

The Primacy of Change, Not of Time

Clocks, Dynamics, and the Structure of Physical Change

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Abstract

Our mathematical descriptions of physics have achieved extraordinary success in predicting the observed physical world. Central to these descriptions are dynamical models that describe and predict how physical quantities change, with time introduced as a parameter through which that dynamics is expressed. Yet the predictive success of these models does not by itself determine whether time is a primitive physical entity represented by the readings of clocks. This paper develops and tests a relational reading in which physical change and the non-temporal structure constraining possible changes are primary, while duration is constructed by comparing physical processes. A clock is therefore another changing system, not a detector of an invisible temporal substance.

We test this interpretation across classical mechanics, quantum mechanics, and relativity. In classical mechanics, a Jacobi-type formulation shows concretely how duration can be recovered from a path through configuration space. Norton's dome separates temporal parametrization from determinism, while the Loschmidt objection separates reversible laws from a statistical arrow that also requires a special boundary condition. In quantum theory, unitary evolution, decoherence, physical clocks, and the Wheeler–DeWitt constraint distinguish change, ordering, and stable records. We then turn to relativity, where clock comparison becomes geometrical without requiring a universal present.

These results do not select a unique account of physical reality or predict departures from established physics. They show that a consistent change-first interpretation is available, identify the assumptions it inherits—including clock quality, causal order, and the low-entropy boundary condition—and locate it relative to Barbour, Rovelli, thermal time, and other relational programmes. Worked examples and technical derivations are retained in appendices so that the main argument remains accessible without concealing its mathematical basis.

Keywords: *time · change · reversibility · decoherence · entanglement · relational time · shape dynamics · retrocausality · interaction-free measurement · quantum eraser*

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Author Summary

This paper asks a simple question that is often hidden by successful mathematics: when physics uses the symbol t , must it also posit a thing called time that exists and flows independently of physical change? Its answer is that the established equations admit a coherent alternative. Clocks are changing physical systems; duration is constructed by comparing changes; and order, records, and temporal arrows should not be folded into a single invisible substance.

The paper's central interpretive proposal concerns what happens between record-forming interactions. Fundamental microscopic laws commonly permit a history and its time reverse; they do not, by themselves, select the direction in which the film must be played. We explore taking that symmetry seriously as physical structure rather than treating backward evolution only as a formal calculation. An isolated coherent interval can then be read as one reversible relation between its boundary events, admitting both temporal orientations, rather than as a process pushed moment by moment by an external flow. The paper develops this point through unitary evolution, time-reversal symmetry, path amplitudes, and the standing-wave comparison used later in the quantum discussion. This is a claim about the structure of a coherent history, not about one classical object literally making two journeys through time.

Quantum interference is the sharpest testing ground for this reading. Before a path-distinguishing interaction creates a stable record, alternatives such as the two slit paths belong to one coherent amplitude structure and need not be assigned separate, uniquely directed classical histories. Once a system becomes entangled with many environmental degrees of freedom, that coherence becomes locally inaccessible and records accumulate. Decoherence explains this conversion of coherent alternatives into stable records; the observed macroscopic arrow additionally depends on a special low-entropy boundary condition. Thus reversible dynamics, record formation, and the arrow of time are related, but they are not the same thing.

The argument is developed across subjects usually taught separately. Jacobi's principle reconstructs duration from change in classical mechanics. Unitary dynamics, interference, decoherence, and physical-clock constructions develop the reversible and relational picture in quantum mechanics. Relativity then replaces a universal present with geometrical comparisons of clocks along worldlines. The main text gives the conceptual route; the appendices preserve the full examples and derivations.

No new dynamical law or altered experimental prediction is proposed. The claim is nevertheless substantive: familiar physics permits a unified change-first interpretation in which a coherent microscopic history is a relation among physical configurations, while definite records and a macroscopic temporal direction arise only through interactions, environmental entanglement, and boundary conditions. The paper asks how much explanatory work remains for independently flowing time once those physical structures have been made explicit.

1. Introduction

Physics gives precise answers to questions involving time. It predicts how long a pendulum takes to swing, how rapidly an unstable nucleus decays, and how two clocks separate after following different paths through spacetime. Those successes do not settle a different question: what physical thing, if anything, does the symbol t for time in these equations represent?

Some presentations *reify* time, treating the mathematical parameter t as an independent background container, flow, or fundamental primitive. This move can generate pseudoproblems in theoretical physics, from metaphysical paradoxes (such as simulation arguments that assume an external global clock) to foundational misunderstandings in quantum cosmology, where the absence of t in fundamental equations is misconstrued as a “frozen” universe.

The proposal examined here is direct. A *configuration* specifies physically distinguishable relations among a system’s degrees of freedom. A *change* is a distinguishable relation between configurations. A *record* is a correlation whose pattern is encoded redundantly across multiple degrees of freedom and can be revealed by a specified further interaction. This definition contains no “later”: it characterizes a physical structure within a configuration rather than presupposing the temporal order the structure will help us reconstruct.

Ordering is not eliminated. The paper assumes that configurations along a chosen path, or interactions within a physical history, can be ordered. Its claim is that no additional temporal magnitude or independently flowing substance is required beyond such order and the physical comparisons that assign duration.

The *dynamical structure constraining change* specifies which neighboring configurations and correlations are physically allowed and how they are weighted. At the fundamental level this phrase cannot simply hide an external d/dt ; it must be expressible through constraints, a reparametrization-invariant action, or equivalent relations among configurations. Masses, couplings, conservation laws, and potential landscapes can then appear within that structure without making an independently flowing time primitive. A clock is a subsystem whose ordered correlations provide a useful reference for other changes.

The elementary equation $d = v\Delta t$ illustrates the operational part of this proposal. The distance d belongs entirely to the target system being studied. The interval Δt , however, is not a property of space or an abstract continuum, but an operational measurement imported from a *second* physical system—such as a pendulum, quartz crystal, or atomic transition. The equation $d = v\Delta t$ is thus a parametric re-expression of a direct physical ratio between two systems: $\Delta\text{System}_1 / \Delta\text{System}_2$. The purpose of this paper is to test this relational interpretation against the mathematical formalisms of classical mechanics, quantum mechanics, and relativity.

Five questions are often compressed into the single word “time.” What orders physical changes? How is duration assigned by comparing one changing system with a clock? What makes a dynamical map invertible or invariant under time reversal? What produces the thermodynamic arrow and stable records? And what produces the experienced passage of a moving present? The equations do not give these questions one answer. A parameter can order a trajectory without guaranteeing a unique trajectory; clocks can accumulate unequal durations without detecting a universal flow; and a microscopic law can be reversible even when its macroscopic solutions display a strong arrow. The felt passage of time is a further question about physical observers, memory, and attention. A spacetime metric can compare clock readings without deciding whether time is physically fundamental or whether a present literally advances through the world.

Versions of a relational view reach back to Aristotle, Mach, and Leibniz. The contribution here is to connect that view across subjects that are normally taught separately. The paper does not modify the

dynamical equations. It asks what those equations require, what additional assumptions create an arrow or a record, and where familiar descriptions add an unforced, misleading reification to the mathematics.

The issue also concerns how physics is taught. Fluency with t in differential equations, Hamiltonians, path integrals, and metrics can obscure the fact that the symbol does different physical work in different theories. The aim is to make that work explicit rather than allowing one notation to carry an unstated picture of reality. Appendix F preserves the fuller argument about training: expertise can make a notation cognitively automatic without resolving what, if anything, that notation represents.

Table 1. The argument at a glance. The three columns separate physical roles that are often grouped together under the single word “time.”

Domain	Order or duration	Reversibility	Records and arrow
Classical	Relations along a configuration-space path	A property of the laws, distinct from determinism	Coarse-graining plus a special low-entropy boundary
Quantum	Correlations with a physical clock subsystem	Unitary invertibility plus the relevant symmetry	Entanglement, decoherence, and redundant encoding
Relativistic	Proper-time comparison along worldlines	Local field dynamics and causal structure	Records and boundary conditions, without a global present

Position among relational programmes

This paper develops a change-first reading while drawing on several existing relational approaches. Barbour’s programme shows how histories and duration can be reconstructed from ordered configurations and, in its stronger form, treats the apparent flow of time as non-fundamental [Barbour and Bertotti, 1982, Barbour, 2003]. Rovelli’s relational quantum mechanics instead makes physical values definite relative to other systems; it is principally a thesis about quantum facts, not a complete theory of temporal emergence [Rovelli, 1996]. The present paper borrows from both without identifying them: it asks whether the time variables used across physics can be understood as measures of constrained relations among changes.

Two contrasts mark the limits of that claim. The thermal-time hypothesis shows how a state on an observable algebra can generate a one-parameter flow; it is a technically developed example of temporal structure arising from a state and an algebra, not from an external clock [Connes and Rovelli, 1994]. Causal-set theory, by contrast, places a primitive partial order among events at its foundation [Bombelli et al., 1987, Dowker, 2005]. It is relational in not starting from a spacetime continuum, but it warns against equating “relational” with “timeless”: some relational theories retain temporal order as fundamental. A stronger causal-set proposal treats sequential growth as a candidate physical passage through the birth of spacetime atoms [Dowker, 2014]; the present paper does not assume that physical picture, but it is an important example of passage being formulated as physical structure rather than undefined flow.

Section 2 separates Newtonian temporal structure from determinism and from the statistical arrow. Section 3 examines unitary change, decoherence, two-boundary descriptions, and timeless constraints like the Wheeler–DeWitt equation ($H\Psi = 0$). Section 4 asks whether spacetime geometry makes time fundamental and compares the standard account with Shape Dynamics. Section 5 uses selected experiments as checks on the interpretation; the full walkthroughs are retained in Appendix D. Section 6 states the scope and inherited problems. Appendices preserve the extended case studies, philosophical arguments, and mathematical derivations. The derivations are collected under Appendix L; each ends by separating what follows from the equations from the additional interpretation proposed here.

2. Classical Mechanics: Time Before It Was a Dimension

The kinematics and dynamics used in this act are standard classical mechanics [Kibble and Berkshire, 2004]. The question asked here is not whether those methods work, but what claim about physical reality their temporal notation requires.

2.1. What $d = vt$ Actually Says: Ratios of Change

For motion at constant speed, write

$$d = v\Delta t. \quad (1)$$

Here d is the distance travelled, v is the constant speed, and Δt is the interval assigned to the motion. For directed motion in one dimension, position is denoted by x . The displacement and average velocity are

$$\Delta x = x(t_2) - x(t_1), \quad \bar{v} = \frac{\Delta x}{\Delta t}, \quad \Delta t = t_2 - t_1. \quad (2)$$

The instantaneous velocity is the limit

$$v(t) = \lim_{\Delta t \rightarrow 0} \frac{\Delta x}{\Delta t} = \frac{dx}{dt}. \quad (3)$$

This notation separates distance d , position $x(t)$, displacement Δx , and the differential dx . The distinction is elementary, but it matters when asking what the parameter t represents physically.

In a laboratory, Δt is never measured directly as a raw, isolated entity; it is read from a clock. A clock is simply another physical system. Its state might be the angle of a pendulum, the phase of a quartz oscillator, or the phase accumulated by a caesium transition. This makes a clock different from a sensor in an important way. A thermometer or photodetector responds to a property of another system at its location; a clock does not detect a local field or substance called time. It supplies its own regular physical change, which we use as a reference for comparing other changes. Let q denote such a clock variable. If both the system position x and the clock state q are parametrized by an auxiliary label λ , then

$$\frac{dx}{dq} = \frac{dx/d\lambda}{dq/d\lambda}. \quad (4)$$

The auxiliary label λ cancels completely. What remains is the change of x relative to the change of q . The rate of that change is governed by the systems' dynamics, including their masses, potential landscapes, and internal couplings. These should not all be conflated with mechanical inertia, which has a narrower meaning and will be treated explicitly in Section 4.2. A calibrated scale converts intervals in q into standard units (seconds). This is the full operational content of a clock reading: it is a relational ratio between two physical systems ($\Delta \text{System}_1 / \Delta \text{System}_2$), not a detector sampling an underlying temporal substance.

2.2. Newton's Absolute Time, and What the Equations Actually Require

Newton was explicit that he did not think this relational reading was the whole story. In the *Principia*, he distinguished “absolute, true, and mathematical time,” which “flows equably without relation to anything external,” from the relative, sensible measures of it (clocks) that we actually use. Leibniz famously objected that two universes differing only by an overall shift in absolute time would have identical observable relations, rendering absolute time empirically redundant.

Mach later pressed a parallel objection against Newton's absolute space. Newton's rotating-bucket argument treated rotation as meaningful even without a nearby reference body. Mach asked whether inertial effects should instead be understood through relations among physical bodies, ultimately including the distribution of matter in the universe, rather than motion relative to an invisible spatial background [Mach, 1919]. There are several inequivalent versions of what later became known as Mach's principle, and general relativity is not fully Machian under all of them. The conceptual parallel needed here is narrower: Mach questioned whether motion and inertia require absolute space; this paper asks whether change requires absolute time.

Newtonian mechanics nevertheless requires more than an unordered list of configurations. It assumes a common temporal ordering, durations, and an affine parameter with which velocities and accelerations can be defined. For an inertial-frame transformation,

$$t' = t + b, \quad \mathbf{x}' = R\mathbf{x} + \mathbf{u}t + \mathbf{a}, \quad (5)$$

where R is a spatial rotation, $\mathbf{u}$ a constant boost, and $\mathbf{a}$ and b constant translations. All inertial observers share the same time interval because $dt' = dt$. Newton's equation

$$m \frac{d^2 \mathbf{x}}{dt^2} = \mathbf{F} \quad (6)$$

uses this structure directly.

The relational point must therefore be stated carefully. Newtonian mechanics requires temporal order and an affine parameter to compute rates of acceleration. It does not follow that it requires an independent physical substance that literally "flows equably" behind the scenes. Newton's reification of t was an interpretive addition to his own differential equations. The equations determine how physical configurations are dynamically correlated across parameter values; reifying t into a primitive substance confuses the mathematical bookkeeping index for the physical cause.

2.3. Constructing Duration from Change

The clock comparison above is operational; by itself it does not construct a single consistent duration for a closed mechanical system. Jacobi's principle does. For configuration coordinates q_i , fixed total energy E , potential $V(q)$, and an arbitrary path label λ , define

$$S_J = 2 \int d\lambda \sqrt{(E - V)T_\lambda}, \quad T_\lambda = \frac{1}{2} \sum_i m_i \left(\frac{dq_i}{d\lambda} \right)^2. \quad (7)$$

The action is unchanged by a monotonic relabeling of λ : the path through configuration space matters, not the speed at which an external parameter traces it. Along an extremal path one may define

$$dt_J = \sqrt{\frac{T_\lambda}{E - V}} d\lambda. \quad (8)$$

With this duration, the configuration-space equations become the familiar Newtonian equations. The intuitive picture is a route measured with its own physical terrain: masses provide the configuration-space metric, while the available kinetic energy $E - V$ fixes how changes along the route compare. The parameter t_J is reconstructed from ordered changes; it was not placed beside the system as an independently flowing substance.

This construction requires real assumptions: a fixed-energy conservative system, an ordered path, and suitable regions where $E > V$. It therefore does not prove that every use of time is emergent. It demonstrates the narrower claim needed here: even the affine duration used by Newtonian mechanics can, in an important class of systems, be obtained from a non-temporally parametrized dynamics [Barbour and Bertotti, 1982]. Appendix K gives the variational details.

2.4. The Dome: A Parameter Does Not Cause an Evolution

Norton's dome provides a clean separation between a temporal parameter and determinism [Norton, 2008]. Its equation of motion,

$$\ddot{r} = \sqrt{r}, \quad (9)$$

admits both $r(t) = 0$ and solutions that remain at rest until an arbitrary t_0 and then follow $r(t) = (t - t_0)^4/144$. The failure occurs because $\sqrt{r}$ is not Lipschitz at the apex, so the usual uniqueness theorem does not apply. Nothing about a flowing time selects one history.

The example uses a point particle and a dome whose curvature is singular at the apex; whether it represents a physically realizable failure of classical determinism is therefore disputed. That dispute does not affect its role here: under either interpretation, uniqueness is supplied by the force law and admissibility assumptions, not by the symbol t .

The crucial feature is that the ball can reach the apex with zero velocity in a finite time. In a smooth comparison potential, an upward-moving ball at the critical energy generally approaches an unstable apex only as $t \rightarrow \infty$; there is then no finite stopping event from which an arbitrary waiting period can be attached. Norton's non-Lipschitz force instead permits a trajectory to end at rest at the apex after a finite interval. Time reversal therefore also permits a ball resting there to wait for any duration and then depart. The loss of uniqueness is tied to this finite-time arrival and the force law's lack of smoothness, not to time itself. The geometry, solutions, and idealization issue are worked through in Appendix A.

2.5. Loschmidt Against Boltzmann: Reversibility Is the Default

Boltzmann described macroscopic irreversibility using reversible molecular dynamics [Boltzmann, 1872]. For a macrostate containing Ω compatible microstates, the Boltzmann entropy is

$$S_B = k_B \ln \Omega. \quad (10)$$

Equilibrium macrostates occupy much larger phase-space volumes than organized non-equilibrium states. A system prepared in a low-entropy state will therefore evolve toward higher-entropy macrostates for almost all initial microstates.

Loschmidt's objection highlights the time-reversibility of the underlying laws [Loschmidt, 1876]. If every particle velocity is inverted at instant t^* , the system retraces its trajectory, decreasing S_B . The fundamental equations $m\ddot{\mathbf{x}} = \mathbf{F}$ pick no preferred direction. Boltzmann's kinetic H -theorem breaks this symmetry only by introducing a statistical assumption—molecular chaos (*Stosszahlansatz*):

$$f_2(\mathbf{x}, \mathbf{p}_1, \mathbf{p}_2, t) \simeq f_1(\mathbf{x}, \mathbf{p}_1, t) f_1(\mathbf{x}, \mathbf{p}_2, t). \quad (11)$$

This assumption discards pre-collisional phase correlations, effectively asserting that incoming states are uncorrelated while outgoing states build correlations.

The thermodynamic arrow of time is thus not a fundamental vector embedded in the parameter t . It is an emergent property arising from: 1. Reversible, timeless microscopic dynamics, 2. Extremely special low-entropy cosmological boundary conditions, and 3. A coarse-grained perspective that tracks the accumulation of stable physical *records* while ignoring fine-grained phase correlations.

The parameter t orders the sequence of states symmetrically; the arrow emerges strictly from the directional accumulation of correlations across complex systems. The passage from microscopic rules to stochastic continuum behavior is a broader theme in nonequilibrium statistical mechanics. For example, microscopic transition rules for epitaxial growth can yield effective Langevin equations at larger scales [Vvedensky et al., 1993]. This analogy does not derive the thermodynamic arrow; it illustrates why microscopic and coarse-grained laws must not be treated as the same level of description. Appendix L.4 quantifies the related practical fragility: exact reversal is permitted, but small Hamiltonian errors rapidly reduce the recovered overlap.

3. Quantum Mechanics: The Jersey and Reversible Dynamics

Two images will organize the discussion. They are guides to the mathematics, not substitutes for it.

