

# Time Symmetry, Quantum Correlations, and the Open Present

## A Dissertation on Retrocausality, Measurement Independence, and the Block Universe

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### Synopsis

*Fundamental dynamical laws in physics largely respect time-reversal symmetry, yet everyday experience presents a directed "arrow of time". This dissertation examines the tension between these two facts through the lens of quantum theory, focusing on Bell nonlocality, the measurement-independence (freedom-of-choice) assumption, delayed-choice interferometry, and modern "loophole-free" tests. It then evaluates two broad strategies for reconciling quantum correlations with relativistic causal structure: superdeterminism and retrocausality. The discussion integrates influential interpretive frameworks, including the transactional interpretation and the two-state vector formalism, alongside philosophical arguments that attempt to derive retrocausality from time symmetry plus the discreteness of quantum outcomes. The dissertation then turns to the block-universe picture suggested by relativity and explores what, if anything, follows for agency, deliberation, regret, and the phenomenology of temporal passage. Throughout, experimental claims receive scrutiny, especially those commonly associated with delayed-choice "quantum eraser" set-ups, which frequently become overstated in popular treatments. The dissertation closes with an assessment of the present research landscape and the standards required for retrocausality to move from interpretive preference to empirically differentiable physics.*

### Introduction

Time enters physics in two markedly different ways. In the formalism of classical and quantum dynamics, time often functions as a parameter governing reversible equations of motion, such that reversing velocities or taking complex conjugates can recover equally valid trajectories. In thermodynamics and statistical mechanics, time enters through asymmetric boundary conditions and entropy gradients that underpin irreversibility in practice. This divide fuels a long-standing problem: the laws appear broadly time-symmetric, while lived experience and macroscopic phenomena appear time-directed.

Quantum mechanics sharpens the puzzle by combining time-symmetric unitary evolution with measurement outcomes that register as discrete, irreversible records. Bell's theorem then adds a further pressure point by showing that quantum correlations exceed the limits of any

theory satisfying locality and realism, when paired with an assumption that measurement settings remain statistically independent of hidden variables (Bell, 1964). Subsequent experiments, from the 1980s to 2015 and beyond, have repeatedly confirmed violations of Bell inequalities in regimes designed to close classical “loopholes” (Aspect et al., 1982; Hensen et al., 2015; Shalm et al., 2015). These results motivate a re-examination of the assumptions underwriting Bell’s derivation, especially measurement independence.

This paper investigates whether time symmetry plus the structure of quantum outcomes makes retrocausality a serious candidate, or whether it remains an interpretive overlay without new empirical content. It also evaluates frequent claims that delayed-choice or quantum-eraser experiments prove that “the future changes the past”, contrasting these claims with what the experiments strictly warrant (Kim et al., 2000).

## **Time Symmetry and the Arrow of Time**

Many core dynamical laws exhibit time-reversal invariance under appropriate transformations. This includes classical mechanics and Maxwellian electrodynamics in their idealised forms, and the unitary dynamics of nonrelativistic quantum theory governed by the Schrödinger equation. Time symmetry at this level does not imply that all physical processes look the same forward and backward in practice. It implies that the dynamical rules do not, by themselves, single out a preferred temporal direction.

A standard response locates the arrow of time in boundary conditions. Thermodynamic irreversibility arises because the universe began in an extraordinarily low-entropy macrostate, a condition often called the “Past Hypothesis” in contemporary philosophy of physics. The point here does not concern whether entropy increases, but why it does so in the direction we label “future” rather than “past”. The Past Hypothesis provides a way to treat macroscopic time asymmetry as contingent rather than fundamental. This distinction matters because it shifts explanatory burden. On this view, time symmetry belongs to the dynamical default, while macroscopic arrows require special initial conditions.

The significance for quantum foundations comes from scale. If thermodynamic arrows depend on large ensembles and strong entropy gradients, then at microscopic scales the rationale for privileging forward temporal direction weakens. That weakening does not prove retrocausality. It motivates a careful audit of which asymmetries belong to laws and which belong to boundary conditions, coarse-graining, or epistemic limitations.

## **Bell’s Theorem and What Experiments Establish**

Bell's theorem demonstrates that no theory satisfying both locality and realism can reproduce all the statistical predictions of quantum mechanics, given the auxiliary assumptions used in the derivation, including measurement independence (Bell, 1964). The theorem's operational heart lies in an inequality, such as the CHSH form, constraining correlations that any locally realistic model can produce.

Experiments beginning in the early 1980s provided strong evidence that nature violates Bell inequalities. Aspect's experiments in 1981–1982, including fast switching of measurement settings while photons were in flight, significantly strengthened the case by addressing locality-style concerns about subluminal coordination (Aspect et al., 1982). Later experiments improved detector efficiencies and timing constraints.

A major milestone arrived in 2015, when multiple groups reported Bell tests engineered to close the detection and locality loopholes in a single set-up. The Delft experiment used entanglement between electron spins in diamond separated by 1.3 km and reported a Bell violation with a modest p-value (Hensen et al., 2015). Two further high-profile experiments used entangled photons with high-efficiency detectors, reporting extremely strong statistical significance (Shalm et al., 2015). These results jointly support a clear conclusion: the conjunction of locality and realism cannot be maintained under the standard assumptions of Bell's framework in a way that reproduces observed correlations.

The interpretive question remains open because the data underdetermine which premise fails. One can deny locality, deny realism, deny measurement independence, or revise other structural assumptions about how probabilities map to physical states.

