor-gravity reconstruction,} \\ \text{classical records.} \end{cases}$$

These sectors may be co-present in the full structure. They become distinct only when we ask what kind of measurement extracts which kind of information.

2.1 What co-emergence does and does not mean

The term *co-emergence* is restricted here. It does not mean that all sectors are metaphysically simultaneous in some mystical sense. It means two things.

First, the sectors are not chronologically ordered in ordinary metric time. Scalar timing is not built earlier, with gravity arriving later.

Second, the sectors are not derived from each other in a simple definitional cascade. Scalar load is not a little machine that becomes gravity by adding ingredients. Rather, scalar load, gauge-like circulation, tensor reconstruction, and records are different projections or reconstructions of a larger relational structure.

The substrate may still contain update order, causal order, constraint order, or algebraic dependency. The framework is neutral about that deeper ordering. Its only commitment is that such order should not be confused with the time measured by clocks after projection.

3. Why scalar timing is the simplest readable projection

The scalar branch deserves its privileged place only if "simplest" is made explicit.

A scalar load requires one number per effective locus. It has no direction, spin, holonomy, gauge redundancy, or tensor index. A clock response then requires a single susceptibility parameter α:

$$\omega_{\text{eff}} = \frac{\omega}{1 + \alpha\Lambda}.$$

A vector or gauge sector requires more: orientation, edge variables, circulation, phase, and a notion of holonomy around closed loops. A tensor-gravity sector requires still more: the joint behavior of clocks and rods, light cones, free-fall trajectories, stress-energy response, universality across matter species, Lorentz compatibility, and a spin-2-like mode or equivalent constraint structure.

The instrument inventory therefore grows monotonically:

clock alone $\rightarrow$ clock plus oriented loop $\rightarrow$ clock plus rod plus matter species plus radiation.

Scalar timing sits at the bottom of this inventory. It is not simpler because it is more fundamental. It is simpler because it asks less of an instrument.

4. Relational substrate and projected sectors

Let the deepest substrate be described abstractly as a lawful relational system rather than a differentiable manifold. Depending on the model, it may be represented as a graph, hypergraph, tensor network, causal set, quantum cellular automaton, or another structure of updates, adjacencies, memory, constraints, and correlations.

Let the full microscopic state be denoted

$$\rho_{\text{micro}}.$$

Observers do not access ρ_{micro} directly. Instead, they access stable projected sectors. The scalar timing sector is the image of a coarse-graining channel

$$\mathcal{E}_{\text{scalar}} : \rho_{\text{micro}} \longmapsto \{W, L_w, \Lambda, \omega_{\text{eff}}\}.$$

Here $W = (w_{ij})$ is an effective weighted adjacency matrix, $L_w = D - W$ is the weighted graph Laplacian, Λ is the retained scalar load, and ω_{eff} is the effective clock rate.

This projection discards most of the microscopic state. It does not retain all phase information, all nonlocal correlations, all gauge-like loops, all tensorial degrees of freedom, or the entire global topology. It keeps the part that survives into scalar timing measurements.

The scalar sector is therefore not the whole world. It is the smallest world a clock can read.

5. Postulates of co-emergent scalar timing geometry

Postulate I: relational substrate

The deepest physical description is not assumed to be a smooth spacetime manifold. It is modeled as a lawful relational substrate of updates, adjacencies, constraints, memory, and correlations.

Postulate II: co-emergence

Scalar timing, mass-like persistence, gauge-like circulation, tensor geometry, and classical records do not arise in a temporal sequence and are not built from each other in a definitional cascade. They are projected or reconstructed aspects of one relational structure.

Postulate III: asymmetric readability

Although sectors may be co-emergent, they are not equally readable. Finite observers access reduced projections. The scalar timing projection is simpler than tensor reconstruction because it requires only a scalar load and a clock response.

Postulate IV: scalar timing law

The minimal timing response is

$$\omega_{\text{eff}} = \frac{\omega}{1 + \alpha\Lambda}, \qquad \frac{\delta\omega}{\omega} \approx -\alpha\Lambda \quad \text{for weak load.}$$

Postulate V: operator closure

The scalar load is not an arbitrary fitted field. It should satisfy, at leading order,

$$(\kappa L_w + \mu^2 I)\Lambda = A\rho,$$

with possible dynamical completion

$$\partial_t \Lambda + \Gamma(\kappa L_w + \mu^2 I)\Lambda = \Gamma A \rho(t).$$

The same operator that controls response must also control smoothing, relaxation, and effective dimension.

Postulate VI: richer sectors require richer observables

Mass, magnetism, gauge structure, topology, and tensor gravity are not denied. They are higher-readability sectors requiring persistence, oriented loops, holonomy, stress-response, tensorial degrees of freedom, and universal coupling beyond what a clock alone provides.

6. The clock as a projection device

A clock in this framework is not merely an object inside geometry. It is a projection device that converts inaccessible relational structure into accumulated phase.

Let a local clock have bare frequency ω. If the local scalar load is $\Lambda_i(t)$, then

$$\omega_{\text{eff}}(i,t) = \frac{\omega}{1+\alpha\Lambda_i(t)}.$$

The accumulated phase is

$$\phi_i(T) = \int_0^T \omega_{\text{eff}}(i,t)\,dt.$$

For two clocks A and B,

$$\phi_A(T) - \phi_B(T) = \int_0^T \left[\frac{\omega}{1+\alpha\Lambda_A(t)} - \frac{\omega}{1+\alpha\Lambda_B(t)}\right] dt.$$

In the weak-load regime,

$$\phi_A(T) - \phi_B(T) \approx -\alpha\omega \int_0^T [\Lambda_A(t) - \Lambda_B(t)]\,dt.$$

This is the minimal measurable signature: not the full geometry, not the source, not the tensor structure, only differential accumulated phase. The clock does not tell us what the substrate is. It tells us that the substrate casts a scalar timing shadow.

7. Scalar load from an effective graph

The scalar sector is modeled on an effective weighted graph $G = (V, E, w)$. The weights w_{ij} may arise from microscopic couplings, bond occupations, frustration patterns, dressed interactions, or

another medium-specific extraction map.