The jersey. A quantum system that becomes correlated with an environment is like a thread being woven into fabric. Each interaction ties the system to more degrees of freedom. The resulting record becomes hard to undo because reversing it requires control of the whole correlated network. The image represents decoherence and redundant environmental recording.

Reversible dynamics. For a closed system, unitary evolution is invertible; when the Hamiltonian also has the relevant time-reversal symmetry, the reversed history satisfies the same dynamical law. This does not imply that a quantum system has a definite classical trajectory between observations.

3.1. A Thread Not Yet Woven

Quantum mechanics inherits t exactly as classical mechanics used it, an external label with respect to which a state evolves,

$$|\psi(t)\rangle = \hat{U}(t, t_0) |\psi(t_0)\rangle, \quad \hat{U}(t, t_0) = \exp\left[-\frac{i}{\hbar} \hat{H} (t - t_0)\right], \quad (12)$$

and Equation 12 carries no intrinsic thermodynamic arrow. If the Hamiltonian is invariant under the antiunitary time-reversal operator $\hat{T}$, the time-reversed state is also a valid solution. Unitary invertibility and time-reversal symmetry are related but distinct. The first follows from Hermiticity. The second also requires the relevant dynamics to be invariant under $\hat{T}$. Stable measurement records require additional interaction with an environment. Appendix L.1 derives the inverse unitary evolution and separates invertibility from the additional symmetry condition imposed by $\hat{T}$.

Here is where the jersey picture becomes useful. Picture the classical world we experience, tables, detectors, a particle's recorded position, as a piece of fabric perpetually being woven, never actually finished, out of threads continually being locked into place relative to one another. A quantum system that has not yet interacted with anything is a loose thread, not yet part of the jersey, with no settled position relative to the jersey's pattern, because nothing has yet tied it there. It can be described as existing in several possible states

at once, not because it is hiding a single true state from us, but because there is a fact about its own evolution and not yet a fact about its state relative to anything else, no correlating interaction having established one. The moment the needle catches it, that changes.

The “fabric” in this image is not spacetime and is not a medium through which an object moves. It is the network of sufficiently stable, redundantly accessible correlations that constitutes the effectively classical record. A coherent subsystem is comparatively untethered only in the sense that its alternatives have not yet been redundantly encoded in that record network. It still couples to external fields and obeys the applicable dynamics; gravitational coupling, in particular, does not require prior decoherence.

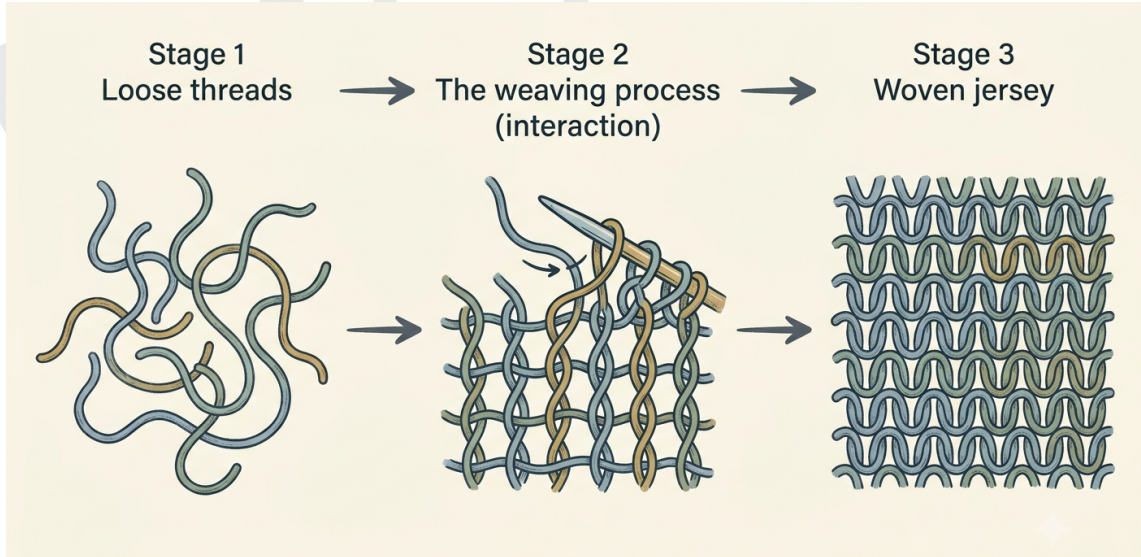


Figure 1. The jersey-weaving picture: loose threads with no fixed relation to one another, the weaving process (interaction), and the finished, interlocked jersey. Section 3.3 gives the mathematics this picture stands for.

3.2. Coherent Possibility Is Not Classical Ignorance

The phrase “several possible states at once” needs a qualification before the jersey picture is made mathematical. Three physically different situations can otherwise be mistaken for one another. A covered coin has an established face that an observer does not know. A coin not yet tossed has ordinary alternative outcomes. A quantum system can instead occupy a coherent superposition,

$$|\psi\rangle = \frac{1}{\sqrt{2}} (|A\rangle + e^{i\phi}|B\rangle). \quad (13)$$

The first case is ignorance about an existing classical fact. The second is an ordinary probability distribution over possible results. The third contains a relative phase ϕ that can alter the probabilities observed after the branches are recombined. It therefore cannot mean only that one classical result is already true but unknown, or that a future result will be chosen from an ordinary list.

The distinction appears directly in the density matrices. A coherent superposition and an incoherent 50–50 mixture have the same diagonal probabilities in the $\{|A\rangle, |B\rangle\}$ basis, but they differ in their off-diagonal

terms:

$$\rho_{\text{coh}} = \frac{1}{2} \begin{pmatrix} 1 & e^{-i\phi} \\ e^{i\phi} & 1 \end{pmatrix}, \quad \rho_{\text{mix}} = \frac{1}{2} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}. \quad (14)$$

The off-diagonal elements allow interference and are experimentally consequential. Classical ignorance has no corresponding phase to recover.

In the relational language of this paper, a superposition is therefore better described as a coherent structure of possible relations than as several contradictory classical properties possessed simultaneously. Nor should those possibilities be called fundamentally “future” events, because that wording would quietly restore the temporal container under question. They are possible relations not yet incorporated into the relevant system’s established record. Amplitudes, including their relative phases, describe how those possible relations combine. Interaction can then correlate one alternative with other systems, and redundant environmental recording can make the alternatives behave locally like the classical mixture on the right of Equation 14.

This language does not solve the measurement problem by declaration. Decoherence explains why interference becomes inaccessible to a subsystem and why stable records form. By itself it does not select one unique outcome for all interpretations of quantum mechanics. The narrower point needed here is that whatever account of outcomes is adopted, quantum coherence is more than uncertainty about an unknown classical fact.

3.3. Weaving, Made Precise: The Reduced Density Matrix

Suppose a particle is in the two-path superposition $|\psi\rangle_S = \frac{1}{\sqrt{2}}(|A\rangle + |B\rangle)$. Let the environment begin in state $|E_0\rangle$. It may include air molecules, a detector, or any degrees of freedom affected differently by the two paths. If the path leaves a distinguishable trace, then

$$|A\rangle|E_0\rangle \longrightarrow |A\rangle|E_A\rangle, \quad |B\rangle|E_0\rangle \longrightarrow |B\rangle|E_B\rangle, \quad (15)$$

this is the stitch. The particle and its environment together become entangled, $|\Psi\rangle = \frac{1}{\sqrt{2}}(|A\rangle|E_A\rangle + |B\rangle|E_B\rangle)$, and the best description of the particle alone, averaging over everything about the environment we are not tracking, is the reduced density matrix

$$\rho_S = \text{Tr}_E[|\Psi\rangle\langle\Psi|] = \frac{1}{2}(|A\rangle\langle A| + |B\rangle\langle B|) + \frac{1}{2}\langle E_B|E_A\rangle |A\rangle\langle B| + \frac{1}{2}\langle E_A|E_B\rangle |B\rangle\langle A|. \quad (16)$$

The first term is the woven part, a plain mixture with no interference left. The remaining terms survive only in proportion to the overlap $\langle E_A|E_B\rangle$ between the two environment states: perfect recording, $\langle E_A|E_B\rangle = 0$, gives full weaving. With no recording, $\langle E_A|E_B\rangle = 1$, leaves the thread exactly as uncaught as it started. Appendix L.2 works through the trace operation behind Equation 16 in full. Section 5 gives the main experimental consequence—coherent alternatives and recorded alternatives behave differently—while Appendix D gives the complete double-slit walkthrough.

The joint state $|\Psi\rangle$ of particle and environment together remains perfectly pure and reversible throughout, still governed by Equation 12. What changed is only ρ_S , the particle described on its own, and only because an environment exists to trace out.

3.4. Why a Stitch Stays a Stitch

A real environment does not record a result only once. It records it in many nearly independent fragments. Each fragment may reveal which alternative occurred. Zurek calls the robust, classical-looking states pointer

states and the selection process einselection [Zurek, 2003]. Quantum Darwinism describes the redundant copying of information into the environment [Zurek, 2009]. Undoing such a record would require finding and reversing all relevant copies, not merely controlling the original system. A fossil or a memory is a macroscopic example of an environment carrying a persistent record of an earlier interaction. The resulting asymmetry is epistemic as well as thermodynamic. We possess memories, photographs, fossils, and scattered radiation correlated with one orientation of the history, but not an otherwise comparable archive of the opposite orientation. The past therefore appears fixed and the future open not merely because of a convention of speech: observers themselves are physical systems whose memories are written within the same entropy-increasing network of records. This does not by itself explain conscious temporal passage, but it identifies the physical asymmetry on which that experience depends. Wherever there is an observed arrow of time, there is a directional pattern of record formation like this behind it. Appendix L.3 marks an important boundary of the analogy: decoherent phase averaging can suppress a collective contribution, but it is not classical oscillator synchronization.

3.5. Why the Rule Does Not Forbid Unweaving

It is worth being precise that nothing above says undoing a stitch is against the laws of physics, only that it is unmanageably hard in practice. Define the overlap between forward evolution under the true Hamiltonian $\hat{H}$ and an attempted reversal under some other Hamiltonian $\hat{H}'$,

$$M(t) = \left| \langle \psi_0 | e^{i\hat{H}'t/\hbar} e^{-i\hat{H}t/\hbar} | \psi_0 \rangle \right|^2. \quad (17)$$

At $\hat{H}' = \hat{H}$, $M(t) = 1$ for every t : an isolated system can, in principle, always be returned exactly to where it started, simply by running its own Hamiltonian backward, which is Equation 12 with $t \rightarrow -t$. Real irreversibility comes not from a failure of this identity but from the practical impossibility of achieving $\hat{H}' = \hat{H}$ exactly once a system has become entangled with an environment of the size discussed in Section 3.4. This is the precise, quantum answer to the question Loschmidt asked in Section 2.5, a century and a half later and one physical theory further along, with the same structure intact: reversibility is the default, an arrow requires an environment. Appendix L.4 derives the short-time sensitivity to a reversal error and shows mathematically why practical unweaving becomes fragile while exact unitarity remains intact.

3.6. The Reversible Interval, Stated Precisely

Consider a closed system divided into two parts. The bulk B contains many interacting degrees of freedom and stable records. A subsystem Q is prepared at the event labelled t_0 and does not interact with B again until the event labelled t_1 .

The clock used to assign t_0 and t_1 belongs to B . Synchronizing any clock with B requires a physical correlation, such as exchanging a signal or comparing records. During the isolated interval, no such correlation is created between Q and the clock in B . The parameter t in Equation 12 therefore describes Q relative to that external clock. It is not an observable carried privately by Q .

This does not forbid internal relational change within Q . If Q contains two distinguishable subsystems, one may serve as a clock for the other in the Page–Wootters sense developed in Section 3.10. What is absent is a clock within Q that is already synchronized with B without an interaction. The distinction is the same one expressed by Equation 4: change can be defined relative to another change, but the relation must be physically specified.

In that composite case, an ordered succession of correlations inside Q may constitute a physically real internal relational history even though it does not define a thermodynamic arrow relative to B . If Q is elementary within the model and contains no distinguishable clock subsystem, standard quantum mechanics supplies its state, amplitudes, and the external parameter in Equation 12, but it does not thereby supply a private clock observable. Calling the coherent interval “timeless” would therefore be too quick; calling every unrecorded parameter value an internally measured moment would be too quick in the opposite direction.

The state of Q evolves unitarily between the two boundary events. This is real dynamics. The narrower claim is that the isolated evolution does not by itself create a thermodynamic arrow or a redundant record in B . Absence of such an arrow is not absence of change.

Central claim. B exhibits an effective arrow because its interactions create records and because it occupies a low-entropy boundary condition of the kind discussed in Section 2.5. The isolated evolution of Q creates no corresponding record in B between t_0 and t_1 . Its dynamics remain reversible in the sense of Equation 17. At t_1 , interaction correlates Q with B and makes the result part of the recorded macroscopic history.

Reversibility here means that the dynamical map between t_0 and t_1 can be inverted and, when the relevant time-reversal symmetry holds, that the appropriately reversed history obeys the same law. It does not imply a repeated trip between the two events, and it does not establish whether Q has a definite intermediate value of a chosen observable. Section D.4 treats that separate question experimentally. The interpretive commitment made here is nevertheless stronger than saying that the interval is only a bookkeeping device: the coherent relation and its phase structure are physical because they change observable interference at the next interaction. A still stronger claim in which a system literally repeats forward and backward traversals would require an additional account of what parameter counts those repetitions and what dynamical rule reverses their direction. Unitary invertibility alone permits the inverse history; it does not make the system alternate between the history and its inverse.

3.7. One Coherent Process, or Many Worlds?

Everett’s relative-state formulation offers a natural comparison because it also retains unitary quantum dynamics and denies that the formalism requires a fundamental collapse at measurement [Everett, 1957]. In the many-worlds reading commonly associated with that formulation, entanglement and decoherence produce effectively autonomous branches, each containing a record correlated with a different outcome. The image of a universe literally splitting at an observer’s conscious choice should not be confused with Everett’s mathematical claim: the relevant branching structure is normally understood as emerging from physical interaction and environmental decoherence, not from consciousness selecting a result.

The reading developed here makes a different claim about physical reality. Before a record distinguishes alternatives, their amplitudes and relative phases form one physically real coherent process. There is no need to identify each term in an arbitrary expansion of the state with a separately persisting macroscopic universe. The process may be described as temporally unoriented in the restricted sense established above: its dynamical inverse is lawful and it carries no thermodynamic arrow of its own. The record-forming boundary interaction embeds the result in the directed history of B . This is a claim that the coherent relation is real, not that a classical particle secretly occupies one path or that it repeatedly shuttles between forward and backward histories.

This contrast does not refute Everett. If two interpretations retain the same unitary state and make the same experimental predictions, a simpler physical picture and explanatory coherence can favor one without experimentally excluding the other. The present proposal challenges the inference from coherent alternatives to multiple persisting worlds: one coherent relation between record-forming events can carry the interference structure instead. An empirical rejection of Everett would require additional dynamics or a prediction on which the accounts differ.

Both readings also face a basis question. A state vector can be expanded in infinitely many bases, while a laboratory records definite alternatives such as two detector positions or spin along a chosen axis. The experimenter's setting physically changes the interaction Hamiltonian; it is not merely a mental selection. Decoherence then favors robust pointer states determined by the system–apparatus–environment coupling [Zurek, 2003]. This explains why some alternatives become stable and redundantly accessible, but the resulting branch or record structure is approximate and dynamically selected, not a unique decomposition supplied by the bare state vector. The present interpretation inherits this issue: it must identify its physically relevant relations through actual interactions rather than through an arbitrary choice of coordinates in Hilbert space.

Histories-based formulations provide a neighboring one-world route without being identical to the proposal here. They take quantum histories and their interference structure as primary, with ordinary probabilities becoming available for suitably decoherent coarse-grainings [Dowker and Halliwell, 1992]. This reinforces the limited point that a sum over coherent alternatives need not be read as a literal inventory of separately persisting universes.

Finally, this paper does not solve the outcome problem by declaration. It does not derive a unique result from decoherence, add a stochastic collapse law, or choose among hidden-variable, event-based, two-boundary, and relational accounts of outcome definiteness. Merely calling a collapse stochastic would rename rather than explain the selection unless a physical law and its probabilities were supplied. The narrower claim is designed to remain compatible with more than one such account: whatever establishes a definite outcome, coherent alternatives before a distinguishing record need not be reified as separate universes, and record formation should not be conflated with an independently flowing time.

3.8. Wigner's Friend: Whose "Now"?

Wigner's friend is a thought experiment about applying quantum mechanics to an observer and measuring apparatus rather than only to a microscopic particle. A friend inside an isolated laboratory measures a system and records one outcome. Wigner, remaining outside, may nevertheless apply unitary quantum mechanics to the complete laboratory and describe the friend, apparatus, and system as one entangled state [Wigner, 1961]. The familiar puzzle is how the friend's definite internal record relates to Wigner's superposed external description. Here the setup will be used for a narrower question: what establishes which event in the friend's history corresponds to Wigner's "now"?

Place the friend, detector, and measured system inside the isolated laboratory. Internally, the measurement interaction produces correlations of the form

$$|\Psi\rangle = \alpha|A\rangle|\text{friend records A}\rangle + \beta|B\rangle|\text{friend records B}\rangle. \quad (18)$$

The friend can possess a record, compare it with an internal clock, and order laboratory events as $F_1 \rightarrow F_2 \rightarrow F_3$. Wigner also changes and can order his own records as $W_1 \rightarrow W_2 \rightarrow W_3$. Isolation does not freeze the laboratory. Internal change does not require an external clock.

The more delicate question is what physical content belongs to the request, “What state is the entire laboratory in right now?” A mathematical model may assign the composite system a state at a chosen coordinate parameter, and nothing here forbids that useful description. The phrase “right now,” however, can suggest a stronger, observer-independent correspondence,

$$W_i \longleftrightarrow F_j, \quad (19)$$

identifying one event in Wigner’s record with one event in the friend’s record. If the systems are isolated, no signal exchange, clock comparison, or common record has established which correspondence is physically instantiated. Writing both histories as $W(t)$ and $F(t)$ supplies a common parameter, but the parameter alone is not a synchronization interaction.

The claim is therefore not that Wigner is merely ignorant of a globally settled classical fact, nor that it is mathematically impossible to choose a foliation and describe the laboratory on it. It is that such a choice does not by itself create a privileged physical relation between Wigner’s present record and the friend’s. When Wigner later interacts with the laboratory, a new correlation is established. Their records can then be compared, and the phrase “when the friend’s event occurred relative to Wigner” acquires operational content.

Everett’s relative-state formulation, compared directly in Section 3.7, supplies the nearest standard parallel: the friend has a definite record relative to the laboratory branch, while Wigner retains a state for the isolated composite system. The additional emphasis here is not a rival collapse rule. It is that a correspondence between their records becomes a physical relation only when an interaction makes that comparison available.

This separates two questions that standard phrasing often combines: internally, what correlations and records exist among systems in the laboratory; externally, what correlations have been established between Wigner and that laboratory? The first may be well defined while the second is not yet physically fixed. Time is not a container that supplies the missing comparison. The physical comparison is what gives the temporal statement its content. Section 4.6 will find the relativistic analogue: a permissible global assignment of simultaneity need not be a privileged relation instantiated by nature.

3.9. Paths, Interference, and the Principle of Least Action

Feynman’s path integral makes the relation between interference and classical motion explicit. The amplitude to go from event A to event B is a sum over paths, not a single trajectory. Each path is weighted by a phase determined by its classical action S [Rivers, 1987]:

$$\langle B|A \rangle = \int \mathcal{D}[x(t)] e^{iS[x]/\hbar}. \quad (20)$$

Far from a stationary path, small changes in the path produce rapidly changing phases. The contributions then largely cancel. Near a path that satisfies $\delta S = 0$, neighboring phases vary slowly and reinforce one another. The classical trajectory is recovered by this stationary-phase condition. Appendix L.5 derives the expansion around a stationary path; its conceptual point is that a stable classical history can emerge through phase cancellation without time acting as a selecting force.

A standing wave provides a simpler physical comparison. Send a pulse along a rope fixed at both ends and allow it to reflect repeatedly. Forward and backward travelling waves interfere. After many reflections, fixed nodes and oscillating antinodes form a stable pattern. The pattern is stationary, but its components

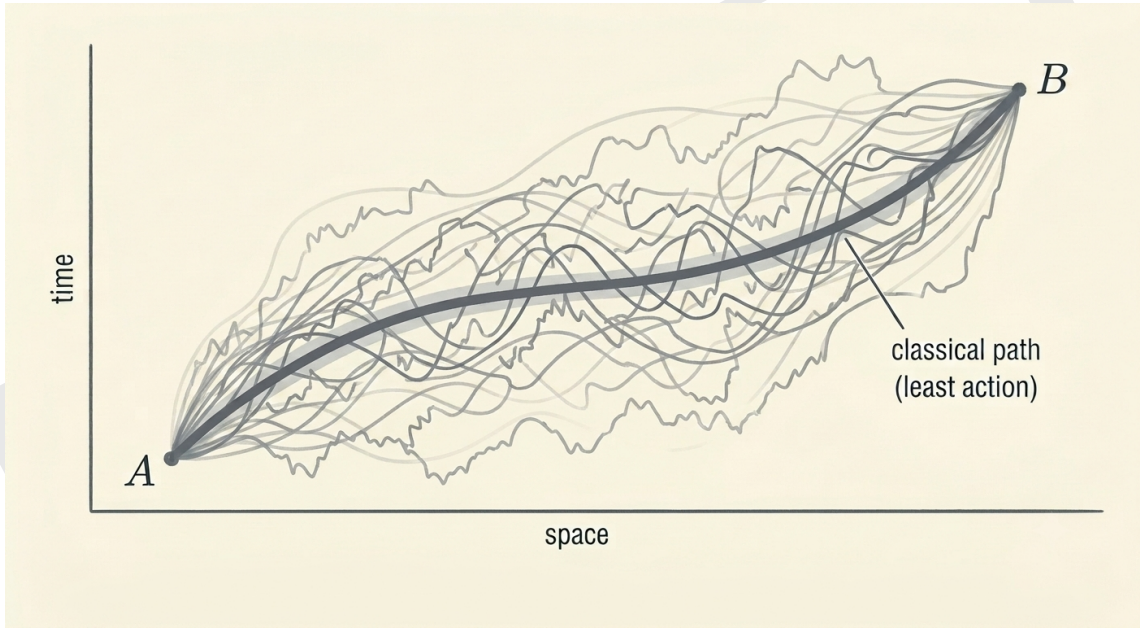


Figure 2. The path integral as a sum over histories connecting events A and B : individual non-classical paths (light grey) wander repeatedly to both sides of the classical path. Their rapidly varying phases largely cancel, while paths near the classical, stationary-action trajectory (dark) reinforce one another. “Least action,” used inside the schematic, is the familiar shorthand. Stationarity, $\delta S = 0$, is the precise condition.

remain in motion. Treat the two fixed ends as the events A and B in Equation 20, and the iterative buildup of the standing wave is a physical, step-by-step picture of how a sum over forward and backward contributions settles into a single stationary interference pattern, the same settling that Equation 20’s stationary-phase condition describes abstractly. The comparison has a limit. A path integral sums infinitely many paths, not only two travelling waves. It nevertheless shows how motion can produce a stable interference pattern. This is not another version of the jersey. The closed rope loses no information to an environment. Its settled pattern comes from coherent interference, not from irreversible recording.

3.10. The Universe Has No Clock of Its Own Either

A constraint is easiest to introduce with a familiar system. A pendulum of length ℓ is usually described by its angle. It can instead be written using both Cartesian coordinates and a term that enforces the fixed length:

$$L = \frac{1}{2}m(\dot{x}^2 + \dot{y}^2) - \lambda(x^2 + y^2 - \ell^2), \quad (21)$$

The Lagrange multiplier λ enforces $x^2 + y^2 = \ell^2$. It is not an additional pendulum coordinate. After the constraint is imposed, one physical degree of freedom remains, which may be taken to be the swing angle.

Canonical quantization of general relativity produces a constraint rather than an evolution equation, the Wheeler–DeWitt equation,

$$\hat{H}|\Psi\rangle = 0, \quad (22)$$

where $|\Psi\rangle$ is the state of the entire universe [DeWitt, 1967, Isham, 1993]. $\hat{H}$ is a Hamiltonian constraint rather than an ordinary Hamiltonian generating evolution in an external time. This produces the “problem of time.” The equation contains no external parameter with respect to which the universal state evolves. It

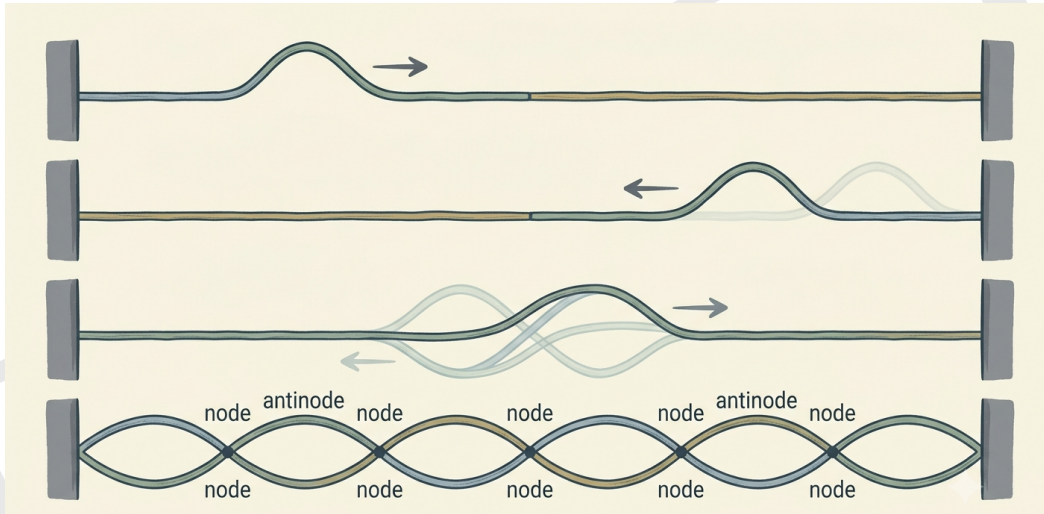


Figure 3. Building a standing wave by hand: a single pulse travels forward (top), reflects and returns (second), interferes with the next outgoing pulse (third), and after enough reflections settles into a stable pattern of nodes and antinodes (bottom), built entirely from motion in both directions.

does not follow that nothing changes. Instead, change must be recovered from relations among internal degrees of freedom. Page and Wootters showed one way to do this. Split the universe into a clock subsystem C and everything else, R , and ask what R looks like conditional on a given reading of the clock,

$$|\psi_R(t)\rangle \propto \langle t|_C |\Psi\rangle. \quad (23)$$

For an ideal or sufficiently accurate clock, and under appropriate assumptions about the clock Hamiltonian and clock–system coupling, this conditional state can obey an effective Schrödinger equation in t , even though $|\Psi\rangle$ is globally stationary [Page and Wootters, 1983, Kuchař, 1992, Moreva et al., 2014]. Generic clocks do not guarantee unitary conditional evolution; this limitation is part of the problem the construction addresses, not a technical footnote. Time, on this construction, is what results when one part of a timeless whole describes itself relative to another part acting as a clock, exactly Q acquiring an arrow only relative to its interaction with B , run at the scale of the whole universe. Rovelli’s relational quantum mechanics makes the identical move for properties rather than time: a system does not possess a definite value for any physical quantity by itself, only relative to another system it has interacted with [Rovelli, 1996]. The same distinction between internal change and an externally assigned clock can therefore be posed at the largest scale physics currently knows how to describe.

3.11. Worldlines That Run Backward: Feynman–Stückelberg

A worldline is nothing more exotic than a particle’s path plotted on a diagram with space along one axis and time along the other, traced out as a curve $x^\mu(\tau)$ parametrized by τ , exactly the kind of diagram already used in Section 3.9. Feynman’s own path-integral treatment of quantum electrodynamics found that the mathematics admits solutions that look, formally, like a particle moving backward in time, tracing $x^\mu(\tau)$ with τ decreasing, and rather than discard them, he reinterpreted them: a negative-energy segment oriented backward in coordinate time can be redescribed as a positive-energy antiparticle—a positron for the electron—oriented forward. At the level of the charged worldline coupling, the relevant redescription combines worldline reversal with charge conjugation; the time-reversal operator $\hat{T}$ alone does not turn an

electron into a positron [Feynman, 1949]. In a loop diagram, a single line can run forward, turn around, run backward, and turn forward again, contributing to one physical process with no preferred direction anywhere along it. This is standard, textbook quantum electrodynamics, and it places genuinely two-directional motion exactly where Q , in Section 3.6, sits before it interacts with B .

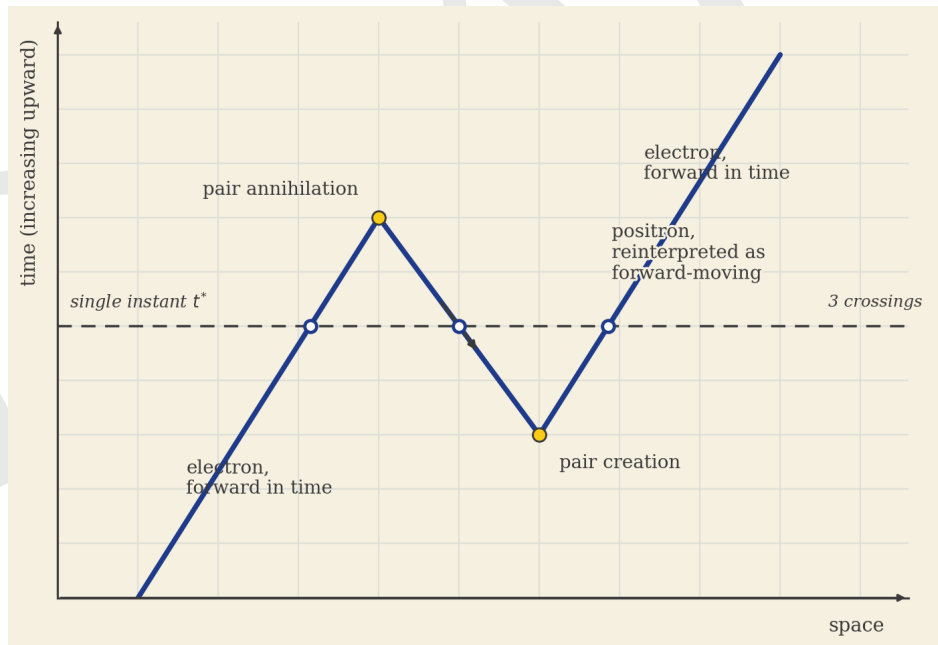


Figure 4. The Feynman–Stückelberg zigzag. A single oriented worldline runs forward in coordinate time, reverses direction between pair annihilation and pair creation, and then runs forward again. The backward-oriented middle segment is reinterpreted as a positron propagating forward. A single time slice t^* therefore intersects the same global worldline three times, producing three apparent particles at that instant.

Historical case: one electron

Wheeler once suggested that all electrons might be a single worldline weaving forward and backward through time. The strong proposal fails empirically, most plainly because it predicts a symmetry between electrons and positrons that the observed universe does not possess. Its lasting value as an explanatory example is narrower: quantum field theory identifies electrons as indistinguishable excitations of one field, without assigning each a private classical identity. The history and the precise worldline argument are retained in Appendix B.

3.12. Time-Symmetric and Two-Boundary Descriptions

Time-symmetric equations allow descriptions conditioned at both ends of a process. Wheeler–Feynman absorber theory combines retarded and advanced electromagnetic solutions subject to a global absorber condition. Cramer’s transactional interpretation applies related imagery to quantum amplitudes, while the Aharonov–Bergmann–Lebowitz rule conditions intermediate outcomes on both preparation and postselection. These are different constructions; none licenses signalling into the past, and none by itself derives the Born rule or the thermodynamic arrow.

Their common relevance is modest but useful. A completed physical relation can depend on boundary data at both ends without requiring a substance called time to push the process from one end to the other. The fuller historical and mathematical discussion, including the limitations of the standing-wave and “handshake” analogies, appears in Appendix C. The ABL and weak-value calculation in Appendix L.8 shows exactly where conditioning on both boundaries changes an intermediate probability without enabling a message to the past.

3.13. Two Recent Experiments That Do This for Real

The common experimental question is whether a subsystem can acquire a directional thermodynamic description while the larger quantum system remains reversible. One approach coherently controls alternative orders of operations. Another tracks entropy exchanged between a visible subsystem and degrees of freedom that are deliberately left unobserved. These are not tests of whether time literally flows backward. They are controlled tests of which correlations make an arrow or an internal clock meaningful for one part of a larger system.

Two results published within the last several years turn Sections 3.11–C.1 into measured physics rather than reinterpretation of old equations. Rubino, Manzano and Brukner built a photonic setup in which a control qubit places a thermodynamic process Λ and its exact time-reverse $\tilde{\Lambda}$ into a coherent superposition of orderings, a quantum switch [Chiribella et al., 2013], and the thermodynamic arrow of time is genuinely undefined for the target system until a measurement of entropy production forces the control qubit, and with it the arrow, onto one branch or the other [Rubino et al., 2021], realizing a superposition of opposite thermodynamic arrows in the laboratory. A quantum switch is the quantum version of choosing whether operation A precedes B or B precedes A : a control qubit coherently controls the two orders instead of selecting one by an ordinary random choice.

Barontini realized a cold-atom Bose–Einstein condensate split into an observed “bright” sector and an unobserved “dark” sector, and defined an entropic clock from the accumulated entropy exchange between the two [Barontini, 2026]. The source’s control parameter and orientation convention are specific to that experimental construction, so the full formula is not promoted here as a universal definition of time. At very low temperature, the atoms in a Bose–Einstein condensate share a coherent collective quantum state, making the many-atom system controllable as a single quantum object. Here that controllability allows entropy exchange between the two sectors to be isolated and measured. The combined system is closed and measured to be time-symmetric, exactly as Section 3.6 predicts for Q . The bright sector alone acquires a real, directional τ only because it exchanges entropy with the dark sector it does not observe.

A philosophical boundary

Any physical computation or proof-inscription requires distinguishable state changes, but that fact does not decide between relationalism and an eternalist picture of spacetime. The stronger philosophical argument concerning mathematical construction is therefore separated from the physics argument and retained as Appendix G.

4. Relativity: Does Spacetime Put Time Back In?

4.1. The Tension Stated Plainly

Relativity gives the strongest objection to the interpretation developed so far. Special and general relativity do not use a universal external time. They combine temporal and spatial intervals in the spacetime metric,

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu, \quad (24)$$

Proper time is the interval measured along a timelike worldline. Different worldlines can accumulate different proper times between specified events. This effect is measured with high precision. The question is therefore not whether relativistic clock effects are real. It is whether the metric must be interpreted as a fundamental substance, or whether it may encode relations among physical rods, clocks, and fields. Shape Dynamics provides a useful comparison because it reorganizes part of the same gravitational physics using spatial conformal geometry rather than four-dimensional refoliation symmetry.

4.2. Uniform Motion, Acceleration, and Accumulated Change

Imagine a single ball in an otherwise empty universe. Its constant velocity has no operational meaning until another system supplies a frame relative to which that velocity can be measured. Add a second ball and their relative velocity becomes meaningful, but neither ball thereby acquires an absolute velocity through an unseen background. Given a spacetime geometry, proper acceleration is different: an accelerometer carried by either ball can register a nonzero reading locally, without consulting distant objects. Uniform velocity is relational, whereas proper acceleration measures departure from geodesic motion. In general relativity, however, the metric and connection that define geodesics are themselves dynamical and affected by the wider matter distribution. Local measurability does not turn acceleration into motion relative to an absolute background.

Special relativity preserves this distinction. For a body of invariant mass m moving at speed v relative to a specified inertial frame,

$$E = \gamma mc^2, \quad p = \gamma mv, \quad d\tau = \frac{dt}{\gamma}, \quad \gamma = \frac{1}{\sqrt{1 - v^2/c^2}}. \quad (25)$$

The rest mass does not increase. Energy, momentum, and the comparison between proper time τ and the frame's coordinate time t depend on the relative velocity. As v approaches c , additional work produces large changes in energy and momentum but progressively smaller changes in coordinate velocity in that frame.

The same Lorentz factor appears in the momentum and proper-time relations, but one should not be presented as causing the other. A freely moving unstable particle exhibits time dilation without a force resisting its decay, and in its own inertial frame its rest mass and local physics remain ordinary. Nor does the moving body possess an intrinsic condition of being “slow”: each inertial observer may describe the other's clock as slow until their histories are related through specified signal exchanges or common comparison events.

The change-first reading reverses only the explanatory emphasis. Instead of starting with a substance called time that slows and thereby causes physical processes to complete fewer cycles, it starts with physical processes along different worldlines and compares their accumulated cycles between specified events. Proper time is the invariant geometrical measure that records this difference. Relativistic momentum and time dilation are therefore distinct consequences of the same Lorentz geometry, not a causal chain from increased inertia to slowed internal change.

4.3. Static Clocks, Free Fall, and Relational Comparison

An atomic clock is a physical process. So is a mechanical or biological clock. Each clock records the proper time along its own worldline. Locally, a freely falling observer sees ordinary nongravitational physics, as required by the equivalence principle. Gravitational time dilation appears when the proper times accumulated along different worldlines are compared. It is not a local sensation that one clock is running slowly.

For a clock held at fixed Schwarzschild radius, the comparison is related to the acceleration required to prevent free fall. The proper acceleration is

$$a = \frac{GM}{r^2 \sqrt{1 - r_s/r}}, \quad r_s = \frac{2GM}{c^2}, \quad (26)$$

and the redshift factor of the static clock is $\sqrt{1 - r_s/r}$ [Hartle, 2003]. Hence

$$a \sqrt{1 - r_s/r} = \frac{GM}{r^2}. \quad (27)$$

Both quantities follow from the same Schwarzschild metric. This identity supports a useful intuition: a static clock follows an accelerated rather than a geodesic worldline, and the required resistance to free fall grows as the redshift becomes stronger. It is not a derivation of time dilation from “resistance to change.” Freely falling clocks on different trajectories can also accumulate different proper times without any local proper acceleration. The resistance language is therefore an interpretation of the static case, not a replacement for the metric account. Appendix L.7 works through the derivation of Equation 26 in full.