The weighted Laplacian is

$$(L_w f)(i) = \sum_j w_{ij} \left[f(i) - f(j) \right].$$

The leading scalar closure is

$$(\kappa L_w + \mu^2 I)\Lambda = A\rho.$$

This is a leading weak-load closure, not a final ontology. Beyond it one expects corrections:

$$(\kappa L_w + \mu^2 I)\Lambda + \beta\Lambda^2 + \eta L_w^2 \Lambda + \int_0^t M(t-s)\Lambda(s)\, ds = A\rho.$$

The scientific question is whether the leading scalar closure suffices in any real or simulated scaling window.

8. Effective dimension from the same operator

The same operator L_w that governs scalar response also defines diffusion on the promoted graph:

$$K(t) = e^{-tL_w}.$$

The mean return probability is

$$P_{\text{return}}(t) = \frac{1}{|V|} \operatorname{Tr} K(t).$$

When a scaling regime exists, the diffusion-based effective dimension is

$$d_{\text{eff}}^{(\text{diff})}(t) = -2 \frac{d \log P_{\text{return}}(t)}{d \log t}.$$

Independently, a scalar load sourced at a point or hotspot yields a shell-averaged profile

$$\Lambda_{\text{shell}}(r) = \frac{1}{|S_r|} \sum_{i \in S_r} \Lambda_i.$$

In a Gaussian scaling regime,

$$\Lambda_{\text{shell}}(r) \sim r^{2-d_{\text{eff}}} \quad (d_{\text{eff}} \neq 2), \qquad \Lambda_{\text{shell}}(r) \sim \log r \quad (d_{\text{eff}} = 2).$$

Thus the shell-based estimate is

$$d_{\text{eff}}^{(\Lambda)}(r) = 2 - \frac{d \log |\Lambda_{\text{shell}}(r)|}{d \log r}.$$

The closure test is not whether either estimator gives a pleasing number. It is whether

$$d_{\text{eff}}^{(\text{diff})} \approx d_{\text{eff}}^{(\Lambda)}$$

in the same scaling window where the scalar timing law fits best.

9. The 3D branch as a readability condition

If the scalar closure admits a Gaussian scaling regime, then

$$\Lambda(r) \sim r^{2-d_{\text{eff}}}.$$

For

$$d_{\text{eff}} \approx 3,$$

one obtains

$$\Lambda(r) \sim \frac{1}{r}, \qquad \frac{\delta\omega}{\omega} \approx -\alpha\Lambda(r) \sim -\frac{1}{r}.$$

This resembles the radial envelope of weak gravitational redshift. The resemblance is not yet a derivation of gravity. It identifies a scalar precondition: in an effectively three-dimensional branch, scalar timing has the right radial form to become gravity-like if richer sectors are also available.

Three is therefore not assumed as a background. It is a target of closure. The strong version of the program must demonstrate that a substrate family supports a stable window in which $d_{\text{eff}} \approx 3$ is selected or at least robustly supported, not merely imposed by construction.

10. Gravity as richer reconstruction, not later creation

Full gravity is not scalar timing. A scalar redshift-like channel is not equivalent to general relativity. A complete gravitational sector must account for metric-like structure $g_{\mu\nu}$ or its effective equivalent, universal coupling, free-fall behavior, light cones, stress-energy response, Lorentz-compatible dynamics, gravitational radiation, and a spin-2-like sector or equivalent constraint structure.

Scalar timing relates to gravity as a shadow relates to an object. It is not the object. It is a projection of the object under a particular readout.

The correct expression is not

$$\Lambda \to \text{gravity},$$

but

$$\mathcal{R}_{\text{full}} \longrightarrow \begin{cases} \Lambda, \omega_{\text{eff}} & \text{scalar timing projection,} \\ A_\mu, \text{ holonomy} & \text{gauge-like projection,} \\ g_{\mu\nu} & \text{tensor reconstruction,} \\ \text{records} & \text{classical projection.} \end{cases}$$

Gravity and scalar timing may be co-emergent projections of the same deeper structure. Scalar timing is not earlier. It is simpler to read.

11. Mass, magnetism, and records

The scalar timing program should not demote other sectors. It should locate them.

11.1 Mass-like persistence

Mass may correspond to stable localized patterns: defects, knots, scars, standing excitations, or self-maintaining concentrations of relational load. A clock may read their scalar effect before the

full nature of their persistence is reconstructed.

11.2 Gauge-like circulation

Magnetism cannot be captured by scalar load alone. It requires orientation, phase, circulation, and holonomy. In graph language it lives on edges, cycles, and phase relations rather than nodes:

$$\text{oriented information flow} \rightarrow \text{loop phase} \rightarrow \text{gauge field} \rightarrow \text{magnetism-like sector.}$$

Scalar timing asks how loaded a place is. Magnetism asks how relational phase circulates around a place.

11.3 Tensor gravity

Tensor gravity requires the joint reconstruction of metric-like structure from many observables, not just clock rate. It belongs to a richer projected algebra.

11.4 Classical records

A classical world requires stable, redundant, coarse-grained states that persist long enough to be compared. Records are not passive backdrop. They are part of the projection machinery itself.

12. The readability ladder

The language of "before clock lag" and "after clock lag" should be replaced by a hierarchy of projection depth. The table below is not a temporal sequence. It is a readability ladder. Lower levels are not earlier; they are less reconstructed. Higher levels are not later; they require more structure to read.

Level	Description	Status
0	Full relational substrate	Hidden / not directly observed
1	Stable relational topology	Adjacency, paths, loops, bottlenecks
2	Effective operator	W, L_w, response law
3	Scalar load	Λ, minimal retained scalar
4	Clock-readable projection	ω_{eff}, accumulated phase, lag
5	Gradient behavior	$\nabla\Lambda$, force-like scalar bias
6	Persistent excitations	Mass-like sources
7	Oriented loop sectors	Gauge / magnetism-like behavior
8	Tensor reconstruction	Gravity-like geometry
9	Stable records	Classical world

13. Internal loads and external observables

A scalar load inside a medium does not automatically imply an externally measurable scalar field. This distinction is essential and is one of the cleanest ways the program can fail.

Let Λ_i be internal scalar load on graph vertex i. An external sensor at position x measures, at most,

$$\Lambda_{\text{ext}}(x) = \sum_i C(x,i)\Lambda_i.$$

The kernel $C(x,i)$ determines how internal load couples to an external probe.