4.4. Shape Dynamics: A Different Formalism, Not a Different Reading

General relativity ordinarily represents gravity as the geometry of a four-dimensional spacetime. Shape Dynamics asks whether part of the same classical gravitational physics can instead be organized around a sequence of three-dimensional spatial shapes, with overall local scale treated as gauge information. It exchanges general relativity’s freedom to describe the same spacetime using different slicings for a different freedom to rescale spatial geometry locally. Where the equivalence has been established, the observable classical histories agree even though the fundamental-looking variables and symmetries differ. That is why Shape Dynamics matters here: it does not prove spacetime unreal, but it shows that successful predictions need not select four-dimensional spacetime as the unique starting point.

The ADM formulation writes general relativity in terms of a spatial metric h_{ij} and its conjugate momentum on a sequence of spatial hypersurfaces [Arnowitt et al., 1962]. The lapse and shift are Lagrange multipliers that enforce the Hamiltonian and momentum constraints. The constraints generate gauge transformations, including changes of foliation. Physical gravitational degrees of freedom remain after the constraints are imposed, but no unique external time parameter is selected. Canonical quantization promotes the Hamiltonian constraint to the Wheeler–DeWitt equation discussed in Section 3.10 and Appendix L.6.

The Jacobi–Barbour–Bertotti construction in Section 2.3 provides the mechanical precursor: absolute position and orientation are removed, and duration is recovered from change along a configuration-space path [Barbour and Bertotti, 1982, Barbour, 2003].

Barbour, Foster and Ó Murchadha then connected relational spatial geometry to gravity [Barbour et al., 2002]. Shape Dynamics develops this program by trading general relativity’s refoliation symmetry for local spatial conformal symmetry [Gryb and Mercati, 2015]. In the settings where the link is established, the two formulations describe the same classical solutions through different gauge structures. Shape Dynamics still

has an ordering of configurations and a global evolution parameter. Its importance here is not that every notion of time disappears. It is that four-dimensional spacetime is not the only possible choice of fundamental variables.

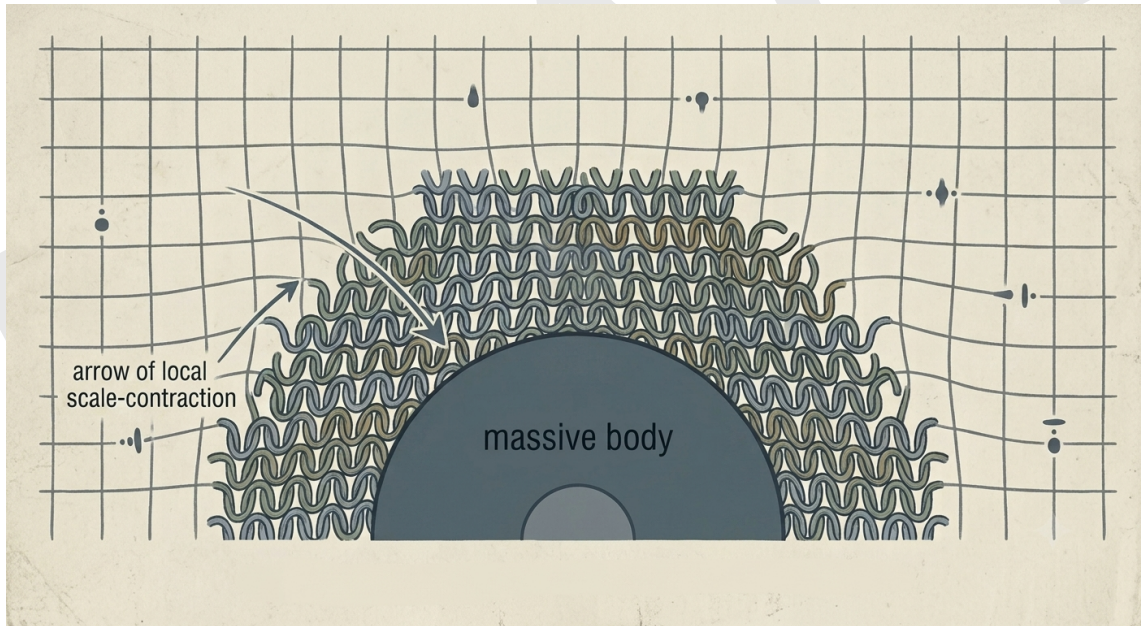


Figure 5. A relational illustration motivated by Shape Dynamics. The changing mesh represents a description in terms of spatial conformal geometry rather than a literal material weave. It is an analogy, not a derivation of gravitational redshift or a claim that interaction density causes clocks to slow.

The equivalence between Shape Dynamics and general relativity is established only in specified classes of solutions. It is not a theorem that every spacetime, quantum regime, or observational setting is covered. Within its domain, however, the reformulation has a clear conceptual consequence. Some gravitational predictions do not require four-dimensional spacetime to be the starting picture. That shows that successful predictions need not fix a single account of physical reality; it does not prove that time is unreal.

4.5. Spacetime as One Parametrization Among Others

Relativity is not wrong to combine space and time. The metric is the most successful description of gravitational clock and ruler comparisons we have. Shape Dynamics shows that a different set of fundamental variables can reproduce part of the same physical content. The comparison is deeper than changing from Cartesian to polar coordinates because the gauge symmetries differ. It is also narrower than proving that spacetime is only bookkeeping. The result is an open choice about physical interpretation, constrained by a precise mathematical equivalence in its known domain.

4.6. Local “Now” and the Andromeda Example

Relativity permits two passing observers to assign different distant events in Andromeda to their respective simultaneity surfaces. Over 2.5 million light-years, even a walking-speed difference shifts the assignment by days. The calculation is not disputed. The relational question is what physical status to give the distant portions of coordinate slices when neither observer is causally connected to those events.

This paper is neutral between an eternalist spacetime history and stronger metaphysical accounts of becoming. Its narrower claim is that a physically privileged “now” is local and established through causal relations, not a unique global hypersurface supplied by nature. That is close to Stein’s reply to Rietdijk and Putnam [Stein, 1968, Rietdijk, 1966, Putnam, 1967]; it does not show that distant events are unreal. The numerical example and its connection to Wigner’s friend are retained in Appendix H.

4.7. A Second Worked Example: Bell’s Theorem and Entangled Correlations

Bell’s theorem is the sharpest version of a puzzle Einstein, Podolsky and Rosen raised in 1935 and Bell made precise three decades later [Bell, 1964]. Einstein, Podolsky and Rosen asked whether quantum mechanics might be incomplete, with additional facts determining results that the wavefunction supplies only probabilistically. Such additional facts are called *hidden variables*. Bell showed that no theory in which those variables obey a particular local-causal structure can reproduce every quantum correlation. The resulting inequalities let an experiment distinguish that entire class of explanations from quantum mechanics without needing to know what the proposed hidden variables are.

In the standard setup, Alice and Bob receive two parts of an entangled pair, choose measurement settings a and b , and record binary outcomes $A, B \in \{-1, +1\}$. A locally causal hidden-variable model factorizes the conditional probability as

$$P(A, B|a, b, \lambda) = P(A|a, \lambda)P(B|b, \lambda), \quad (28)$$

with the hidden variables λ statistically independent of the later setting choices. This assumption leads to the CHSH bound

$$|S| = |E(a, b) + E(a, b') + E(a', b) - E(a', b')| \leq 2. \quad (29)$$

Quantum mechanics predicts values as large as $2\sqrt{2}$, and loophole-free experiments observe violations of the classical bound [Hensen et al., 2015]. The violations rule out the stated local-causal factorization, not every possible realist interpretation. They also do not permit controllable faster-than-light communication. Appendix L.9 derives both the classical bound and the quantum value so the conceptual point rests on the precise inequality rather than on the word “nonlocal.”

The relational interpretation does not alter Bell’s theorem, the Born rule, or the Tsirelson bound $2\sqrt{2}$. It also does not create a faster-than-light signalling mechanism. The local outcome probabilities remain independent of the distant setting in the way required by no-signalling.

What changes is the intuitive starting point. The usual puzzle begins with two independently existing objects separated in a fundamental space and then asks how a correlation crosses the distance between them. An entangled state is instead one joint state prepared at a common source. It is not a pair of independent local states plus a message sent later. If spacetime geometry is emergent from a deeper relational structure, spatial separation need not be the primitive fact from which the correlation must be built. Work relating entanglement to emergent geometry explores a mathematically developed version of this reversed explanatory direction [Van Raamsdonk, 2010].

This point is interpretive but important. Equation 28 defines locality within a causal structure. Declaring spacetime emergent does not evade that equation. A complete relational theory would still need to recover Lorentz invariance, no-signalling, and the observed value of the correlations. The framework offered here raises a question about physical reality, not that derivation: should localized events be taken as primitive and their correlations explained afterward, or can stable events emerge from a more fundamental network of correlations? Bell experiments make this question unusually sharp because the correlations are measured while signalling remains forbidden.

The same reversal of explanatory priority becomes especially vivid near a black hole. Prepare two systems A and B in an entangled state outside a Schwarzschild black hole, retain A far away, and allow B to fall across the event horizon. Locally, nothing singular occurs when B crosses the horizon, and a coherent infalling system continues to obey the applicable curved-spacetime dynamics. In the global description the state remains a joint state, even though the classical causal geometry prevents any later signal from the interior returning to the exterior.

Entanglement does not provide a communication channel through the horizon, and the infalling system has not become detached from spacetime. The example nevertheless sharpens the relational question. If the correlation was established before the systems separated, it may be backwards to picture it as something that must subsequently travel through the intervening geometry. The question “Where is the infalling system now?” contains both assumptions examined in this paper: “where” suggests a fundamental spatial container, while “now” suggests a fundamental global temporal slice. A classical spacetime model can assign coordinates to the event; the interpretive question is whether those assignments describe the basic physical structure or deeper relations.

The conjectural EPR=ER programme explores a considerably stronger version of this reversed explanatory direction, asking whether entanglement and spacetime connectivity can be understood as aspects of related underlying structure [Maldacena and Susskind, 2013]. Its original setting involved entangled black holes and Einstein–Rosen bridges. It does not establish that every entangled particle pair is joined by an ordinary traversable wormhole, and it is cited here as a neighboring research programme rather than evidence for this paper’s interpretation.

5. Experimental Checks on the Interpretation

No experiment below distinguishes the proposed interpretation from standard physics. Each instead tests a boundary the interpretation must respect: coherence versus recorded alternatives, absence of interaction versus absence of a classical trajectory, spatial versus temporal separation, and correlation versus signalling.

Table 2. Five experiments and the diagnostic distinction each one enforces.

Experiment	What it prevents the interpretation from confusing
Double slit	Coherent alternatives are not classical ignorance.
Delayed-choice eraser	Later sorting changes accessible correlations, not an already recorded past.
Interaction-free measurement	A possible interaction can alter amplitudes without a classical collision history.
Leggett–Garg test	Temporal correlations constrain macrorealist histories, not merely spatial hidden variables.
Double slit in time	Temporally separated windows interfere although they do not coexist as two spatial openings.

The last case makes the change-first point especially clearly. Two short time windows modulate a field at one location. Their separation Δt produces spectral fringes with characteristic spacing

$$\Delta\omega = \frac{2\pi}{\Delta t}. \quad (30)$$

Unlike two spatial slits, the two windows cannot coexist as simultaneous objects. What interferes are amplitudes associated with two distinguishable interaction opportunities. The measured pattern is real, but it does not require time to be pictured as a second material screen. The complete setups, equations,

and interpretive limits for all five experiments appear in Appendix D. Appendix L.10 supplies the Fourier derivation of the temporal fringe spacing. Appendices L.11 and L.12 provide the Mach–Zehnder and repeated-interrogation calculations behind the interaction-free example: altered amplitudes do not require assigning the particle a definite classical collision history.

6. Discussion

6.1. What Kind of Claim This Is

The contribution is an interpretive synthesis rather than a modification of the dynamical laws. It places three distinctions—order versus duration, reversibility versus an observed arrow, and correlations versus stable records—into one framework spanning classical mechanics, quantum theory, and relativity. That synthesis has explanatory value even though it is not a new-particle or new-decay-rate prediction: it shows which parts of familiar temporal language are required by the equations and which belong to an optional physical interpretation.

The scope boundary can be stated once. The transactional discussion interprets rather than derives Born weights; Bell’s theorem and the Tsirelson bound are unchanged; and the relational account introduces no preferred rest frame. The proposal should therefore be judged by its coherence, economy, and ability to connect established results, while any future empirically distinct model would require an additional construction beyond this paper.

Two familiar objections help mark what the change-first proposal does and does not claim. The first asks whether time might simply belong to a deeper level of reality—for example, to a computer that generates the world we observe.

Does a simulated universe explain time?

A simulation hypothesis proposes that an observed world is generated by an underlying computational or physical system. A conventional computer updates states in an external sequence, so invoking it does not explain temporal order; it presupposes such order at the simulator level. A timeless structural simulation is logically possible, but then “simulation” names a mapping between structures rather than a process running on an outside clock. The extended argument and its relation to Bostrom’s probabilistic proposal are in Appendix E.

The second objection reverses the concern. If relations replace a temporal background, perhaps the proposed relational “fabric” is only an old ether under a new name. The relevant test is whether that fabric introduces an observable state of absolute rest.

Is this a modernized ether? The luminiferous ether was a substance in space with a privileged state of rest, so motion relative to it was meant to be measurable. The relational “fabric” used here has neither property. It is a network of correlations from which stable spatial and temporal descriptions are read; it is not an object through which systems move. Uniform translation of a complete relational configuration creates no new internal fact, and the proposal predicts no preferred inertial frame. Entities and relations are jointly required—an edge needs vertices—but no additional temporal fluid is needed. Appendix I gives the fuller comparison with Michelson–Morley, emergent spacetime, and the entities–relations question.

6.2. Inherited Problems and Open Directions

Relationalism does not explain the universe's exceptionally low-entropy boundary condition. In timeless language the past hypothesis becomes a claim that one end, region, or orientation of the allowed configuration-space history has extraordinarily small phase-space volume and unusually sparse records. The early universe was hot and nearly homogeneous, which can sound like thermodynamic disorder if gravity is ignored. With gravity included, however, such smoothness is highly special: generic gravitating matter can clump, form compact objects, and ultimately produce black holes with enormous entropy. The smooth initial geometry therefore left a vast range of higher-entropy gravitational structures available to form. Changing the physical account of duration relocates this asymmetry; it does not derive it. The origin and status of that boundary condition remain an open cosmological problem.

Nor does this essay establish that Shape Dynamics covers every spacetime, that Page–Wootters clocks are always adequate, or that emergent spacetime has been derived from the jersey metaphor. Those are technical research programmes with domains and limitations. Appendix J retains the extended assessment of existing consistency checks, possible experiments, and routes by which a change-first reading might eventually acquire distinct empirical content.

7. Conclusion

The same symbol t does several jobs in physics. It labels states in a trajectory, defines durations in Newtonian mechanics, enters the unitary evolution operator in quantum theory, and forms part of the spacetime metric in relativity. These mathematical roles are precise. They do not, by themselves, require time to be a substance through which physical systems move.

Classical mechanics showed why the distinctions matter. Jacobi's principle constructs duration from a path through configuration space for an important class of systems, while Norton's dome demonstrates that a time parameter does not guarantee a unique evolution. The Loschmidt–Boltzmann argument demonstrates that reversible microscopic laws do not generate a macroscopic arrow without statistical assumptions and a special boundary condition.

Quantum mechanics adds a second separation. Unitary evolution is reversible and preserves the full state. Decoherence creates correlations with an environment and suppresses interference in a subsystem. Redundant records make that suppression effectively irreversible. The jersey image represents this growth of records. Time-reversal symmetry is instead a precise property of the dynamics and should not be conflated with record formation. Coherent alternatives also differ from classical ignorance because their relative phases can interfere. Wigner's friend then exposes a related assumption in the phrase "right now": internal change and records do not automatically establish a privileged synchronization with an isolated external observer.

Relativity makes clock comparisons geometrical. This is a major physical advance, not merely a change of notation. It still leaves room for a relational question: whether spacetime is fundamental or an effective description of a deeper structure. Uniform velocity supplies no absolute motion against a background. Given a geometry, proper acceleration is locally detectable, although in general relativity the geometry defining geodesic motion is itself dynamical. Proper time records invariant comparisons of accumulated change without making inertia the cause of time dilation. Shape Dynamics establishes that at least some gravitational physics can be organized with different fundamental variables. It does not prove that the relational account developed here is uniquely correct.

The same limitation governs the simulation argument. A computer that updates a global state through

successive cycles has not explained time but presupposed an external ordering and moved the question to another level. A timeless structural simulation is not excluded, but its additional simulator is not part of the relational physics accessible from within.

The resulting claim is modest in form but broad in reach. Change, relation, and record formation can be identified within established mathematics, and time can consistently be read as the quantitative ordering and comparison of those changes. This reading neither selects a unique picture of physical reality nor explains the special low-entropy boundary condition responsible for the observed arrow. Its purpose is to make the interpretation, its inherited assumptions, and its possible extensions explicit rather than hiding them inside a familiar symbol.

About the Author

The author read physics as an undergraduate at Imperial College London from 1994 to 1998, taking a substantial share of theoretical coursework taught, among others, by Sir Tom Kibble, Prof. Ray Rivers, Prof. Fay Dowker, and cosmologist Prof. Andreas Albrecht. He stayed at Imperial for a PhD in condensed matter theory from 1998 to 2002, working with Prof. Dimitri Vvedensky. A postdoctoral position in applied mathematics followed at the University of California, Los Angeles, from 2002 to 2004, working with Prof. Russel Caflisch. Active publication in physics did not continue past that point, but the question this paper works through, what time actually is beneath the mathematics that uses it, did not stop being asked in the interval.

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Disclaimer

The author takes full responsibility for, and endorses, everything written in this paper. Any individuals acknowledged above do not necessarily endorse this work.

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A. Norton's Dome: Full Derivation and Idealization Caveat

Norton's dome sharpens exactly this point by showing what happens when determinism fails in classical physics: the breakdown lies entirely in the dynamics, exposing the parameter t as a passive label rather than an active causal agent [Norton, 2008].

The dome's shape. Build a dome whose height falls off with r , the arc length a ball has rolled along the surface away from the apex, according to

$$h(r) = -\frac{2}{3g} r^{3/2}, \quad (31)$$

with g the gravitational acceleration and $h(0) = 0$ at the apex. Because r is measured along the curved surface itself, not horizontally, the slope dh/dr equals $\sin \theta$ exactly, with θ the surface's angle of descent at that point, no small-angle approximation needed. The tangential component of gravity pulling the ball down the slope is then $-g \sin \theta = -g dh/dr$ exactly, and Newton's second law along the surface, $\ddot{r} = -g dh/dr$, becomes

$$\ddot{r} = \sqrt{r} \quad (32)$$

once $h(r)$ is fixed by Equation 31.

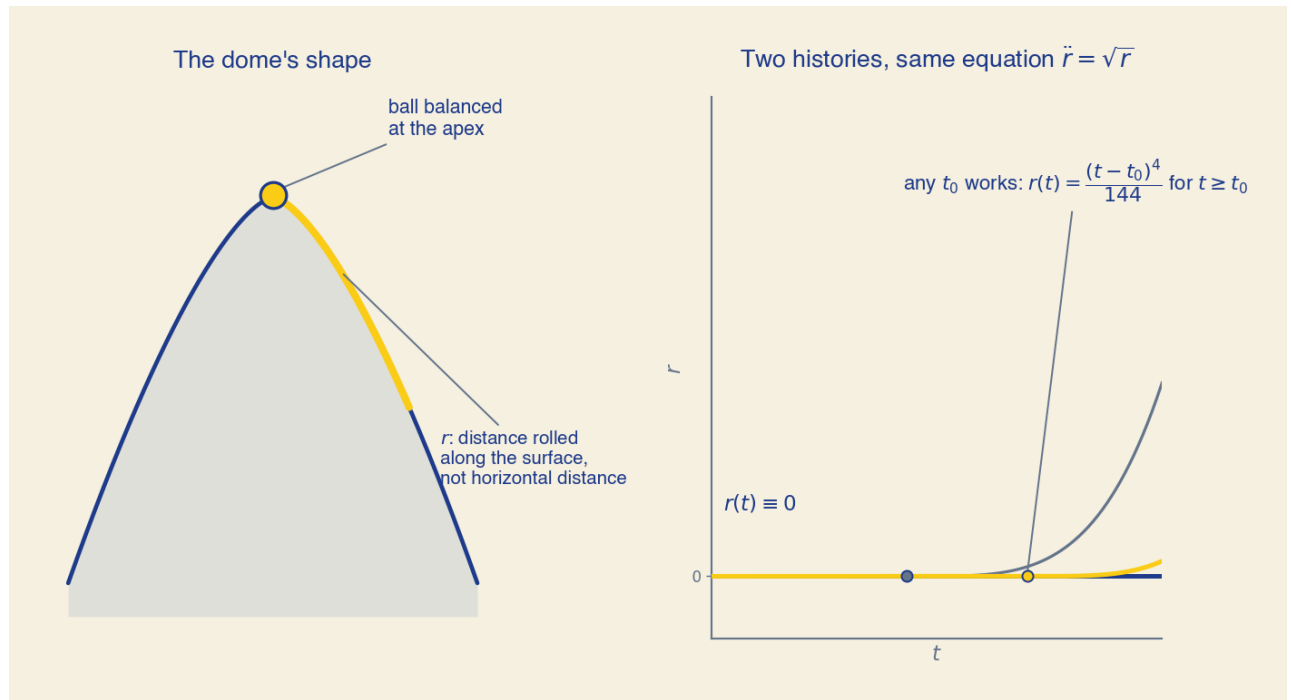


Figure 6. Norton's dome. Left: the dome's shape, Equation 31, with the ball balanced at the apex, $r = 0$. The highlighted arc marks r , the distance rolled along the surface. Right: two histories that both satisfy Equation 32 with the same starting condition: staying at rest forever, or beginning to roll at an arbitrarily chosen later time t_0 .

More than one history fits the same start. A ball sits at the apex, $r(0) = 0$, $\dot{r}(0) = 0$. Equation 32 admits infinitely many valid histories consistent with that single initial state. The solution $r(t) \equiv 0$ solves

Equation 32 trivially—the ball remains at rest indefinitely. Less obviously, so does

$$r(t) = \frac{(t - t_0)^4}{144}, \quad t \geq t_0, \quad (33)$$

with $r(t) = 0$ before t_0 , for any choice of $t_0 \geq 0$. Writing $u = t - t_0$, $\dot{r} = u^3/36$ and $\ddot{r} = u^2/12$, while $\sqrt{r} = \sqrt{u^4/144} = u^2/12$, so Equation 32 holds for every $t > t_0$. At $t = t_0$ itself, position, velocity, and acceleration are all identically zero, matching the trivial solution smoothly. Newtonian mechanics permits both solutions; the ball can spontaneously begin rolling at any moment t_0 without violating $F = m\ddot{x}$ and with no physical cause or trigger.

Why uniqueness fails. The mathematical reason is well understood. Differential equations of the form $\ddot{r} = f(r)$ are guaranteed a unique solution by the Picard–Lindelöf theorem provided $f(r)$ is Lipschitz continuous near the starting point. Here $f(r) = \sqrt{r}$ is continuous at $r = 0$, but its derivative,

$$f'(r) = \frac{1}{2\sqrt{r}}, \quad (34)$$

diverges as $r \rightarrow 0^+$. The Lipschitz condition fails at the apex, which is precisely why determinism breaks down there and nowhere else.

The apex is reached, not just approached. One might suspect $r = 0, \dot{r} = 0$ is an unphysical, unreachable boundary condition. For a standard unstable equilibrium where $f(r)$ is Lipschitz, uniqueness prevents any moving body from reaching the apex in finite time (it only approaches asymptotically as $t \rightarrow \infty$). Norton’s dome has no such restriction. Because Equation 32 is time-symmetric ($t \rightarrow -t$), running Equation 33 backward yields

$$s(t) = \frac{(t_1 - t)^4}{144}, \quad t \leq t_1, \quad (35)$$

with $s(t) = 0$ for $t > t_1$. This describes a ball launched up the dome that comes to a complete, exact stop at the apex at finite time t_1 . The subsequent indeterminacy is therefore a physical feature of a state reached by a real trajectory, not an artifact of idealized initial conditions.

What this means for t . The dome does not suffer from a failure of time; it suffers from a non-Lipschitz force law. If time were an active, flowing substance driving physical change, one might expect “time’s flow” to enforce continuity and cause. Instead, the parameter t merely labels the manifold of states. Determinism, causality, and uniqueness are properties of the force law $F(r)$ and boundary conditions, not of the temporal parameter t . Norton’s dome demonstrates that parameterizing motion does not automatically imbue t with generative power or causal determinism.

B. Wheeler’s One-Electron Universe

In the spring of 1940, John Wheeler telephoned a young Richard Feynman with an idea Feynman would recount in his own 1965 Nobel lecture, Wheeler’s opening line being that he knew why all electrons have the same charge and the same mass: “they are all the same electron!” [Feynman, 1965]. This was not a loose metaphor. A single electron worldline, if it zigzagged backward and forward through time enough times, would intersect any fixed instant at many points, and each intersection would look, to an observer confined to that instant, like a separate electron. What looks like countless electrons filling the universe would be one worldline, tied in an enormous knot, sliced by the plane of “now.”

The seed of the idea is real physics, not whimsy, and worth making precise. A free relativistic particle satisfies $E^2 = p^2c^2 + m^2c^4$, which has two roots,

$$E_{\pm} = \pm \sqrt{p^2c^2 + m^2c^4}, \quad (36)$$

and the negative branch, present in the relativistic wave equation from the start, is exactly what motivated the reinterpretation this section is about. The mechanism is cleanest to see directly on the worldline $x^\mu(\tau)$ already introduced above: a charge q coupled to an electromagnetic field contributes a term to the action,

$$S_{\text{int}} = -q \int_{\text{worldline}} A_\mu(x) dx^\mu, \quad (37)$$

a line integral along the curve. Retrace the identical worldline, the same points in the same order in space, but in the opposite direction, and $dx^\mu \rightarrow -dx^\mu$ at every point, exactly as reversing the direction of any line integral flips its sign. Equation 37 then becomes

$$S_{\text{int}}[\text{reversed}] = -q \int A_\mu(-dx^\mu) = -(-q) \int A_\mu dx^\mu, \quad (38)$$

term for term, the action of a particle carrying charge $-q$ tracing the original direction. Reversing which way a worldline is traced and flipping the sign of its charge produce the identical coupling to the field. That one-line calculation, not a metaphor about time travel, is the entire mathematical content of “a positron is an electron moving backward in time.”

Feynman kept exactly this piece of the idea and nothing more. Read as the statement that Equation 38 lets a backward-running segment of worldline be reinterpreted as a forward-running antiparticle, the reinterpretation became standard, load-bearing quantum electrodynamics, already at work in Figure 4 [Feynman, 1949]. Wheeler’s stronger claim, that there is therefore only one electron in the entire universe, did not survive contact with a simple count. If one worldline zigzags forward and backward through time with equal ease, forward-running segments (electrons) and backward-running segments (positrons) ought to appear in roughly equal numbers at any instant. The observed universe contains vastly more electrons than positrons. Wheeler’s own response, half joking, was that the missing positrons might be hiding inside protons [Feynman, 1965]. The strong version was never seriously pursued again, by Wheeler or anyone else.

What survives the historical failure of the strong claim is worth keeping for a different reason than Feynman kept it. Equation 38 never actually says anything travels backward through time. It says that reversing a curve’s direction and flipping a charge’s sign are two descriptions of the identical physical coupling, the same kind of equivalence Section C below puts to use for a single amplitude, $\psi_{A \rightarrow B}$ and $\psi_{B \rightarrow A}$ describing one relational process read in opposite orientations rather than two objects independently in motion. Nothing forces the further step, made informally so often that it stops sounding like a further step at all, of picturing a small charged object literally swimming upstream through a substance called time to reach that reversed description. An electron worldline running one way and a positron worldline running the other are, on this reading, two orientations of one relational process between the same boundary events, exactly as Section 4.5 and the ether discussion already argue for space and simultaneity more generally. This also sharpens, rather than rescues, Wheeler’s original intuition about why all electrons are identical. Modern quantum field theory does not treat an electron as a small object carrying a private identity tag through spacetime. It treats “electron” as a name for a particular kind of excitation of a single underlying field, the entities-and-relations picture developed in the ether discussion already commits to. Two electrons being indistinguishable never required them to be numerically the same electron, wearing Wheeler’s single worldline like a very long piece of string. It only required that the relational structure producing each excitation be exactly the same kind, every time.

C. Time-Symmetric and Two-Boundary Case Studies

Recall from ordinary electrodynamics that a source's field obeys a wave equation,

$$\square A_\mu = \mu_0 J_\mu, \quad \square \equiv \frac{1}{c^2} \partial_t^2 - \nabla^2, \quad (39)$$

and that a wave equation like this always admits two families of solutions built from the same source, a retarded one, using the source's state at the earlier time $t - |\mathbf{r} - \mathbf{r}'|/c$, and an advanced one, using its state at the later time $t + |\mathbf{r} - \mathbf{r}'|/c$. Ordinary practice keeps only the retarded solution: this is a causality postulate added on top of Equation 39, not something the equation itself forces, since the advanced solution solves it exactly as well and is discarded purely by convention.

Decades before decoherence theory existed, Wheeler and Feynman ran into a version of the same puzzle for electromagnetism: the field equations are time-symmetric, admitting both a forward-running solution and a backward-running one, yet radiation is only ever observed traveling forward. Rather than discard the backward solution by hand, they took each source's field to be genuinely symmetric,

$$A_\mu = \frac{1}{2} (A_\mu^{\text{ret}} + A_\mu^{\text{adv}}), \quad (40)$$

half retarded, running forward from emitter to absorber, half advanced, running backward [Wheeler and Feynman, 1945]. The retarded radiation observed in the absorber account depends on the response of a sufficiently complete absorbing universe and on global boundary conditions. Its resemblance to decoherence is limited: both invoke many degrees of freedom, but absorber cancellation is not the local environmental-entanglement mechanism described in Section 3.4.

Wheeler–Feynman absorber theory and Cramer's later transactional interpretation are related proposals, not the same theory. The first is an account of classical electrodynamic radiation using time-symmetric emitter–absorber interactions. Cramer borrowed the advanced and retarded structure as an interpretation of quantum processes, calling the forward-directed amplitude an “offer” and the returning amplitude a “confirmation.” The transactional interpretation reads Equation 40 as a standing “handshake” between emission at t_0 and absorption at t_1 , built from both directions of time at once and completed only once absorption occurs [Cramer, 1986]. On this reading, Q 's interval between t_0 and t_1 is represented by one transaction whose constraints span both boundary events. This is an interpretation of standard quantum predictions, not an experimentally established mechanism of collapse.

What this does not derive. The transactional picture assumes, rather than derives, the relation between offer and confirmation amplitudes required for Born weights. With that limitation stated first, it can give an interpretation of the ordinary Born rule, not only of the two-boundary generalization Section C.1 takes up next. Write the amplitude connecting a fixed earlier event A to a candidate later event B as $\psi_{A \rightarrow B}$, playing the role the retarded field A_μ^{ret} plays in Equation 40 for the electromagnetic case, and the confirming amplitude the handshake requires as $\psi_{B \rightarrow A}$, playing the advanced field's role.

The handshake can be pictured as feedback across the whole interval from emission to absorption: an offer reaches possible absorbers and their confirmations return toward the emitter. The forward and backward components belong to one time-symmetric relation between the two boundary events. Their phases matter. Contributions that agree in phase reinforce one another, while those that disagree can cancel, just as in the usual sum over paths. This picture must not be mistaken for a measured series of repeated cycles taking place in a second time outside the experiment. In Cramer's account the completed transaction is the whole standing relation, and the apparent back-and-forth sequence is a way of describing that relation rather than an extra observable motion.

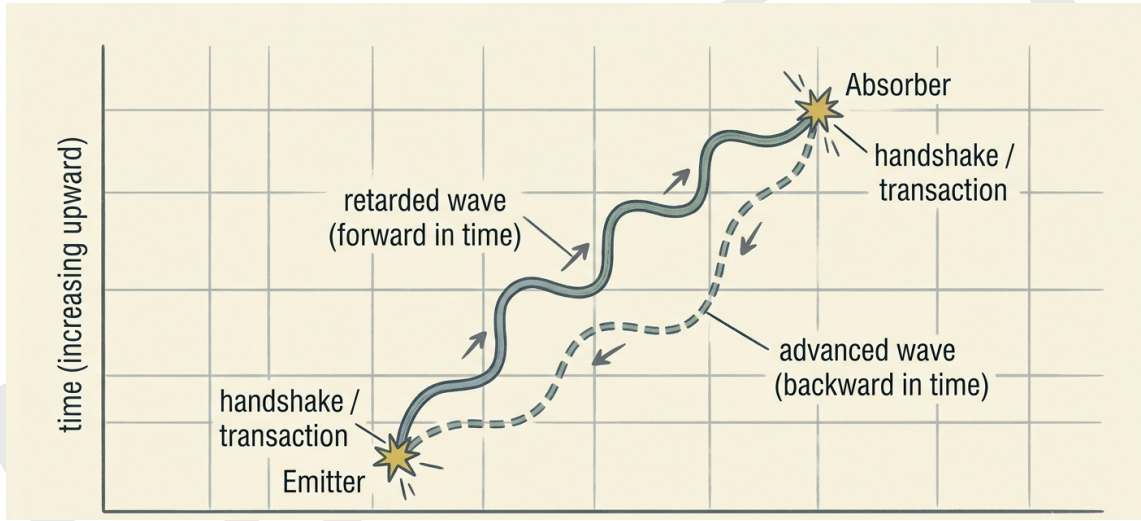


Figure 7. Cramer’s transactional picture: a retarded wave running forward from emitter to absorber and an advanced wave running backward, meeting at both ends in a “handshake” that completes only once absorption occurs.

If the confirmation is taken to be the complex conjugate of the offer, $\psi_{B \rightarrow A} = \psi_{A \rightarrow B}^*$, their product is

$$P(A \rightarrow B) \sim \psi_{A \rightarrow B} \psi_{B \rightarrow A} = \psi_{A \rightarrow B} \psi_{A \rightarrow B}^* = |\psi_{A \rightarrow B}|^2, \quad (41)$$

reproducing the ordinary Born weighting, Equation 42 below, as two amplitudes meeting at a completed transaction. The classical rope in Section 3.9 supplies a limited visual analogy: forward and backward waves can form a stationary pattern once both ends are fixed. Here the two ends are events rather than positions on a rope, and the physical mechanisms should not be identified. At a bright fringe the contributing path amplitudes reinforce; at a dark fringe they cancel. Transactional language describes this by saying that no completed transaction is supported at the cancelled outcome. It is a physical reading of the same interference calculation, not a separate effect.

Nothing above derives the confirming amplitude’s complex-conjugate relation or the rule that turns the resulting weights into frequencies of outcomes. Those assumptions are part of the transactional account. As Section 6.1 states as a general policy, this is an interpretation of the Born rule, not a derivation of it.

C.1. Shaped by Both Ends: Aharonov’s Two-State Formalism

Two laboratory procedures supply the basic idea. *Preselection* means preparing a system in a known initial state and keeping every trial that meets that preparation. *Postselection* means retaining only the subset of those trials in which a specified later measurement result is obtained. Once both selections are made, probabilities for an intermediate measurement may be conditioned on both the known preparation and the known final result. The two-state-vector formalism packages those two boundary conditions symmetrically rather than treating the later one only as information appended after a forward calculation.

Recall how this question is normally answered, propagating $|\psi\rangle$ forward alone: the probability of an intermediate outcome c_k , measured with projector $\hat{P}_k$ at some time between preparation and a later measurement, is the ordinary Born rule,

$$P(c_k) = |\langle c_k | \hat{U}(t, t_0) | \psi \rangle|^2, \quad (42)$$

using only the earlier boundary condition and nothing about how the system is later found. Aharonov, Bergmann and Lebowitz asked what changes once the later outcome $|\phi\rangle$ at t_1 is taken into account as well, rather than discarded, and answered using both boundary conditions at once instead of Equation 42's forward propagation alone. The probability of that same intermediate outcome c_k becomes the ABL rule,

$$P(c_k) = \frac{|\langle\phi|\hat{P}_k|\psi\rangle|^2}{\sum_j |\langle\phi|\hat{P}_j|\psi\rangle|^2}, \quad (43)$$

weighting each outcome by its consistency with both boundary conditions at once [Aharonov et al., 1964]. Aharonov, Albert and Vaidman extended this to the weak value,

$$\langle\hat{A}\rangle_w = \frac{\langle\phi|\hat{A}|\psi\rangle}{\langle\phi|\psi\rangle}, \quad (44)$$

obtained by measuring $\hat{A}$ gently enough between the same two boundary conditions to avoid collapsing the state outright [Aharonov et al., 1988]. Equation 44 can lie outside the eigenvalue range of $\hat{A}$ entirely, a documented, measured effect, precisely because the interval between t_0 and t_1 is not, on this formalism, described by a single forward-propagating fact.