Possible classes include:

- near-field or evanescent coupling, $C_{\text{ev}}(x,i) \sim C_0 e^{-d(x,i)/\ell_c}$;
- substrate-mediated diffusive coupling;
- radiative or boundary-modulated coupling;
- vacuum-like Green response;
- the null kernel, $C(x,i) \approx 0$.

An internal scalar timing sector can exist in a medium while producing no external geometric signal. That outcome would not make the internal theory meaningless, but it would limit the scope of any claim about external spacetime geometry.

14. The severe closure criterion

The scalar timing program becomes scientific only when it supplies severe tests. The strongest version passes only if a single substrate family yields a stable scaling window in which

$$d_{\text{eff}}^{(\text{diff})} \overset{?}{\approx} d_{\text{eff}}^{(\Lambda)} \overset{?}{\approx} 3, \qquad \omega_{\text{eff}} = \frac{\omega}{1+\alpha\Lambda} \quad \text{fits},$$

and, when time-resolved data exist,

$$\tau_n^{-1} \approx \Gamma(\kappa\lambda_n + \mu^2)$$

with the predicted finite-fast-sector deviations.

A meaningful pass requires:

1. a nontrivial scaling window in diffusion time or shell radius;
2. agreement between diffusion-based and shell-profile-based dimension estimates;
3. local minimization of timing-law residuals in the same window;
4. finite-size stability;
5. robustness to source placement and graph extraction thresholds;
6. modal relaxation rates tracking the Laplacian spectrum.

If the timing law fits in one window while the dimension estimate works in another, strong closure fails. If the dimension estimate passes through three only transiently without a plateau, the result is suggestive but weak. If no Gaussian scaling window exists, the medium does not support the intended scalar branch.

The virtue of the program is that failure has shape.

15. Experimental posture

The experimental program should not begin by claiming new gravity. It should begin by bounding scalar timing response in controlled media.

A minimal experiment would require:

1. a reconfigurable medium whose internal graph W can be changed;
2. a clock-like or phase-sensitive observable coupled to the medium;
3. topology changes at nearly fixed mass-energy distribution;
4. distance-law measurements;
5. thermal, electromagnetic, vibrational, and mechanical controls;
6. comparison of transient response against the graph Laplacian spectrum.

The desired signature is not merely "a frequency changed." Frequency changes are easy to fake through ordinary systematics. The desired signature is the conjunction

timing shift+graph dependence+topology sensitivity+modal relaxation+mass/force null controls.

A null result is useful. It constrains α, A, μ, Γ, or the coupling kernel $C(x, i)$. It tells us whether scalar timing is external, internal, screened, or absent in that medium.

16. Relation to existing ideas

The present framework sits near several established research families but is not identical to any one of them.

Relational approaches to time emphasize that time is not an external universal parameter but a relation between physical systems. Quantum clock and Page-Wootters-type approaches show how time-like behavior may arise from correlations between subsystems. Causal set theory and graph-based models explore the possibility that spacetime is not fundamentally a smooth manifold. Quantum graphity studies how locality and low-dimensional structure may emerge from dynamical graphs. Tensor-network and entanglement-based approaches suggest that geometry may be encoded in quantum information structure. Scalar gravity historically explored whether gravity could be described by a scalar field, though scalar theories do not reproduce full general relativity.

The present proposal differs by combining these motifs into a timing-first scalar-selection program:

> A relational substrate may give rise to many observable sectors, but the minimal readable projection for a local observer is scalar clock lag governed by an effective graph operator.

This is not a claim of total priority. It is a claim of synthesis and testability.

17. Limits

This paper does not prove full general relativity, Lorentz invariance, electromagnetism, mass, a spin-2 sector, external scalar geometry, dark energy, quantum gravity, or a theory of everything.

It proposes a reduced observable sector and an interpretation of its possible significance.

The main risks are:

1. the scalar timing law may be only a fitting artifact;
2. the effective dimension may not stabilize in any scaling window;
3. the graph Laplacian may not control timing and response together;
4. the external kernel $C(x, i)$ may be null in accessible media;
5. ordinary thermal or electromagnetic effects may dominate;
6. tensor reconstruction may not follow from scalar closure;
7. the $d_{\text{eff}} \approx 3$ branch may be imposed by model construction rather than dynamically selected.

These are not peripheral concerns. They are the tests.

18. Conclusion: the scalar face of a simultaneous world

The universe may not unfold according to the order in which we explain it.

Clock lag need not happen before gravity. Scalar timing need not be built before geometry. Mass, gauge structure, tensor curvature, and records need not wait in line. They may be co-emergent aspects of a single relational structure, at least in the restricted sense that they are neither chronologically ordered nor cascaded by definition.

But observers do not receive that structure whole. They ask partial questions, use finite instruments, and extract stable projections. Among those projections, clock timing is unusually primitive: a local system accumulates phase, and phase can be compared.

The claim of scalar timing geometry is therefore not that the clock comes before gravity in time. It is that the clock may reveal the scalar face of co-emergent geometry before richer reconstruction is possible.

A relational universe may be a chord. Gravity may be the full harmony. Clock lag may be the first note our instruments can reliably hear. The scientific task is to determine, in a single scaling window with severe controls, whether that note is real.

References

[1] A. Einstein, "Zur Elektrodynamik bewegter Koerper," *Annalen der Physik* 17, 891-921 (1905).

[2] A. Einstein, "Die Grundlage der allgemeinen Relativitaetstheorie," *Annalen der Physik* 49, 769-822 (1916).

[3] G. Nordstroem, "On the possibility of unifying the electromagnetic and gravitational fields," *Physikalische Zeitschrift* (1914).

[4] C. Rovelli, "Time in quantum gravity: An hypothesis," *Physical Review D* 43, 442-456 (1991).

[5] D. N. Page and W. K. Wootters, "Evolution without evolution: Dynamics described by stationary observables," *Physical Review D* 27, 2885-2892 (1983).

[6] L. Bombelli, J. Lee, D. Meyer, and R. D. Sorkin, "Space-Time as a Causal Set," *Physical Review Letters* 59, 521-524 (1987).