C.2. Taking It Literally: Retrocausality

Equations 43 and 44 are often read as bookkeeping: a compact way to summarize what an observer can infer about the past, given information that happens to arrive later. There is a more radical reading, retrocausality, which takes the future boundary condition to have a genuine physical influence on the present, not merely an epistemic one. Wharton, Miller and Price develop this directly out of the classical principle of least action in Section 3.9: Hamilton's principle already treats a system's trajectory as fixed by two boundary conditions simultaneously, an initial state and a final state, with the true path the one that makes $\delta S = 0$ between both. Ordinary classical mechanics resolves this by solving forward from the initial condition and simply noting that the final condition happens to be satisfied. The retrocausal reading takes both boundary conditions equally seriously as physical constraints, in which the later measurement does not reveal a pre-existing value so much as it constrains what value could have been there, exactly as the earlier boundary condition does [Wharton et al., 2011]. This is not the majority position in quantum foundations, and this paper does not need it to be true for Section 3.6's central claim to hold. It is worth stating because it is the natural end point of taking Equation 43 at face value rather than as bookkeeping, and because it reframes the delayed-choice quantum eraser of Section D.2 and the double-slit-in-time experiment of Section D.5 as concrete, present-day laboratory settings in which this exact question, is the later boundary condition merely revealing or actually constraining, is being probed rather than merely debated.

D. Five Experiments, Walked Through in Full

None of the five experiments below was designed to test the claim in Section 3.6, and none of them can, for reasons Section 6 takes seriously rather than glossing over. Each one is, however, a case where a real experiment already draws an unusually sharp line between “interacted” and “did not interact,” which makes each a natural place to see Equation 16 turn the arrow of time on and off in practice. Each experiment is described in full, in words, before any equation.

D.1. The Double-Slit Experiment

Send a single particle toward a barrier with two narrow slits, A and B , and a screen beyond, with no detector watching the slits, and over many repetitions the particles build up a pattern of alternating bright and dark fringes, the pattern two overlapping waves produce, not the two bands tiny bullets would leave. Nothing has been woven into anything, so the full superposition, $|\psi\rangle = \frac{1}{\sqrt{2}}(|A\rangle + |B\rangle)$, survives to the screen, and the detection probability carries the interference term responsible for the fringes, $P(x) \propto 1 + V \cos \Delta\phi(x)$, with visibility $V = |\langle E_B | E_A \rangle|$ taken directly from Equation 16. Place a which-path detector at the slits, a stitch, and the fringes wash out as the detector's ability to distinguish the paths improves. Englert's duality relation makes the trade-off exact, calling D the distinguishability and V the visibility,

$$D^2 + V^2 \leq 1, \quad (45)$$

with equality for a pure joint state [Englert, 1996]. Full which-path distinguishability, $D = 1$, forces $V = 0$. If $D = 0$, unit visibility is possible. The detector interaction therefore controls the observable coherence and creates a record. Neither fact by itself supplies the low-entropy boundary condition required for a complete thermodynamic arrow.

D.2. The Delayed-Choice Quantum Eraser

The phrase “delayed choice” refers to choosing how to measure one member of an entangled pair only after the other member has already been detected. Popular descriptions sometimes suggest that this later choice changes which path the earlier photon took. The experiment does not alter the earlier detector's unsorted record. Its significance is that different correlation patterns appear when the already recorded events are grouped according to the later measurement result.

Kim and colleagues produced entangled photon pairs, a signal photon sent through a double-slit setup and an idler photon sent to a separate detection stage, in the joint state

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|A\rangle_s |a\rangle_i + |B\rangle_s |b\rangle_i), \quad (46)$$

with $|a\rangle_i, |b\rangle_i$ perfectly distinguishable [Kim et al., 2000]. Reduced to the signal photon alone, this is Equation 16 with the idler as environment: no fringes, already woven. Measure the idler instead in a rotated basis $|\pm\rangle_i = \frac{1}{\sqrt{2}}(|a\rangle_i \pm |b\rangle_i)$. Sort the signal detections according to the idler outcome. The two conditional subensembles show complementary fringe and antifringe patterns because $\langle +|a\rangle\langle b|+ \rangle \neq 0$. Their sum still has no fringes. No local statistics at the signal detector change after the later idler measurement, and no information travels backward in time. A retrocausal interpretation may treat both boundary conditions as part of the physical description. Standard quantum mechanics needs only the joint state and conditional probabilities.

D.3. The Elitzur–Vaidman Interaction-Free Measurement

An empty Mach–Zehnder interferometer first divides a photon's amplitude between two arms and then recombines the arms at a second beam splitter. The path lengths can be adjusted so that the two amplitudes reinforce at one output, the bright detector, and cancel at the other, the dark detector. A click at the dark detector is then evidence that something has disturbed the relation between the paths, even when that object did not absorb the detected photon.

The Elitzur–Vaidman proposal places an idealized bomb, absorbing and detonating on contact with a single photon, in one arm and asks whether the bomb’s presence can be confirmed without a photon touching it [Elitzur and Vaidman, 1993]. A photon enters a 50:50 beam splitter,

$$\hat{B} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix}, \quad (47)$$

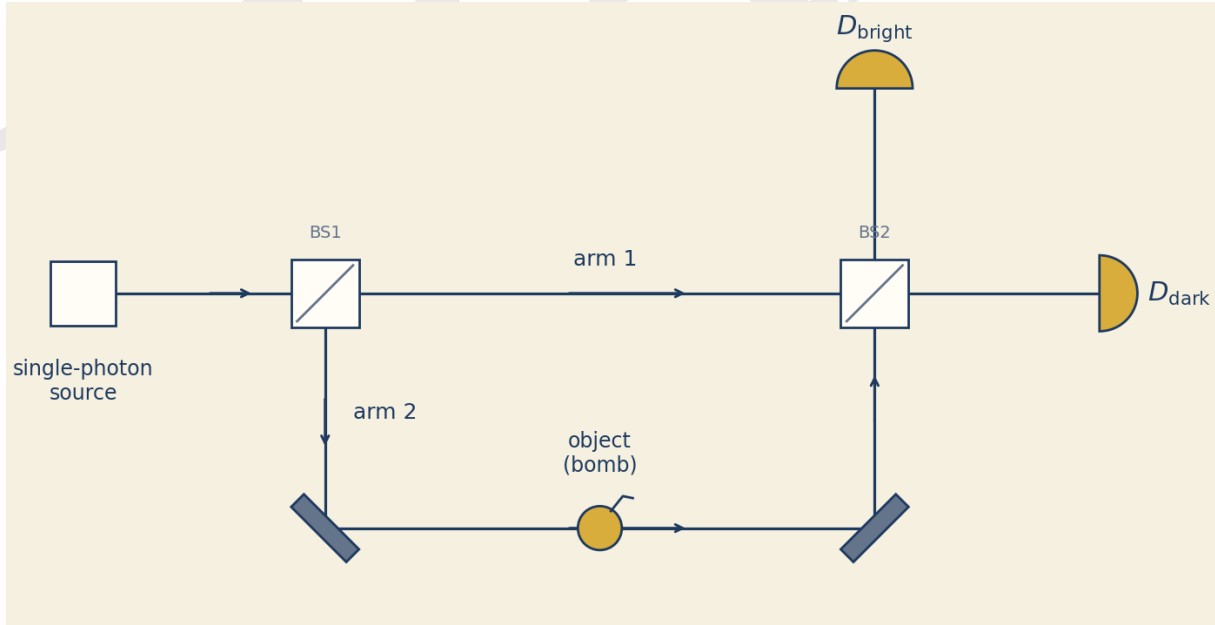


Figure 8. The Elitzur–Vaidman interferometer: a photon splits at the first beam splitter into arm 1 and arm 2, with the object (bomb) in arm 2. A click at D_{dark} identifies a live object. In that successful branch, the object does not absorb the photon.

splitting into $|\psi\rangle = \frac{1}{\sqrt{2}}(|1\rangle + i|2\rangle)$. The full matrix bookkeeping is in Appendix L. With no bomb, a second beam splitter sends every photon to D_{bright} , none to D_{dark} . With a live bomb in arm 2, half the trials end in absorption. In the remaining branch, the second beam splitter gives equal probabilities for the bright and dark detectors. A dark-detector click therefore identifies the bomb without absorption in that branch. Its probability is one quarter per input photon. This statement concerns the quantum branches and the conditional outcome. It does not establish that the photon possessed a classical path through arm 1.

Kwiat and colleagues replaced the single interferometer with N weak steps [Kwiat et al., 1995]. Each step rotates the state by approximately $\pi/2N$. Repeated coupling to the absorbing branch inhibits the accumulated rotation through the quantum Zeno effect. The absorption probability approaches $\pi^2/4N$, so the successful interaction-free probability approaches one. Appendix L gives the derivation.

D.4. A Leggett–Garg Test of the Same Scenario

Bell inequalities constrain correlations measured on separated systems. Leggett–Garg inequalities apply a related strategy to one system measured at different clock readings. They ask whether the observations can be explained by a classical history in which the measured property always had a definite value that could, in principle, be read without disturbing its subsequent evolution.

Leggett and Garg considered a two-valued observable $Q = \pm 1$ measured at three times. Macrorealism per se assigns a definite value at each time. Noninvasive measurability assumes that the value can be determined without altering the later dynamics. Together these assumptions imply

$$K_3 = C_{12} + C_{23} - C_{13} \leq 1. \quad (48)$$

Robens and colleagues implemented a related protocol with single caesium atoms and measured a violation [Robens et al., 2017]. The experiment rules out the conjunction of macrorealism and the operational noninvasiveness assumptions used in the inequality. It does not, by itself, prove the single statement that the atom had no definite position. Its relevance here is more precise: quantum dynamics cannot be replaced by a noninvasively observable sequence of pre-existing classical values.

D.5. The Double Slit in Time

Recall the ordinary double slit from Section D.1: two slits sit side by side, open at the same instant, and a single particle's wave interferes with itself because nothing has yet forced a fact about which slit it went through. Every experiment discussed so far, including that one, places its two alternatives in space. It is worth asking directly whether the same interference mathematics applies if the two alternatives are placed in time instead, two brief windows during which a wave is let through, one after the other, rather than two openings side by side.

The reason this is not obviously true, and worth testing rather than assuming, is that the two cases differ in an important way. The two spatial slits genuinely coexist: both are open, at once, for the same photon to encounter simultaneously. Two windows in time cannot coexist in that sense, the first is already closed before the second opens, so whatever interferes here is not two options present at once in the way the spatial slits are. If interference still shows up, it is evidence that the mathematics governing superposition does not care whether the two alternatives it is superposing are separated in space or separated in time, which is a stronger, more direct statement of this paper's claim than the spatial double slit alone can give.

The relevant mathematics is Fourier analysis. For root-mean-square widths, a temporal envelope and its angular-frequency spectrum satisfy

$$\Delta t \Delta \omega \geq \frac{1}{2}, \quad \text{compare} \quad \Delta x \Delta p \geq \frac{\hbar}{2}. \quad (49)$$

The first relation is a Fourier bandwidth relation. It should not be confused with an uncertainty relation between two universal self-adjoint operators, because time is normally a parameter in quantum mechanics.

Let a single temporal window have envelope $g(t)$. Two identical windows separated by τ have

$$A(t) = g(t + \tau/2) + g(t - \tau/2). \quad (50)$$

Fourier transformation gives

$$\tilde{A}(\omega) = 2\tilde{g}(\omega) \cos(\omega\tau/2), \quad I(\omega) = 4|\tilde{g}(\omega)|^2 \cos^2(\omega\tau/2). \quad (51)$$

The single-window spectrum supplies the envelope. The cosine factor supplies the fringes. Replacing t by x , τ by the slit separation d , and ω by transverse wave number k_x gives the corresponding spatial double-slit expression. This is the precise analogy shown in Figure 9.

Tirole and colleagues implemented this structure experimentally. A beam of light was gated twice in rapid succession using the optical response of a thin indium-tin-oxide film near its epsilon-near-zero point

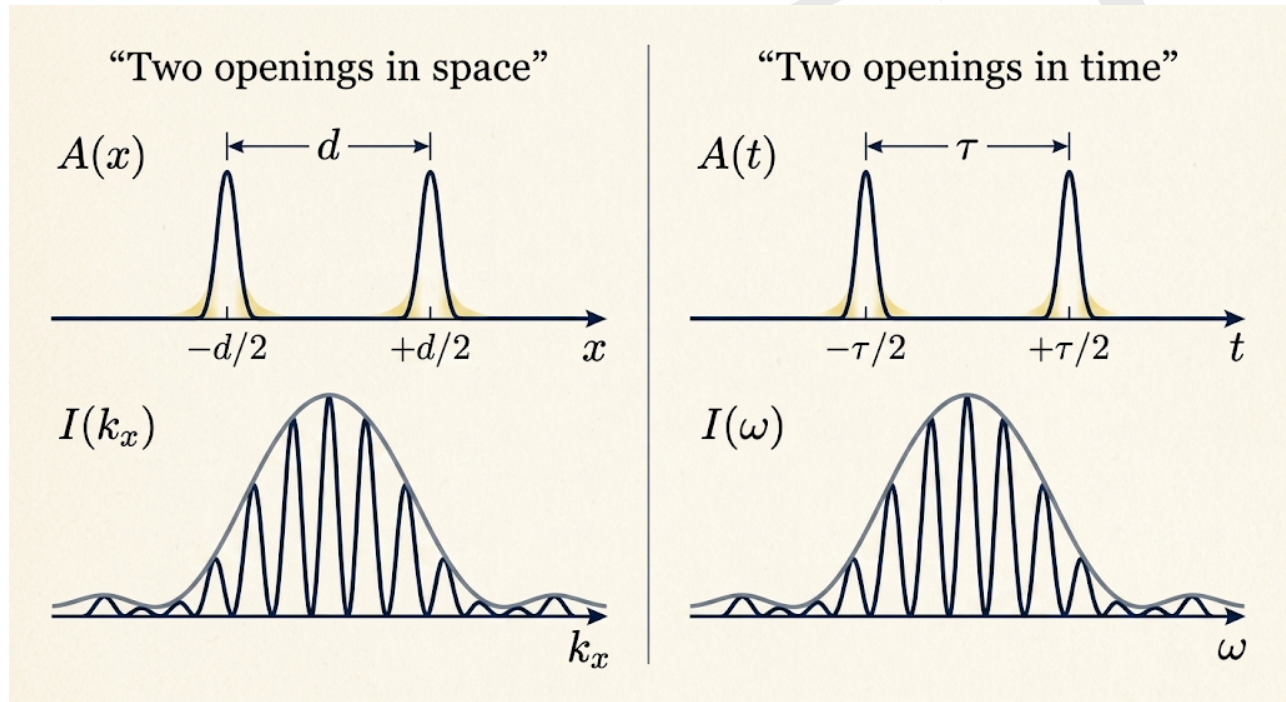


Figure 9. Spatial and temporal double slits. Two openings separated in space by d , represented schematically by the aperture profile $A(x)$, produce interference fringes in transverse spatial frequency k_x . Two optical-interaction windows separated in time by τ , represented by $A(t)$, produce corresponding fringes in optical frequency ω . The grey curves show the single-opening envelopes and the navy curves the two-opening interference modulation. These curves illustrate the Fourier correspondence $x \leftrightarrow k_x$ and $t \leftrightarrow \omega$. They are schematic, not fitted reconstructions of the measurements reported by [Tirole et al. \[2023\]](#).

[[Tirole et al., 2023](#)]. The result is not a spatial fringe pattern but a modulation of the optical frequency spectrum. The experiment demonstrates temporal diffraction in a driven optical system. It does not show a particle travelling backward in time, and it does not make time an operator. Its importance for this paper is narrower and clearer: alternatives separated in the clock parameter can interfere, and their observable structure is determined by the same Fourier mathematics that governs alternatives separated in space.

E. Simulation Arguments and External Clocks

The modern simulation argument is most closely associated with Bostrom, who asked what follows if technologically mature civilizations could create large numbers of detailed “ancestor simulations” containing conscious observers like us. His argument is probabilistic: if simulated observers vastly outnumber observers in an original civilization, an observer who does not know which kind they are may have statistical reason to suspect they are simulated [Bostrom, 2003]. The argument does not by itself specify how such a simulation would be implemented.

Popular presentations often supply a more concrete implementation and imagine a computer continually updating the state of our universe. One familiar version repeatedly updates a global state of the universe,

$$S_{n+1} = F(S_n), \quad S_0 \longrightarrow S_1 \longrightarrow S_2 \longrightarrow \cdots \quad (52)$$

In an ordinary molecular simulation, n is a genuine computational order in the executing machine, and a simulated duration is often assigned by $t_n = n\Delta t$. Applied literally to the universe, this picture supplies a global state, a global update order, and an external sequencing variable. It can therefore appear to provide a God’s-eye answer to what exists everywhere at one computational “now.”

The framework developed here gives a precise reason this picture does not explain the emergence of time. The ordering variable needed to advance the simulation has been assumed in advance. It relocates temporal order to the simulator rather than deriving it from relations inside the simulated world. If the simulator changes through computational states $C_1 \rightarrow C_2 \rightarrow C_3$, the original question simply returns: what gives physical content to the order and duration of those changes? Appealing to another external clock either begins a regress or declares the simulator’s time fundamental without explaining why the same move was needed outside the universe but not within it.

The Wheeler–DeWitt constraint in Section 3.10 sharpens the objection. Canonical quantum gravity does not provide an external universal parameter through which a universal wavefunction is advanced. Conditional and relational clock descriptions must instead be recovered from within the constrained state. A hypothetical computer is free to calculate such a state in some sequence, but its CPU order is not automatically the physical time described by the calculation, just as the order in which a computer calculates points on a spacetime manifold is not an additional time coordinate within that spacetime.

This last distinction also limits the argument. Relativity does not prevent a computer from calculating an entire four-dimensional spacetime, and an external execution clock need not correspond to any observable universal clock inside the modeled universe. A more sophisticated simulation hypothesis could posit that a simulator instantiates a timeless relational structure, a causal network, quantum history, or complete spacetime solution, rather than advancing reality frame by frame. Nothing in this paper rules out that metaphysical possibility.

The conclusion is therefore not that physics refutes Bostrom’s statistical argument or proves reality is not simulated. It is that a dynamically updated, global-state simulation presupposes the temporal structure it is sometimes invoked to explain. A timeless structural simulation avoids that objection, but then the physics available to internal observers is the relational structure itself. The additional statement that an external entity instantiated it does no explanatory work within the theory and appears empirically inaccessible. The closer the simulation hypothesis comes to respecting relational time and relativistic causal structure, the less it resembles a cosmic computer stepping the universe through a succession of universal presents.

F. Why the Question Recedes During Training

The relational status of clock readings is usually introduced early and then left behind. Later courses require students to manipulate t fluently in differential equations, Lagrangians, Hamiltonians, path integrals, and metric tensors. The mathematical skill is essential. It can also make the meaning of the parameter less likely to be reconsidered.

Research on expertise describes a relevant general mechanism. Automaticity and learned schemas allow an expert to solve difficult problems without reconstructing every elementary assumption [Dror, 2011]. Education research calls the corresponding loss of attention to beginner-level concepts the expert blind spot [Nathan and Petrosino, 2003]. These studies are not evidence about physicists specifically. They explain how a foundational question can become less visible as technical competence increases. One purpose of this paper is to reconnect that question across the parts of physics in which the same symbol t performs different formal roles.