[7] T. Konopka, F. Markopoulou, and S. Severini, "Quantum graphity: A model of emergent locality," *Physical Review D* 77, 104029 (2008).

[8] R. Burioni and D. Cassi, "Universal properties of spectral dimension," *Physical Review Letters* 76, 1091-1093 (1996).

[9] G. Calcagni, D. Oriti, and J. Thuerigen, "Spectral dimension of quantum geometries," *Journal of Physics A* 47, 355402 (2014).

[10] F. Chung and S.-T. Yau, "Discrete Green's functions," *Journal of Combinatorial Theory, Series A* 91, 191-214 (2000).

[11] B. Swingle, "Spacetime from entanglement," *Annual Review of Condensed Matter Physics* 9, 345-358 (2018).

[12] T. Jacobson, "Thermodynamics of spacetime: The Einstein equation of state," *Physical Review Letters* 75, 1260-1263 (1995).

[13] T. Bothwell et al., "Resolving the gravitational redshift across a millimetre-scale atomic sample," *Nature* 602, 420-424 (2022).

[14] S. Wolfram, "A Class of Models with the Potential to Represent Fundamental Physics," Wolfram Physics Project (2020).

[15] J. Farrow, *On the Dynamics of Relational Clocks: Scalar Timing as the Minimal Readable Projection of a Relational Universe* (April 2026).

On the Dynamics of Relational Clocks

Scalar Timing as the Minimal Readable Projection of a Relational Universe

Joshua Farrow
Independent Research
with AI-assisted synthesis
April 2026

Abstract

This paper develops an operational hypothesis for a universe whose deepest structure is relational rather than manifold-like. If spacetime is an emergent projection of a deeper substrate, the first stable quantity readable by a local instrument need not be the full metric tensor, mass, electromagnetism, topology, or a spin-2 sector. It may be a scalar timing channel: the fact that local clocks accumulate phase differently where relational load is retained.

The central claim is not chronological. Clock lag is not asserted to occur before gravity in time. If time is emergent, such a sequence would already assume what is being explained. The claim is instead one of *operational readability*: a full relational structure may give rise to scalar, gauge, tensor, mass-like, and record-forming sectors together, while a finite clock reads only a reduced scalar projection. Scalar timing is therefore proposed as the minimal clock-readable shadow of a richer co-emergent geometry.

The program spine is

$$H_{\text{micro}} \longrightarrow W \longrightarrow L_w \longrightarrow \Lambda \longrightarrow \omega_{\text{eff}},$$

where H_{micro} denotes a microscopic relational medium, W an effective weighted adjacency, L_w the weighted graph Laplacian, Λ a retained scalar load, and ω_{eff} the effective clock rate. The scalar timing law is

$$\omega_{\text{eff}} = \frac{\omega}{1+\alpha\Lambda},$$

with weak-load limit $\delta\omega/\omega \approx -\alpha\Lambda$. The scalar load is required to satisfy a screened graph closure

$$(\kappa L_w + \mu^2 I)\Lambda = A\rho,$$

with a dynamical completion and a finite-coupler diagnostic. A microscopic bridge is supplied by eliminating fast edge variables, yielding a positive weighted Laplacian $L_w = B^T \mathrm{diag}(w_e) B$ under positive diagonal assumptions.

The strong empirical test is not merely whether a timing law can be fitted. It is whether one scaling window simultaneously supports: agreement of diffusion-based and shell-profile-based effective dimension estimators, a near-three scalar branch, low residuals for the timing law, and modal relaxation controlled by the spectrum of L_w. The paper does not claim to derive general relativity, Lorentz invariance, electromagnetism, mass, external scalar geometry, or a theory of everything. It defines a narrow, falsifiable scalar timing sector: if the universe is relational at depth, the first reliable local readout may be delay.

Contents

1 The clock problem **2**

2 Principle and measurement **2**

3 Genesis versus readability **2**

4 Related work and neighboring landscape **3**

5 Postulates of scalar timing geometry **3**
5.1 Relational substrate 4
5.2 Projection 4
5.3 Scalar timing 4
5.4 Operator closure 4
5.5 Co-emergence and asymmetric readability 4
5.6 Higher sectors 5

6 The two-clock thought experiment **5**

7 Depth and readability **5**

8 A microscopic bridge: fast edge variables **6**

9 Static, dynamic, and clock closure **6**
9.1 Static closure 7
9.2 Dynamic rate closure 7
9.3 Clock-phase closure 7

10 Effective dimension from the same operator **8**

11 The 3D branch as a gravity-like scalar profile **8**

12 Substrate selection: which graphs become space **9**

13 Internal loads and external observables **9**

14 Mass, magnetism, and topology revisited **9**

15 Experimental and numerical consequences **10**

16 What would break physics? **10**

17 Limits and proof levels **11**
17.1 Proven inside the fast-coupler model 11
17.2 Derived inside the linear dynamic model 11
17.3 Operationally motivated, not yet proven physically 11
17.4 Not yet proven 11

18 Conclusion: delay as the scalar face of co-emergent geometry **11**

1. The clock problem

Modern physics learned to distrust common-sense space and time through clocks. In special relativity, simultaneity became operational: two distant events are not simply "at the same time" until a synchronization procedure involving clocks and signals is specified. In general relativity, clock rate ceased to be an external bookkeeping device and became part of geometry itself. A clock deeper in a gravitational potential accumulates less proper time than a clock far away.

If spacetime is not fundamental, the clock becomes stranger still. It is no longer merely an instrument inside geometry. It may be one of the simplest systems through which pre-geometric order becomes visible.

The usual mature order of explanation is

$$\text{mass-energy} \longrightarrow \text{geometry} \longrightarrow \text{clock rate}.$$

The operational discovery order explored here is

$$\text{relational substrate} \longrightarrow \text{scalar load} \longrightarrow \text{clock response} \longrightarrow \text{inferred geometry}.$$

This second chain should not be read as a cosmic history. It is a readability chain. A finite observer does not receive the entire relational substrate; a clock receives a timing response. The question is therefore not whether the full universe can be written down at once, but what a clock embedded inside a relational order is forced to report before any larger reconstruction is available.

The proposed answer is simple: lag.