G. Philosophical Coda: Instantiated Mathematics and Change

This philosophical coda asks whether mathematics, insofar as a physical agent instantiates it, also requires change. It is deliberately separated from the physics argument because its conclusion is epistemic rather than a new dynamical result. To arrive at the concept of “two,” a mind, or any processing system, must perform a sequence of distinct acts, draw a boundary around one entity, shift focus and draw a boundary around a second, and then synthesize the two into a set. That “and then” is inherently sequential. It requires a transition from one state of awareness to another, and a completely frozen, changeless system could never compute $1 + 1 = 2$, because computation is the transition between states, not a fact sitting still to be read off. A Turing machine, the mathematical ideal of computation, cannot function without a tape moving from one state to the next. This line of reasoning belongs to the mathematical intuitionist tradition founded by L.E.J. Brouwer, who grounded all of mathematics on what he called the intuition of two-oneness, the fundamental awareness of a “now” separating a “before” from an “after.” To Brouwer, the perception of sequential change is not a subject studied by mathematics. It is the raw material out of which the mind builds mathematics in the first place.

It is worth separating two claims here that are easy to run together. The first, epistemic, is that any agent, a mind, a Turing machine, a physical computer, that recognizes, counts, or proves anything must undergo a sequence of state changes to do it. A completely frozen system computes nothing. This is hard to dispute regardless of what one thinks mathematical objects ultimately are. The second is the stronger claim that mathematical objects themselves cannot exist without change, which a Platonist rejects immediately: the number two, on that view, exists timelessly, and the fact that a mind needs a sequence of thoughts to discover “ $2 + 2 = 4$ ” says something about minds, not about the number two. This paper needs only the first claim, and states it accordingly: it makes no claim about whether mathematical entities exist in a Platonic sense. It claims only that mathematics, insofar as it is instantiated in physical reality, in brains, in computers, in any physical process, presupposes change. Physics is concerned with instantiated structure, not abstract existence, and on that narrower target, change, not time, is the appropriate primitive. The laws of physics are not sitting, finished, in a frozen non-mutable (i.e., “timeless”) Platonic register waiting to be read, whatever one concludes about mathematics itself. They are patterns that appear in physical reality because something there is changing.

H. The Andromeda Example in Full

One classic illustration of Section 4.1's tension is worth walking through directly, because this reading answers it differently from how it is usually resolved. Two people pass each other on a sidewalk at ordinary walking speed, one moving very slightly toward the Andromeda galaxy, the other very slightly away from it. Special relativity's relativity of simultaneity means their planes of "now" are tilted relative to each other by an amount proportional to their relative velocity and the distance considered. Because Andromeda is roughly 2.5 million light-years away, even a walking-speed velocity difference corresponds to several days' difference in what each of them would call "happening now" there. Rietdijk and Putnam used exactly this to argue for a block universe, past, present, and future all equally real, since neither observer's plane of simultaneity is privileged and the two disagree about a real, distant event [Rietdijk, 1966, Putnam, 1967]. Penrose later dramatized the argument by imagining a fleet of alien ships already decided upon for one walker and not yet decided for the other [Penrose, 1989].

The reading developed in this paper does not say special relativity is wrong here, it reproduces ordinary Lorentz geometry exactly, and there is no different numerical prediction to be had. What it says is that the distant part of either observer's simultaneity plane carries no physical weight, because no physical relation connects those spacelike-separated events to either walker at that moment, only actual causal contact does. A global simultaneity surface reaching to Andromeda is, on this reading, bookkeeping, a coordinate choice, exactly as Section 4.5 found spacetime itself to be, not a claim that nature needs to instantiate anything at that distant, uncorrelated slice. This connects directly to material already established above: the ADM foliation of Section 4.4 shows general relativity itself does not pick out a preferred slicing, and Shape Dynamics shows the physically real content is the relational, spatial geometry, not a particular time-slicing of it. The Andromeda paradox makes the same point vivid in a setting every physics reader already has intuition for.

This specific response to the paradox is not new with this paper. It is essentially Howard Stein's reply to Rietdijk and Putnam: that in relativity the present is a local, causally grounded notion that cannot be extended to a global hyperplane [Stein, 1968]. What this paper adds is arriving at Stein's conclusion by a different, physics-motivated route, decoherence, foliation independence, and Shape Dynamics, rather than a purely philosophical one, a convergence worth noting rather than a new resolution to claim credit for.

The same discipline appeared in the Wigner's-friend discussion of Section 3.8. Relativity denies a physically privileged global simultaneity, while the relational quantum reading denies an automatically privileged synchronization between isolated records. These are analogous claims, not identical ones. The first concerns Lorentzian geometry and causal structure. The second concerns state attribution, correlation, and record formation. Their common lesson is narrower: coordinate comparison is mathematically legitimate, but a physically privileged correspondence requires more than assigning two systems the same parameter value.

I. The Ether Objection in Full

The relational structure this paper leans on throughout, the weaving of Section 3.1, the correlated systems of Section 3.6, the no-privileged-slicing argument of Sections 4.4 and 4.6, invites an objection that deserves to be met directly rather than left for a reader to raise unanswered: is this simply a modernized version of the luminiferous ether, the medium special relativity is credited with eliminating? The worry sharpens once Section 4.6 insists that only actual causal contact carries physical weight and a merely coordinate simultaneity does not, since that is exactly the kind of claim that requires something doing the work of

connecting nearby events, and “something doing that work” sounds uncomfortably close to a medium.

The answer turns on what specifically the ether was, and what the Michelson–Morley experiment actually tested. The nineteenth-century ether was posited as a physical medium filling space, at rest in one privileged frame, through which light propagated the way sound propagates through air. Its defining, falsifiable feature was that motion relative to it should be measurable, in principle, by a sufficiently sensitive apparatus. Michelson and Morley looked for exactly that signature, a difference in the speed of light measured along the direction of Earth’s motion through the ether versus perpendicular to it, and found none. Einstein’s resolution was not merely that there is no ether. It was that there is no experimentally detectable preferred inertial frame at all. Nothing argued in this paper requires, or predicts, a preferred rest frame of that kind. The relational structure invoked here does not carry a velocity, does not define a state of rest, and offers no analogue of the Michelson–Morley null result waiting to be explained away, because it was never proposed as a medium that things move through in the first place.

In the jersey language of Section 3.1, the fabric records relations; it is not an object against which velocity is measured. Uniform translation of an entire relational configuration supplies no new internal fact, whereas an interaction changes physically accessible relations. Given a spacetime geometry, proper acceleration is also locally measurable; in general relativity the geometry defining geodesic motion is itself dynamical, so this does not restore an absolute background.

The sharper way to state the distinction, rather than by assertion alone, is this: an ether is a substance situated inside space, through which objects move. What this paper treats as fundamental is not situated inside space at all. Space is, on this reading, an emergent description of the stable, large-scale pattern of relations, precisely the move Section 3.10 already makes for time, extended here to the spatial case. The network is not a thing occupying space that objects push through. Space is what gets read off the network once its structure is stable enough to support the bookkeeping Section 4.5 describes. Several existing, independently motivated approaches to quantum gravity are relational in exactly this sense, treating spacetime as reconstructed from a more fundamental relational structure rather than as a container that structure occupies, and none of them is described as reviving the ether, for the same reason given above: none defines a preferred frame for motion. Causal set theory takes spacetime to emerge from a discrete, partially ordered set of causal relations with no additional geometric structure assumed in advance [Bombelli et al., 1987]. Loop quantum gravity’s spin networks encode quantum geometry directly as a graph of relations with no background spacetime presupposed [Rovelli and Smolin, 1995]. Work on holography shows spacetime connectivity itself tracking patterns of quantum entanglement, to the point that disentangling two regions is what pulls them apart [Van Raamsdonk, 2010]. Rovelli’s relational quantum mechanics, already invoked in Section 3.10 for a different purpose, belongs to the same family for the same reason [Rovelli, 1996]. None of these citations is offered as evidence that this paper’s specific proposal is correct. They establish only that treating relations as prior to spacetime, rather than as occupying it, is an active, respectable move elsewhere in physics.

One caution belongs here rather than in the main argument. This is not a place to reach for dark energy or quantum-field vacuum structure as confirming evidence, on the reasoning that empty space is not really empty, so a relational substrate is more plausible now than it was in 1905. Dark energy is an effective description of an observed cosmic acceleration whose microscopic origin is not yet known, and quantum fields being fundamental degrees of freedom does not by itself imply a relational-network structure of the kind used here. Invoking either as support would be exactly the kind of overreach Sections 6.1 and J.1 are otherwise careful to avoid, trading a clean conceptual distinction for a resemblance that has not actually been argued for.

A related worry follows immediately once the first is resolved: if relations are what is fundamental, does that not require something for the relations to relate, meaning relations cannot be all there is? The worry is correct as stated, and the resolution is not to insist that only relations exist, but to be precise about what is jointly primitive. An edge presupposes the vertices it connects. A relation presupposes entities capable of entering into it. What this paper’s argument actually needs, examined carefully, is entities-with-the-capacity-for-interaction and interactions-that-actualize-that-capacity, taken together, with neither reducible to the other. This is not a new commitment introduced here to patch a hole. It is what Sections 3 and 3.6 have been doing all along without naming it. Q and B are never treated as bare relations floating free of anything to relate. They are always systems that become correlated, decohere, or entangle, which presupposes there being a Q and a B in the first place, prior to any particular interaction between them. On this view, entities supply the potential for interaction, interactions actualize that potential, stable interactions become the records Section 3.4 describes, and records are what Sections 3.4–3.5 already showed producing temporal order. Nothing above is eliminated in favor of relations alone. What is eliminated is only the idea that time needs to be added as a further primitive once entities and their interactions are already in place.

J. Extended Limitations and Research Directions

One point above needs sharpening rather than restating. Shape Dynamics and general relativity are constructed to be classically equivalent, but the equivalence has been established rigorously only in specific settings, asymptotically flat and closed cosmological spacetimes chief among them, and extending it to fully general, arbitrary spacetimes remains active mathematical work, not a settled result. Nothing in this paper depends on Shape Dynamics being the unique correct alternative to standard general relativity. It depends only on at least one mathematically consistent alternative existing in which fundamental time is dispensable, and that existence claim is established in the settings where the equivalence has been proven.

J.1. What Is Already Consistent With It

What can be asked is whether existing experiments are consistent with this reading rather than some rival account, and several lines of evidence already are. Rubino et al.’s superposed thermodynamic arrows show the arrow of time is fixed only at the level of a measurement outcome, never at the level of unitary evolution [Rubino et al., 2021]. Barontini’s entropic time shows a real, directional clock built entirely from entropy exchange between an observed and unobserved sector, with the whole staying provably reversible [Barontini, 2026]. The quantum eraser shows entanglement, not contact, governs the loss of interference [Kim et al., 2000]. The Leggett–Garg violation is a direct, measured statement that a non-interacting branch carries no definite intermediate state [Robens et al., 2017]. And the double-slit-in-time result shows the same wave mechanics ordinarily reserved for spatial superposition applying directly to superpositions in time [Tirole et al., 2023]. None of these experiments were built to test this paper’s claim specifically, and none rule out other accounts of the same evidence. Together, they show the claim is a description current physics keeps landing on, separately, rather than a picture standing apart from it.

J.2. A Natural Extension

The most direct extension this reading points toward, an extension of an existing experimental program rather than a genuinely new proposal, would run Barontini’s construction with a truly entangled, non-decohering Q sector in place of a merely unobserved one. The expectation is that the subsystem’s entropic clock is not merely slow but undefined before the relevant exchange, becoming well-defined once the required

correlations are established. That is decoherence theory examined at a resolution fine enough to compare with Barontini's construction, not a new prediction distinguishing this reading from decoherence theory as it stands.

J.3. Where This Kind of Reading Could Become More Than Interpretation

This section deliberately stops short of the more ambitious step a sympathetic reader might expect next: identifying one precise, literal consequence that would follow only if this physical picture is correct, something distinguishable from standard physics rather than a reinterpretation of it. That step belongs to a different, harder kind of paper, closer to proposing new physics than to rereading established physics, and it is left for later work rather than attempted here. What follows instead are the four most concrete places such an attempt could start, each already a real result in the literature, none of them a claim this paper itself makes.

Treating relational time as literally granular rather than smooth, a stronger claim than the one made above, predicts an intrinsic decoherence rate for a totally isolated system, scaling with the square of its energy gap, with no environment required at all [Milburn, 1991]. This has been experimentally constrained, not detected, and remains an open, improvable bound rather than a settled result.

Separately, an ordinary circuit places operations in a definite order: A occurs before B , or B before A . A quantum switch uses a control qubit to place those alternatives in coherent superposition, so the process cannot in general be replaced by an ordinary probabilistic mixture of the two fixed orders [Chiribella et al., 2013]. Experiments of this kind are usually read as puzzles about a pre-existing causal ordering. This paper's reading instead treats them as systems in which a classical relational order has not yet fully emerged, a reinterpretation of the result discussed in Section 3.13 rather than a new prediction. It points to a genuinely unexplored question: whether decoherence, entropy production, and causal indefiniteness are systematically related. Finally, the internal consistency of relational time is a checkable technical question with a real history, not an untested assumption: the Page–Wootters mechanism of Section 3.10 was shown by Kuchař not to reproduce ordinary quantum mechanics correctly in its naive form [Kuchař, 1992], a criticism later addressed by a more careful construction [Giovannetti et al., 2015]. Each of these is a place where “time is relational” has already been, or could be, pushed past interpretation into a checkable claim.

A fourth line sits one level more abstract than the other three, because it does not point to an existing experiment or a known mathematical construction so much as to a question about why relativity's invariant conversion factors exist at all. The speed of light c , and by extension Planck's constant $\hbar$ and possibly Newton's constant G , are ordinarily taken as brute, given numbers, postulates rather than derived quantities. One way a reading like this one could sharpen that question, without claiming any experimental consequence, is to ask whether an invariant conversion factor is what a maximum rate looks like once translated into the language of distance and duration, specifically a maximum rate at which the relational structure developed in Section 3.1 and Appendix G can establish new physical distinctions. Not a maximum speed for objects moving through a pre-existing space: a maximum rate at which new correlations, of the kind Section 3.4 showed decoherence producing, can be established across that structure at all. Photons, massless and therefore always saturating that limit, would then be revealing the network's own limiting rate directly, rather than obeying an independently existing speed limit that happens to carry a fixed numerical value. This is deliberately not a claim that c varies from place to place: doing so would abandon the recovery of existing observations Section 6.1 insists on, and would enter a research program already pursued elsewhere, under considerably higher evidentiary standards, as varying-speed-of-light cosmology [Magueijo, 2003]. The original Albrecht–Magueijo proposal considered a larger early-universe value of c as a possible response to the horizon, flatness, and related cosmological puzzles [Albrecht and Magueijo, 1999]. The question

posed here is narrower and stays inside reinterpretation, not whether the number changes, but why a fixed conversion factor between distance and duration should exist at all, one further place where a relational reading could, in principle, be pushed past interpretation, exactly as the three lines above already are.

K. Jacobi's Principle: Duration from a Configuration-Space Path

Write $W(q) = E - V(q)$ and

$$T_\lambda = \frac{1}{2} \sum_i m_i (q'_i)^2, \quad q'_i = \frac{dq_i}{d\lambda}. \quad (53)$$

The Jacobi Lagrangian $L_J = 2\sqrt{WT_\lambda}$ is homogeneous of degree one in the velocities q'_i , so the action is invariant under monotonic changes of the arbitrary label λ . Its conjugate momenta are

$$p_i = \frac{\partial L_J}{\partial q'_i} = \sqrt{\frac{W}{T_\lambda}} m_i q'_i. \quad (54)$$

Defining

$$\frac{dt_J}{d\lambda} = \sqrt{\frac{T_\lambda}{W}} \quad (55)$$

therefore gives $p_i = m_i dq_i/dt_J$. The Euler–Lagrange equation becomes

$$\frac{dp_i}{dt_J} = -\frac{\partial V}{\partial q_i}, \quad (56)$$

which is Newton's equation expressed using the duration reconstructed along the path. The energy relation follows at once:

$$\frac{1}{2} \sum_i m_i \left(\frac{dq_i}{dt_J} \right)^2 + V = E. \quad (57)$$

Interpretation. The derivation does not eliminate ordering or the choice of a physical trajectory, and it assumes conservative fixed-energy dynamics. It does show that the numerical duration making the equations take their Newtonian form can be obtained from configuration change rather than supplied by an external flowing entity.

L. Mathematical Appendix: Where the Interpretation Meets the Equations

This appendix is not new physics. Every derivation below is standard, and every equation could be found, in some form, in a textbook. What it adds is explicit: after each derivation, a short paragraph marked **Interpretation** states exactly what this paper's reading adds on top of the bare mathematics, and what it does not.

L.1. Time Reversal and the Unitary Evolution Operator

For a time-independent Hamiltonian, the Schrödinger equation is

$$i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle = \hat{H} |\psi(t)\rangle. \quad (58)$$

Its formal solution is

$$|\psi(t)\rangle = \hat{U}(t, t_0)|\psi(t_0)\rangle, \quad (59)$$

$$\hat{U}(t, t_0) = \exp\left[-\frac{i}{\hbar}\hat{H}(t - t_0)\right]. \quad (60)$$

Hermiticity, $\hat{H}^\dagger = \hat{H}$, implies

$$\hat{U}^\dagger(t, t_0)\hat{U}(t, t_0) = \mathbb{1}, \quad \hat{U}^{-1}(t, t_0) = \hat{U}(t_0, t). \quad (61)$$

Equation 61 establishes invertibility. A final state may be evolved back to its initial state if the inverse operation can be implemented exactly.

Time-reversal symmetry is a separate statement. Let $\hat{T}$ be antiunitary, so that $\hat{T}i\hat{T}^{-1} = -i$. If

$$\hat{T}\hat{H}\hat{T}^{-1} = \hat{H}, \quad (62)$$

then

$$\hat{T}\hat{U}(t, t_0)\hat{T}^{-1} = \hat{U}(t_0, t). \quad (63)$$

For a spinless particle in a real scalar potential,

$$\psi_T(x, t) = \psi^*(x, -t) \quad (64)$$

is therefore a solution whenever $\psi(x, t)$ is a solution. Systems with spin or magnetic fields require the corresponding action of $\hat{T}$ on spin and momenta.

Interpretation. Unitary invertibility is general for a closed system with a Hermitian Hamiltonian. Time-reversal invariance additionally requires Equation 62. The paper applies the time-reversal claim only to dynamics satisfying that extra condition. Irreversible record formation is then attributed to reduced descriptions, environmental correlations, and boundary conditions rather than to failure of unitarity.

The weak interaction violates T individually, as confirmed in the neutral B -meson system [Lees et al., 2012]. The CPT theorem instead gives

$$(\widehat{CPT})\hat{H}(\widehat{CPT})^{-1} = \hat{H} \quad (65)$$

for a local Lorentz-invariant quantum field theory with a Hermitian Hamiltonian [Lüders, 1954]. This discrete symmetry statement does not decide whether time is fundamental.