2. Principle and measurement

Physical theory gains sharpness when its words are tied to operations. A time is not a label placed on the world from outside; it is a reading of a clock. A field is not a curve drawn over space; it is a rule of response. A geometry earns its name only when clocks, phases, rods, trajectories, horizons, or records answer to it.

Four disciplines follow.

First, primitive terms must be readable. A relational substrate may be deeper than observation, but its physical content begins where some local system responds.

Second, the postulates must be sparse. If geometry is to emerge, geometry must not be smuggled into the first line under another name.

Third, consequences must be ranked by strength. A scalar timing law is not gravity. Isotropic scalar dispersion is not Lorentz invariance. A weighted graph Laplacian is not a spin-2 field. Each rung carries its own burden of proof.

Fourth, failure must have a shape. A theory that survives every outcome has learned nothing. Bad substrates must trap or scatter modes. Slow couplers must produce lag or ringing. External fields must require explicit coupling kernels. Tensor gravity must wait until tensor structure exists.

The present proposal begins where physical meaning becomes most vulnerable: at the instrument. What is the weakest consequence a clock could measure if the world beneath spacetime is relational?

3. Genesis versus readability

A theory that tries to explain time must not smuggle temporal sequence into its foundation. It is tempting to say that relational updating comes first, then scalar load, then clock lag, then gravity. As a conceptual map this is useful. As a literal chronology it is incoherent. If time itself is emergent,

"first" cannot mean earlier in metric time at the deepest level. A pre-geometric substrate does not wait, then make clocks, then wait again, then make gravity. Waiting is already temporal.

We therefore distinguish *genetic order* from *readability order*. A genetic order says

$$A \longrightarrow B \longrightarrow C,$$

as though A happens, then B, then C. A readability order says

$$\mathcal{R}_{\text{full}} \longrightarrow \Pi_{\text{obs}}(\mathcal{R}_{\text{full}}),$$

where $\mathcal{R}_{\text{full}}$ is the full relational structure and Π_{obs} is the projection imposed by finite instruments, finite resolution, coarse graining, and stable records.

In this second sense scalar timing can be "first" without being temporally first. It is first because it requires the least reconstructed structure. A scalar clock-rate shift requires one local scalar quantity and one susceptibility. A vector or gauge sector requires orientation, circulation, and holonomy. A tensor-gravity sector requires clocks, rods, free-fall behavior, universal coupling, Lorentz-compatible propagation, stress-energy response, gravitational radiation, and a spin-2-like sector or equivalent constraint structure.

The central claim is therefore:

> Clock lag is not before gravity in time. Clock lag is the scalar face of a co-emergent relational geometry under the readout of a local clock.

4. Related work and neighboring landscape

The broad idea that spacetime may emerge from discrete or relational structure is not new. The present proposal is deliberately narrower than the neighboring programs.

Wolfram-style hypergraph rewriting programs begin with abstract relations and update rules, then study whether spacetime, relativity, and quantum phenomena can arise as large-scale consequences of causal-invariant rewriting. Causal set theory replaces a continuum spacetime with a locally finite partial order. Quantum graphity models study dynamical graphs whose high-energy phases may be highly connected while low-energy phases become ordered, local, and effectively low-dimensional. Tensor-network and entanglement-based approaches investigate how geometry-like quantities may arise from quantum information structure.

Relational approaches to time and Page-Wootters-type constructions emphasize that time can be treated through correlations between physical subsystems rather than as an external universal parameter. Scalar-gravity programs show that scalar theories can imitate some redshift-like behavior but do not reproduce full general relativity.

The present work does not compete with these programs at the level of a universal microscopic rule. Instead, it asks a downstream question:

> Suppose some discrete relational substrate exists. What reduced observable sector should be tested first by a minimal local instrument?

The answer is scalar timing. Mass, magnetism, topology, and tensor gravity are not demoted. They are richer and more demanding. Scalar timing is weaker: one number at one locus, read by one clock.

5. Postulates of scalar timing geometry

The following postulates define a research program. They are not asserted as final truths; they are assumptions from which tests follow.

5.1. Relational substrate

The deepest physical substrate is not assumed to be a differentiable manifold. It is modeled abstractly as a lawful system of relations, updates, constraints, memory, and adjacency. A graph, hypergraph, causal set, tensor network, quantum cellular automaton, or programmable coupling medium may represent one effective description of such a substrate.

5.2. Projection

Observers do not access the full substrate. They access stable projected sectors that survive coarse graining, finite resolution, noise, and dynamical selection. The observed world is not the whole substrate; it is a persistent readable layer.

The scalar timing projection may be written schematically as

$$\mathcal{E}_{\text{scalar}} : \rho_{\text{micro}} \longmapsto \{W, L_w, \Lambda, \omega_{\text{eff}}\}.$$

This projection discards most microscopic information: nonlocal correlations not visible in Λ, phase data, gauge-like loops, higher connected correlations, and tensorial structure not accessible through the clock channel.

5.3. Scalar timing

The minimal clock-readable geometric observable is a scalar load Λ, measured operationally through local clock-rate shifts:

$$\omega_{\text{eff}} = \frac{\omega}{1 + \alpha\Lambda},$$

or, for weak load,

$$\frac{\delta\omega}{\omega} \approx -\alpha\Lambda.$$

Here α is an effective susceptibility. This law does not assert full gravity. It asserts a scalar redshift-like channel.

5.4. Operator closure

A scalar timing sector is physically meaningful only if the same effective operator controls response, smoothing, spectral dimension, and timing. The minimal closure chain is

$$H_{\text{micro}} \longrightarrow W \longrightarrow L_w \longrightarrow \Lambda \longrightarrow \omega_{\text{eff}}.$$

At leading order the scalar load should satisfy

$$(\kappa L_w + \mu^2 I)\Lambda = A\rho,$$

with possible dynamical completion

$$\partial_t \Lambda + \Gamma(\kappa L_w + \mu^2 I)\Lambda = \Gamma A\rho(t).$$

5.5. Co-emergence and asymmetric readability

Scalar timing, gauge-like circulation, mass-like persistence, tensor geometry, and records need not arise in a temporal sequence. They may be co-emergent projections of one relational structure. However, they are not equally readable. Scalar timing requires a scalar load and a clock. Gauge sectors require loops and phase. Tensor gravity requires a much larger instrument inventory.