L.2. The Reduced Density Matrix from the Partial Trace

For a joint pure state $|\Psi\rangle_{SE}$, the density operator is

$$\rho_{SE} = |\Psi\rangle\langle\Psi|. \quad (66)$$

Choose any orthonormal basis $\{|e_k\rangle\}$ for the environment. The reduced state of S is

$$\rho_S = \text{Tr}_E(\rho_{SE}) = \sum_k \langle e_k | \rho_{SE} | e_k \rangle. \quad (67)$$

For the entangled two-path state

$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|A\rangle|E_A\rangle + |B\rangle|E_B\rangle), \quad (68)$$

the joint density operator contains four terms:

$$\begin{aligned} \rho_{SE} = \frac{1}{2} & (|A\rangle\langle A| \otimes |E_A\rangle\langle E_A| + |B\rangle\langle B| \otimes |E_B\rangle\langle E_B| \\ & + |A\rangle\langle B| \otimes |E_A\rangle\langle E_B| + |B\rangle\langle A| \otimes |E_B\rangle\langle E_A|). \end{aligned} \quad (69)$$

Completeness of the environmental basis gives

$$\sum_k \langle e_k|E_A\rangle\langle E_B|e_k\rangle = \langle E_B|E_A\rangle. \quad (70)$$

Applying Equation 67 therefore yields

$$\begin{aligned} \rho_S = \frac{1}{2} & (|A\rangle\langle A| + |B\rangle\langle B| \\ & + \gamma|A\rangle\langle B| + \gamma^*|B\rangle\langle A|), \quad \gamma \equiv \langle E_B|E_A\rangle. \end{aligned} \quad (71)$$

The diagonal populations are unchanged. The off-diagonal coherence is multiplied by the environmental overlap γ .

Interpretation. The mathematics says only that ρ_S is the correct description of S alone, given that E is not being tracked. It does not, by itself, say anything about time or about weaving. The jersey language in Section 3.1 is a choice of vocabulary for $\langle E_B|E_A\rangle \rightarrow 0$ versus $\langle E_B|E_A\rangle \rightarrow 1$, not an additional physical claim. A reader who prefers to speak only of overlaps and never of stitches loses nothing from the physics by doing so.

L.3. Phase Averaging and a Limited Kuramoto Comparison

The Kuramoto model describes N classical phase oscillators,

$$\dot{\theta}_j = \omega_j + \frac{K}{N} \sum_{k=1}^N \sin(\theta_k - \theta_j), \quad (72)$$

with collective order parameter [Strogatz, 2000]

$$Re^{i\Phi} = \frac{1}{N} \sum_{j=1}^N e^{i\theta_j}, \quad 0 \leq R \leq 1. \quad (73)$$

Aligned phases give $R \simeq 1$. Widely dispersed phases give $R \simeq 0$.

A dephasing environment can produce the same complex average. Consider conditional environmental states

$$|E_A\rangle = \sum_j \sqrt{p_j} |j\rangle, \quad (74)$$

$$|E_B\rangle = \sum_j \sqrt{p_j} e^{i\phi_j} |j\rangle. \quad (75)$$

Their overlap is

$$\gamma = \langle E_B | E_A \rangle = \sum_j p_j e^{i\phi_j}. \quad (76)$$

For equal weights, Equation 76 has exactly the form of Equation 73. Aligned conditional phases give $|\gamma| \simeq 1$ and preserve interference. Dispersed phases give $|\gamma| \simeq 0$ and suppress the off-diagonal terms of Equation 71.

The comparison is mathematical, not dynamical. Increasing attractive coupling K in the Kuramoto model tends to synchronize phases and increase R . Increasing system–environment coupling commonly makes the conditional environmental states more distinguishable and decreases $|\gamma|$. The directions are therefore usually opposite. Moreover, $R \simeq 0$ is not by itself a classical world or a thermodynamic arrow. It represents phase dispersion. Classical records additionally require environmental entanglement, robust pointer states, redundancy, and suitable boundary conditions.

Interpretation. The Kuramoto order parameter gives a useful visual and mathematical analogy for phase cancellation. It should not be presented as a model from which quantum decoherence follows. Its value here is to show that a small macroscopic coherence measure can emerge from many individually well-defined phases without any single phase ceasing to evolve.

L.4. The Loschmidt Echo and Sensitivity to Perturbation

Let the attempted reversal use

$$\hat{H}' = \hat{H} + \delta\hat{H}. \quad (77)$$

The fidelity amplitude and Loschmidt echo are

$$m(t) = \langle \psi_0 | e^{i\hat{H}'t/\hbar} e^{-i\hat{H}t/\hbar} | \psi_0 \rangle, \quad (78)$$

$$M(t) = |m(t)|^2. \quad (79)$$

For short times, or when the perturbation may be treated as approximately constant in the interaction picture,

$$m(t) = 1 + \frac{it}{\hbar} \langle \delta\hat{H} \rangle - \frac{t^2}{2\hbar^2} \langle (\delta\hat{H})^2 \rangle + O(t^3). \quad (80)$$

Multiplying by the complex conjugate gives

$$M(t) = 1 - \frac{t^2}{\hbar^2} \text{Var}_{\psi_0}(\delta\hat{H}) + O(t^3), \quad (81)$$

where

$$\text{Var}_{\psi_0}(\delta\hat{H}) = \langle (\delta\hat{H})^2 \rangle - \langle \delta\hat{H} \rangle^2. \quad (82)$$

A constant shift of all energies changes only an overall phase and therefore does not reduce the echo. This is why the variance, rather than $\langle (\delta\hat{H})^2 \rangle$ alone, appears.

Interpretation. This is the precise sense in which “reversibility in principle, irreversibility in practice” is not a hand-wave: the decay of $M(t)$ measures the mismatch in an attempted reversal. At $\delta\hat{H} = 0$, Equation 79 gives $M(t) = 1$. Coupling to an uncontrolled environment enlarges the Hamiltonian that must be reversed and makes exact control practically inaccessible. The echo quantifies that loss of control. It does not introduce a new irreversible law.

L.5. Stationary Phase and the Principle of Least Action

Write a path with fixed endpoints as

$$x(t) = x_{\text{cl}}(t) + \eta(t), \quad \eta(t_A) = \eta(t_B) = 0. \quad (83)$$

The functional Taylor expansion of the action is

$$\begin{aligned} S[x_{\text{cl}} + \eta] &= S[x_{\text{cl}}] + \int dt \left. \frac{\delta S}{\delta x(t)} \right|_{x_{\text{cl}}} \eta(t) \\ &+ \frac{1}{2} \int dt dt' \eta(t) K(t, t') \eta(t') + O(\eta^3), \end{aligned} \quad (84)$$

where

$$K(t, t') = \left. \frac{\delta^2 S}{\delta x(t) \delta x(t')} \right|_{x_{\text{cl}}}. \quad (85)$$

The classical path satisfies the Euler–Lagrange equation, which is the stationarity condition

$$\left. \frac{\delta S}{\delta x(t)} \right|_{x_{\text{cl}}} = 0. \quad (86)$$

The linear term in Equation 84 therefore vanishes. To quadratic order, the propagator becomes

$$\langle B|A \rangle \simeq e^{iS[x_{\text{cl}}]/\hbar} \int \mathcal{D}\eta \exp \left[\frac{i}{2\hbar} \int dt dt' \eta(t) K(t, t') \eta(t') \right]. \quad (87)$$

Paths for which the action varies rapidly acquire phases that cancel under integration. Paths near a stationary point have slowly varying phase and add coherently. In the semiclassical limit, the leading phase is therefore set by $S[x_{\text{cl}}]$.

Interpretation. This derivation is Feynman’s own, standard in any path-integral textbook. What Section 3.9 adds is reading the pre-classical, finite- $\hbar$ regime, where many non-classical paths still interfere, through the standing-wave image: a physical picture of what “not yet settled to the classical path” looks like, built from ordinary wave interference rather than from the abstract functional integral directly.

L.6. The Wheeler–DeWitt Constraint from Canonical Gravity

The ADM line element is

$$ds^2 = -N^2 c^2 dt^2 + h_{ij} (dx^i + N^i dt) (dx^j + N^j dt). \quad (88)$$

The spatial metric h_{ij} and its conjugate momentum π^{ij} are the canonical variables. The lapse N and shift N^i are Lagrange multipliers. The Hamiltonian has the constrained form

$$H_{\text{ADM}} = \int d^3x \left(N \mathcal{H} + N^i \mathcal{H}_i \right), \quad (89)$$

and variation with respect to the multipliers gives

$$\mathcal{H}(x) = 0, \quad \mathcal{H}_i(x) = 0. \quad (90)$$

The constraints generate gauge transformations, including changes of spatial coordinates and foliation. They do not imply that general relativity has no physical degrees of freedom. After gauge freedom and constraints are accounted for, two local gravitational degrees of freedom remain.

Canonical quantization formally replaces

$$\pi^{ij}(x) \longrightarrow -i\hbar \frac{\delta}{\delta h_{ij}(x)}. \quad (91)$$

The Hamiltonian constraint becomes the Wheeler–DeWitt equation

$$\hat{\mathcal{H}}(x)\Psi[h_{ij}, \text{matter}] = 0. \quad (92)$$

There is no external Schrödinger parameter on the right-hand side.

In the Page–Wootters construction, a simplified total constraint is

$$(\hat{H}_C + \hat{H}_R)|\Psi\rangle = 0. \quad (93)$$

Conditioning on a clock reading t defines

$$|\psi_R(t)\rangle \propto {}_C\langle t|\Psi\rangle. \quad (94)$$

For an ideal clock satisfying the required covariance conditions, the conditional state obeys

$$i\hbar \frac{\partial}{\partial t} |\psi_R(t)\rangle = \hat{H}_R |\psi_R(t)\rangle. \quad (95)$$

Interpretation. The absence of an external t in Equation 92 is a consequence of the constraint structure, not proof that physical change disappears. Page–Wootters shows how one internal degree of freedom can index another. The recovery of Equation 95 requires an adequate clock and appropriate coupling assumptions. Shape Dynamics then makes a different gauge trade at the classical level. Whether either formalism is closer to physical reality remains an interpretive question.

L.7. The Static-Observer Proper Acceleration and Gravitational Redshift

The Schwarzschild metric is

$$ds^2 = -\left(1 - \frac{r_s}{r}\right) c^2 dt^2 + \frac{dr^2}{1 - r_s/r} + r^2 d\Omega^2, \quad r_s = \frac{2GM}{c^2}. \quad (96)$$

A static observer has $dr = d\Omega = 0$. Equation 96 then gives the redshift factor

$$d\tau = \sqrt{1 - \frac{r_s}{r}} dt. \quad (97)$$

The four-velocity is

$$u^\mu = (u^t, 0, 0, 0), \quad u^t = \frac{dt}{d\tau} = \frac{1}{\sqrt{1 - r_s/r}}. \quad (98)$$

Its four-acceleration is

$$a^\mu = u^\nu \nabla_\nu u^\mu. \quad (99)$$

Only the radial component is nonzero. Using

$$\Gamma_{tt}^r = \frac{1}{2} \left(1 - \frac{r_s}{r}\right) \frac{r_s c^2}{r^2}, \quad (100)$$

one obtains

$$a^r = \Gamma_{tt}^r (u^t)^2 = \frac{r_s c^2}{2r^2} = \frac{GM}{r^2}. \quad (101)$$

The coordinate component a^r is not the proper magnitude. Since $g_{rr} = (1 - r_s/r)^{-1}$,

$$a = \sqrt{g_{rr}} |a^r| = \frac{GM}{r^2 \sqrt{1 - r_s/r}}. \quad (102)$$

Combining Equations 97 and 102 gives

$$a \frac{d\tau}{dt} = \frac{GM}{r^2}. \quad (103)$$

This is a standard Schwarzschild result [Hartle, 2003].

Interpretation. The identity $a\sqrt{1 - r_s/r} = GM/r^2$ is unmodified general relativity. What Section 4.3 adds is reading the two factors together, resistance to deviating from free fall on one side, gravitational redshift on the other, as two faces of a single underlying fact rather than two separate coincidences of the metric. This reading applies specifically to a static observer. Freely falling observers can accumulate different proper times along different geodesics without any local proper acceleration. Equation 103 must therefore not be promoted into a general causal explanation of gravitational time dilation.

L.8. The ABL Rule and Weak Values from Two-Time Boundary Conditions

Consider a system prepared in $|\psi\rangle$ at t_0 , evolving freely to an intermediate time t , measured there with projectors $\{\hat{P}_k\}$, then evolving freely again to t_1 , and postselected in $|\phi\rangle$. The amplitude for intermediate outcome k and final outcome ϕ is

$$\mathcal{A}_k = \langle\phi|\hat{U}(t_1, t)\hat{P}_k\hat{U}(t, t_0)|\psi\rangle. \quad (104)$$

The corresponding joint probability is

$$P(k, \phi|\psi) = |\mathcal{A}_k|^2. \quad (105)$$

Conditioning on successful postselection gives

$$P(k|\psi, \phi) = \frac{|\mathcal{A}_k|^2}{\sum_j |\mathcal{A}_j|^2}. \quad (106)$$

If the freely evolved boundary states at time t are denoted by

$$|\psi(t)\rangle = \hat{U}(t, t_0)|\psi\rangle, \quad (107)$$

$$\langle\phi(t)| = \langle\phi|\hat{U}(t_1, t), \quad (108)$$

then Equation 106 becomes the ABL rule in Equation 43.

For a weak measurement of observable $\hat{A}$, the weak value is

$$A_w = \frac{\langle\phi(t)|\hat{A}|\psi(t)\rangle}{\langle\phi(t)|\psi(t)\rangle}. \quad (109)$$

To first order in a weak system–pointer coupling, the average pointer position shifts in proportion to $\text{Re } A_w$. The conjugate pointer momentum responds to $\text{Im } A_w$.

Interpretation. Every step above is conditional probability theory applied twice, once forward from t_0 and once backward from t_1 , and nothing in the derivation requires that the future boundary condition *cause* anything. Section C.2’s retrocausal reading adds a claim about physical reality: that the later boundary condition genuinely constrains rather than merely conditions, layered on top of a derivation that works identically either way. The mathematics in this subsection is silent on which reading is correct.

L.9. The CHSH Bound and Its Quantum Violation

For a locally causal deterministic hidden-variable model, let $A(a, \lambda)$ and $B(b, \lambda)$ take values ± 1 . For each value of λ , define

$$S_\lambda = A(a, \lambda)B(b, \lambda) + A(a, \lambda)B(b', \lambda) + A(a', \lambda)B(b, \lambda) - A(a', \lambda)B(b', \lambda). \quad (110)$$

Factorizing gives

$$S_\lambda = A(a, \lambda)[B(b, \lambda) + B(b', \lambda)] + A(a', \lambda)[B(b, \lambda) - B(b', \lambda)]. \quad (111)$$

Because $B = \pm 1$, one bracket is zero and the other is ± 2 . Therefore

$$|S_\lambda| = 2. \quad (112)$$

Averaging over a normalized distribution $\rho(\lambda)$ gives

$$|S| = \left| \int d\lambda \rho(\lambda) S_\lambda \right| \leq 2. \quad (113)$$

For the spin singlet, quantum mechanics predicts

$$E(\mathbf{a}, \mathbf{b}) = -\mathbf{a} \cdot \mathbf{b}. \quad (114)$$

Choosing coplanar settings separated by the standard angles 0 , $\pi/2$, $\pi/4$, and $-\pi/4$ gives

$$|S| = 2\sqrt{2}. \quad (115)$$

Interpretation. The derivation fixes what a relational reading may and may not change. It may question whether spatially localized objects are the most basic physical entities. It may not remove the factorization assumption silently, alter the observed correlations, or permit signalling. Any deeper model must still recover Equations 113 and 115 in their respective domains.

L.10. Fourier Derivation for Two Slits in Time

Define the Fourier transform by

$$\tilde{g}(\omega) = \int_{-\infty}^{\infty} dt g(t) e^{i\omega t}. \quad (116)$$

For two identical temporal windows separated by τ ,

$$A(t) = g(t + \tau/2) + g(t - \tau/2). \quad (117)$$

The Fourier shift theorem gives

$$\tilde{A}(\omega) = e^{-i\omega\tau/2}\tilde{g}(\omega) + e^{i\omega\tau/2}\tilde{g}(\omega) \quad (118)$$

$$= 2\tilde{g}(\omega) \cos(\omega\tau/2). \quad (119)$$

The spectral intensity is therefore

$$I(\omega) = |\tilde{A}(\omega)|^2 = 4|\tilde{g}(\omega)|^2 \cos^2(\omega\tau/2). \quad (120)$$

The fringe spacing follows from adjacent maxima:

$$\Delta\omega = \frac{2\pi}{\tau}. \quad (121)$$

The same derivation for two spatial apertures separated by d gives $\Delta k_x = 2\pi/d$.

Interpretation. The temporal experiment tests wave interference between two interaction windows. The derivation requires neither backward time travel nor a universal time operator. It demonstrates that separation in a clock parameter can enter an interference phase in the same way that spatial separation enters a transverse-wave-vector phase.

L.11. Mach-Zehnder Interferometer in Matrix Form

Use the path basis

$$|1\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad |2\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \quad (122)$$

and the beam-splitter convention

$$\hat{B} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix}. \quad (123)$$

The first beam splitter produces

$$\hat{B}|1\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ i \end{pmatrix} = \frac{|1\rangle + i|2\rangle}{\sqrt{2}}. \quad (124)$$

With phases adjusted so that the two arms recombine destructively at the dark port,

$$\hat{B}^2|1\rangle = \frac{1}{2} \begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix} \begin{pmatrix} 1 \\ i \end{pmatrix} \quad (125)$$

$$= \begin{pmatrix} 0 \\ i \end{pmatrix}. \quad (126)$$

Thus one output is dark in the absence of the object.

An ideal absorbing object in arm 2 defines two branches. Absorption occurs with probability

$$P(\text{absorb}) = \frac{1}{2}. \quad (127)$$

Conditional on no absorption, the path state is $|1\rangle$. The second beam splitter then gives

$$\hat{B}|1\rangle = \frac{|1\rangle + i|2\rangle}{\sqrt{2}}, \quad (128)$$

so the conditional probabilities of the two detectors are both $1/2$. Multiplying by the survival probability gives

$$P(D_{\text{dark}}) = \frac{1}{2} \times \frac{1}{2} = \frac{1}{4}. \quad (129)$$

L.12. The Zeno-Enhanced Interferometer

Let

$$\hat{R}(\theta) = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix}, \quad \theta = \frac{\pi}{2N}. \quad (130)$$

Without an object,

$$\hat{R}(\theta)^N = \hat{R}(N\theta) = \hat{R}\left(\frac{\pi}{2}\right). \quad (131)$$

With an absorbing object monitoring the rotated component, survival at one stage has probability

$$p_1 = \cos^2\left(\frac{\pi}{2N}\right). \quad (132)$$

Survival through all N stages is

$$P_N = \left[\cos^2\left(\frac{\pi}{2N}\right) \right]^N. \quad (133)$$

Using $\cos^2 x = 1 - x^2 + O(x^4)$,

$$P_N \simeq \left(1 - \frac{\pi^2}{4N^2} \right)^N \simeq 1 - \frac{\pi^2}{4N}, \quad (134)$$

$$P_{\text{abs}} = 1 - P_N \simeq \frac{\pi^2}{4N} \longrightarrow 0. \quad (135)$$

The limiting success is a consequence of repeated conditional evolution, not of a classical trajectory that avoids the object.