5.6. Higher sectors

Mass, magnetism, gauge structure, topology, and tensor gravity are not denied. They are richer sectors. Mass requires stable localization. Magnetism requires orientation, circulation, phase, and holonomy. Gravity requires tensor structure, universal coupling, Lorentz-compatible dynamics, and a spin-2-like sector or equivalent constraints. Scalar timing sits lower in the readability hierarchy because it assumes the least.

6. The two-clock thought experiment

Consider two identical clocks, A and B, embedded in a relational medium whose microscopic state is not directly observable. No mass has yet been assigned. No curvature tensor has been reconstructed. No electromagnetic field has been identified. The clocks are separated, held for a duration, and then compared.

They disagree.

The minimal question is not yet: what gravitational field caused this? That question assumes a mature interpretation. The minimal question is:

> What must exist for this disagreement to be lawful?

At minimum there must be a scalar quantity along the two histories that changes the accumulated phase of the clocks:

$$\Delta\phi_i = \int \omega_{\text{eff}}(i,t)\,dt.$$

If

$$\omega_{\text{eff}}(i,t) = \frac{\omega}{1+\alpha\Lambda_i(t)},$$

then the clock disagreement is explained by different histories of scalar load:

$$\Delta\phi_A - \Delta\phi_B = \int \left[\frac{\omega}{1+\alpha\Lambda_A(t)} - \frac{\omega}{1+\alpha\Lambda_B(t)}\right] dt.$$

In the weak-load regime,

$$\Delta\phi_A - \Delta\phi_B \approx -\alpha\omega \int [\Lambda_A(t) - \Lambda_B(t)]\,dt.$$

This is the minimal operational geometry: not curvature, not mass, not force, but accumulated differential clock phase.

7. Depth and readability

The earlier language of "before clock lag" and "after clock lag" is replaced here by a hierarchy of projection depth and instrument richness. The levels below are not a temporal sequence. They are a readability ladder.

Level	Description	Observable status
0	Full relational substrate	Hidden / not directly observed
1	Stable relational topology	Paths, loops, adjacency, bottlenecks
2	Effective operator	W, L_w, response law
3	Scalar load	Λ, minimal retained scalar
4	Clock-readable projection	ω_{eff}, accumulated phase lag
5	Gradients of Λ	Force-like scalar bias
6	Persistent excitations	Mass-like sources
7	Oriented loops / phases	Gauge and magnetism-like sectors
8	Tensor reconstruction	Gravity-like geometry
9	Stable records	Classical world

Lower levels are not earlier; they are less reconstructed. Higher levels are not later; they require more structure to read.

8. A microscopic bridge: fast edge variables

The scalar timing program requires a mechanism that produces L_w rather than merely assuming it. A minimal fast-coupler model supplies such a bridge.

Let Λ_i be slow node loads and x_e fast edge variables. Let B be the incidence matrix of an underlying substrate graph. Consider

$$\dot{\Lambda} = -\mu^2\Lambda - B^T G x + A\rho(t),$$

$$\dot{x} = HB\Lambda - \Omega x.$$

Here G, H, Ω are edge-sector matrices. In the positive diagonal regime, the fast variables satisfy approximately

$$x \approx \Omega^{-1} HB\Lambda.$$

Substitution gives

$$\dot{\Lambda} \approx -\left(\mu^2 I + B^T G\Omega^{-1} HB\right)\Lambda + A\rho(t).$$

Thus

$$L_w = B^T G\Omega^{-1} HB.$$

If

$$G\Omega^{-1}H = \operatorname{diag}(w_e), \qquad w_e > 0,$$

then

$$L_w = B^T \operatorname{diag}(w_e) B,$$

which is a positive weighted graph Laplacian. The substrate graph is specified, but the scalar response operator and weights arise from microscopic edge parameters rather than from a direct node-level scalar ansatz. The Schur reduction is where the effective operator acquires content.

9. Static, dynamic, and clock closure

The fast-coupler model yields three different kinds of closure. Conflating them is the source of many false passes and false failures.

9.1. Static closure

At steady state, eliminating x gives

$$(\mu^2 I + L_w)\Lambda = A\rho.$$

This is exact in the linear model under the stated assumptions. It verifies that the scalar response equation can be realized by microscopic edge degrees of freedom.

When $\mu = 0$, a connected graph has a constant null mode. Static closure then requires source neutrality, gauge fixing, or projection off the constant mode. This is not a detail; it is the scalar analogue of removing an unobservable uniform offset.

9.2. Dynamic rate closure

For uniform fast scale Ω, each Laplacian eigenmode with eigenvalue λ_n obeys

$$(r + \mu^2)(r + \Omega) + \Omega\lambda_n = 0.$$

The Markovian scalar prediction is

$$\tau_n^{-1} \approx \mu^2 + \lambda_n.$$

This holds only when the fast sector is genuinely fast. The slow root is

$$r_{\text{slow}} = -(\mu^2 + \lambda_n)\left[1 + \frac{\lambda_n}{\Omega} + O(\Omega^{-2})\right].$$

Thus rate errors scale like λ_n/Ω. High-λ modes fail first. The underdamped condition is

$$(\Omega - \mu^2)^2 < 4\Omega\lambda_n.$$

Finite coupler speed therefore produces predicted memory, lag, and ringing. That is not a blemish on the model. It is the diagnostic shape that distinguishes the model from a generic fitting law.

9.3. Clock-phase closure

A local clock may obey

$$\dot{\phi}_i = \omega_0 + \alpha\Lambda_i(t).$$

The clock phase shift is

$$\Delta\phi_i - \omega_0 t = \alpha \int \Lambda_i(t)\, dt.$$

This matters because clocks integrate scalar load. A rate measurement probes poles of the response; a clock phase measurement probes accumulated area. Under some protocols, the clock integral can recover the static gain even when the instantaneous rate is distorted by finite-coupler memory. Under other protocols, especially when the fast sector begins preloaded or the source drives high-frequency response, the clock integral can inherit the same finite-Ω errors.

The safe conclusion is:

> Rate closure is the strict dynamic test. Clock closure is the robust low-frequency test. The two are related but not identical.

10. Effective dimension from the same operator

The same weighted Laplacian that controls scalar response also defines diffusion on the promoted graph:

$$K(t) = e^{-tL_w}.$$

The mean return probability is

$$P_{\text{return}}(t) = \frac{1}{|V|}\operatorname{Tr} K(t).$$

When a scaling regime exists, the diffusion-based effective dimension is

$$d_{\text{eff}}^{(\text{diff})}(t) = -2\frac{d\log P_{\text{return}}(t)}{d\log t}.$$

Independently, around a source or hotspot, define graph shells S_r and a shell-averaged scalar load

$$\Lambda_{\text{shell}}(r) = \frac{1}{|S_r|}\sum_{i\in S_r}\Lambda_i.$$

In a Gaussian scaling regime, the asymptotic profile is

$$\Lambda_{\text{shell}}(r) \sim r^{2-d_{\text{eff}}} \quad (d_{\text{eff}} \neq 2),$$

with logarithmic behavior at $d_{\text{eff}} = 2$. Thus the shell estimator is

$$d_{\text{eff}}^{(\Lambda)}(r) = 2 - \frac{d\log|\Lambda_{\text{shell}}(r)|}{d\log r}.$$

The central closure question is whether

$$d_{\text{eff}}^{(\text{diff})} \overset{?}{\approx} d_{\text{eff}}^{(\Lambda)}$$

in the same window where the scalar timing law fits best.

11. The 3D branch as a gravity-like scalar profile

If the effective operator admits a Gaussian continuum scaling regime with effective dimension d_{eff}, the scalar Green response behaves as

$$G_{d_{\text{eff}}}(r) \sim r^{2-d_{\text{eff}}}$$

for $d_{\text{eff}} \neq 2$. In the special case

$$d_{\text{eff}} \approx 3,$$

the response becomes

$$\Lambda(r) \sim \frac{1}{r}.$$

The weak clock shift is then

$$\frac{\delta\omega}{\omega} \sim -\frac{1}{r}.$$

This resembles the envelope of weak-field gravitational redshift. The resemblance is not yet a derivation of gravity. It is a scalar precondition: in an effectively three-dimensional branch, scalar timing load has the right radial form to become gravity-like if richer sectors are also supplied.

The caveat is essential: $d_{\text{eff}} \approx 3$ is a target of closure, not a result. The framework does not insert ordinary three-dimensional space at the bottom; it asks whether a promoted relational operator selects or supports an effective dimension near three in the observable scalar branch. Until this is demonstrated on a concrete substrate family, the section identifies the right test, not its answer.

12. Substrate selection: which graphs become space

A relational universe cannot be an arbitrary graph if it is to look like a smooth world. Low-energy modes must be extended. Dispersion must be approximately isotropic. Locality must emerge rather than be assumed by name only.

Random geometric graphs can fail because their modes localize or scatter strongly. Poisson-Delaunay substrates and cotangent Laplacians are better candidates because they are connected to standard discrete approximations of continuum Laplace-Beltrami operators. The issue is not philosophical; it is spectral.

The minimal tests are:

1. Do low eigenmodes extend across the substrate rather than localize?
2. Does $\lambda(k)$ scale like $|k|^2$ at low k?
3. Does angular anisotropy fall with system size?
4. Does the scalar wave equation built from L_w admit approximately isotropic low-energy propagation?

This is not full Lorentz invariance. It is the spatial scalar-wave precondition for a Lorentz-compatible sector.

13. Internal loads and external observables

An internal scalar load does not automatically become an external field. Let Λ_i be internal scalar load on graph vertex i. An external sensor at position x measures, at most,

$$\Lambda_{\text{ext}}(x) = \sum_i C(x,i)\Lambda_i.$$

The kernel $C(x,i)$ determines whether the scalar sector is externally accessible and how it decays with distance.

Possible kernel classes include near-field or evanescent coupling,

$$C_{\text{ev}}(x,i) \sim C_0 e^{-d(x,i)/\ell_c},$$

substrate-mediated diffusive coupling, radiative or boundary-modulated coupling, a vacuum-like Green response, or a null kernel

$$C(x,i) \approx 0.$$

The null outcome is scientifically respectable. It would mean the scalar load is an internal medium observable only. That does not kill the program, but it limits what can be claimed experimentally.

14. Mass, magnetism, and topology revisited

The scalar clock channel is minimal because it is simple, not because it is everything.

Mass belongs to persistent localized structure: stable relational excitations that resist dispersion and act as sources. Magnetism belongs to oriented cycles and phase holonomies: the circulation of relational information around loops. Topology belongs below both: the hidden relational structure from which operators, loads, and sectors are projected. Gravity belongs above scalar timing in readability: the tensor reconstruction in which clocks, rods, free fall, light cones, and stress-energy become one geometry.

The later target is not

$$\Lambda \longrightarrow \text{gravity},$$

as though scalar load mechanically turns into gravity. The more careful structure is

$$\mathcal{R}_{\text{full}} \longrightarrow \begin{cases} \Lambda,\ \omega_{\text{eff}} & \text{scalar timing projection,} \\ A_\mu,\ \text{holonomy} & \text{gauge-like projection,} \\ g_{\mu\nu} & \text{tensor reconstruction,} \\ \text{records} & \text{classical projection.} \end{cases}$$

15. Experimental and numerical consequences

The program makes several concrete demands.

First, microscopic media should be tested for Schur-complement scalar closure. Fast edge degrees of freedom should generate a positive weighted Laplacian, and static response should follow $(\mu^2 I + L_w)^{-1}$.

Second, dynamic tests should measure finite-coupler failure. Rates should deviate as λ_n/Ω, with high modes failing first and ringing in the predicted underdamped windows.

Third, clock tests should separate low-frequency phase robustness from instantaneous rate closure. The same medium may pass a DC timing test while failing a high-frequency modal relaxation test.

Fourth, substrate tests should reject graph families whose modes localize. Extended low-energy modes are not optional. They are the difference between a relational network and an effective space.

Fifth, external-coupling tests must be explicit. A coupling kernel from internal load to external sensor must be specified, measured, or bounded.

The strongest numerical pass requires a single scaling window in which

$$d_{\text{eff}}^{(\text{diff})} \overset{?}{\approx} d_{\text{eff}}^{(\Lambda)} \overset{?}{\approx} 3,$$

$$\omega_{\text{eff}} = \frac{\omega}{1 + \alpha\Lambda}$$

fits with locally minimized residuals, and

$$\tau_n^{-1} \approx \mu^2 + \lambda_n$$

tracks the Laplacian spectrum with finite-Ω deviations of the predicted form.

16. What would break physics?

To break physics is not to abandon discipline. It is to find the point at which the old arrangement of assumptions can no longer remain the natural one.

The reorganization proposed here is this:

> Physics may have mistaken the stable projected dashboard for the engine.

If scalar timing geometry is right, then spacetime geometry is not the first layer of law in the ontological sense. It is a reconstruction from stable clock-readable projections and richer co-emergent sectors. Clocks do not merely live in geometry; clocks may be among the first instruments by which geometry is inferred from a pre-geometric substrate.

This would not falsify general relativity in its domain. It would reinterpret it as an effective theory of a mature projected sector. Likewise, it would not discard quantum theory. It would ask how quantum discreteness, relational updating, and observer projection participate in the emergence of the sectors that clocks and records can read.

The dangerous idea is therefore not that gravity is wrong. It is:

> The observable world is the part of relational reality that can keep time.

17. Limits and proof levels

This paper uses the word proof only in restricted senses.

17.1. Proven inside the fast-coupler model

Under positive diagonal edge-sector assumptions, eliminating fast edge variables produces a positive weighted graph Laplacian:

$$L_w = B^T \mathrm{diag}(w_e) B.$$

Static scalar closure follows.

17.2. Derived inside the linear dynamic model

Finite coupler speed produces mode-dependent corrections governed by

$$(r + \mu^2)(r + \Omega) + \Omega\lambda_n = 0.$$

The leading rate error scales as λ_n/Ω, and underdamped ringing appears in the predicted window.

17.3. Operationally motivated, not yet proven physically

Clock phase is a privileged observable because it integrates scalar load. This explains why timing may be robust in low-frequency protocols, but it does not prove universal clock protection.

17.4. Not yet proven

This paper does not prove mass, electromagnetism, full Lorentz invariance, external scalar geometry, general relativity, a spin-2 sector, or a theory of everything. It also does not yet prove that $d_{\mathrm{eff}} \approx 3$ is dynamically selected rather than imposed by substrate choice. The chief empirical obligation is to demonstrate scalar, dimensional, timing, and dynamic closure on at least one concrete substrate family.

18. Conclusion: delay as the scalar face of co-emergent geometry

If the universe is fundamentally relational, the first observable need not be the whole substrate. It may be the weakest stable projection that a local instrument can read.

A scalar load is such a projection. A clock is such an instrument. Clock lag is therefore a natural first readout of a relational universe, not because it comes before gravity in time, but because gravity is too rich to be the first scalar shadow. In a co-emergent relational structure, scalar timing, gauge behavior, mass-like persistence, tensor reconstruction, and stable records may all be aspects of one deeper order. But observers ask partial questions, and clocks answer one of the simplest.

The first shadow is delay.

References

[1] A. Einstein, "Zur Elektrodynamik bewegter Koerper" [On the Electrodynamics of Moving Bodies], *Annalen der Physik* **17**, 891–921 (1905).

[2] A. Einstein, "Die Grundlage der allgemeinen Relativitaetstheorie" [The Foundation of the General Theory of Relativity], *Annalen der Physik* **49**, 769–822 (1916).

[3] J. R. Oppenheimer and H. Snyder, "On Continued Gravitational Contraction," *Physical Review* **56**, 455–459 (1939).

[4] S. W. Hawking, "Particle Creation by Black Holes," *Communications in Mathematical Physics* **43**, 199–220 (1975).

[5] D. N. Page and W. K. Wootters, "Evolution without evolution: Dynamics described by stationary observables," *Physical Review D* **27**, 2885–2892 (1983).

[6] C. Rovelli, "Time in quantum gravity: An hypothesis," *Physical Review D* **43**, 442–456 (1991).

[7] S. Wolfram, "A Class of Models with the Potential to Represent Fundamental Physics," Wolfram Physics Project (2020).

[8] J. Gorard, "Algorithmic Causal Sets and the Wolfram Model," Wolfram Physics Project Bulletins / arXiv (2020).

[9] L. Bombelli, J. Lee, D. Meyer, and R. D. Sorkin, "Space-Time as a Causal Set," *Physical Review Letters* **59**, 521–524 (1987).

[10] T. Konopka, F. Markopoulou, and S. Severini, "Quantum graphity: A model of emergent locality," *Physical Review D* **77**, 104029 (2008).

[11] M. Levin and X.-G. Wen, "String-net condensation: A physical mechanism for topological phases," *Physical Review B* **71**, 045110 (2005).

[12] F. Chung and S.-T. Yau, "Discrete Green's functions," *Journal of Combinatorial Theory, Series A* **91**, 191–214 (2000).

[13] R. Burioni and D. Cassi, "Universal properties of spectral dimension," *Physical Review Letters* **76**, 1091–1093 (1996).

[14] G. Calcagni, D. Oriti, and J. Thuerigen, "Spectral dimension of quantum geometries," *Journal of Physics A* **47**, 355402 (2014).

[15] F. Doerfler and F. Bullo, "Kron Reduction of Graphs With Applications to Electrical Networks," *IEEE Transactions on Circuits and Systems I* **60**, 150–163 (2013).

[16] A. N. Tikhonov, "Systems of differential equations containing small parameters in the derivatives," *Matematicheskii Sbornik* **31**, 575–586 (1952).

[17] M. Desbrun, M. Meyer, P. Schroeder, and H. Barr, "Implicit fairing of irregular meshes using diffusion and curvature flow," SIGGRAPH (1999).

[18] U. Pinkall and K. Polthier, "Computing discrete minimal surfaces and their conjugates," *Experimental Mathematics* **2**, 15–36 (1993).

[19] B. Delaunay, "Sur la sphere vide," *Bulletin de l'Academie des Sciences de l'URSS* **7**, 793–800 (1934).

[20] T. Bothwell et al., "Resolving the gravitational redshift across a millimetre-scale atomic sample," *Nature* **602**, 420–424 (2022).