### **Measurement Independence and the "Freedom-of-Choice" Loophole**

Measurement independence asserts that the variables characterising the system prior to measurement remain statistically independent of the choice of measurement settings. In Bell's framework, this independence underpins the derivation of Bell inequalities. If the hidden variables and the settings correlate, the derivation can fail even if locality and realism hold.

A striking attempt to constrain this loophole uses cosmological sources to determine measurement settings, pushing any would-be correlation back into deep cosmic history. One well-known approach uses distant astronomical photons to select settings, aiming to exclude large portions of the relevant spacetime region as a locus of common-cause coordination. A prominent implementation used light from distant quasars to choose settings in real time, thereby restricting how recently any hypothetical local mechanism could have coordinated hidden variables with detector choices (Handsteiner et al., 2017). The technical upshot does

not settle the matter. It raises the cost of measurement-dependence explanations by relocating any coordinating correlation far into the past.

Two broad explanatory families violate measurement independence in conceptually opposite directions.

Superdeterminism posits that correlations between settings and hidden variables arise from shared causal ancestry traced back to the universe's initial conditions. Retrocausality posits that settings chosen in the present influence hidden variables in the past, producing correlations without superluminal signalling.

Both options can preserve locality at the cost of disturbing standard intuitions. They differ sharply in their impact on scientific methodology.

### **Superdeterminism and the Epistemic Cost to Experiment**

Superdeterminism holds conceptual appeal for those who wish to preserve relativistic locality while maintaining determinate underlying states. It also confronts a severe methodological objection. If any observed correlation can be attributed to an all-encompassing coordination between experimental choices and system variables, then the ordinary inference from controlled intervention to causal structure becomes fragile. In its strongest forms, superdeterminism threatens to collapse the distinction between genuine causal dependence and pre-established harmony.

This objection appears repeatedly in the literature, including in statements by experimentalists emphasising the practical necessity of treating setting choices as free variables for the purpose of scientific inquiry. The worry does not target determinism as such. It targets a global conspiratorial structure that can emulate any experimental pattern while remaining insulated from refutation. A framework that renders all results compatible with hidden coordination risks becoming empirically inert.

The force of the objection becomes vivid in cosmological-setting experiments. If measurement settings derive from quasar photons emitted billions of years ago, a superdeterministic story must claim that the initial state of the universe arranged correlations among distant sources, terrestrial experimental decisions, and the microphysical variables of the measured systems in a coordinated way that survives independent replication across decades and platforms. Cosmological Bell tests increase the implausibility of ad hoc coordination while not logically excluding it.

For these reasons, many discussions treat superdeterminism as logically possible but methodologically corrosive. That assessment functions as a critique, not a proof of falsity.

### **Retrocausality as a Local Alternative**

Retrocausality offers a different route to measurement dependence. Instead of correlating settings and hidden variables by shared past causes, retrocausality correlates them by allowing influences from future measurement settings to constrain earlier hidden-variable states. The attraction lies in the possibility of preserving locality by permitting causal influence along timelike paths that run backwards for one leg of an explanation, producing an effective “zigzag” through spacetime.

This zigzag proposal has historical antecedents in mid-20th-century attempts to reconcile entanglement with relativity. It also aligns naturally with time-symmetric formulations of physics and with approaches that treat both initial and final boundary conditions as jointly constraining physical histories.

Retrocausality does not imply macroscopic time travel. It aims to preserve the no-signalling constraints of standard quantum mechanics, preventing controllable backward-in-time communication. The relevant influences remain “hidden” in the sense that they shape underlying variables and correlations without enabling engineered signalling to the past.

As a critique, one may ask whether retrocausality merely relocates nonclassical structure into an inaccessible domain, keeping the observable predictions unchanged. If so, retrocausality risks becoming interpretive bookkeeping unless it yields testable differences or yields decisive theoretical unifications unavailable to forward-causal models.

### **Delayed Choice, Interferometry, and What Is Actually Shown**

Wheeler’s delayed-choice thought experiments highlight the dependence of interference phenomena on measurement context, even when measurement choices occur after a particle enters an interferometric apparatus. The canonical message: quantum behaviour resists classical narratives in which a system carries definite path properties independent of later measurement arrangement.

A key critique concerns what delayed choice does and does not establish. Delayed-choice set-ups demonstrate that quantum outcomes depend on the total experimental configuration and that naïve realist path assignments fail. They do not, by themselves, compel backward-in-time causation. Interpretations that deny definite pre-measurement properties can

accommodate these results without retrocausal influence, treating the question “which path did it take?” as ill-posed until measurement context is fixed.

The delayed-choice quantum eraser becomes an even more frequent target of exaggeration. In the landmark experiment by Kim, Scully and collaborators, coincidence counting reveals interference fringes in conditional subensembles correlated with “which-path erased” idler detections, while the unconditioned signal distribution displays no interference (Kim et al., 2000). This matters because the presence of interference depends on post-selection: one filters the data using correlations with outcomes registered elsewhere. The total signal pattern does not display a retroactively “restored” interference across all events.

The most defensible reading treats the quantum eraser as revealing how entanglement distributes coherence and how conditioning on correlated outcomes can uncover interference in subensembles, without implying that a past macroscopic record changes. Claims that these experiments “prove the past changes” overstate what the statistics entail. This critique does not deny that retrocausality remains possible. It denies that delayed-choice quantum erasers establish it uniquely.

### **The Transactional Interpretation**

The transactional interpretation proposes a time-symmetric account of quantum processes using both forward and backward solutions. In Cramer’s formulation, emitters generate “offer waves” and absorbers generate “confirmation waves”, with a completed “transaction” arising from a standing-wave handshake across spacetime (Cramer, 1986). The formal aim involves reinterpreting collapse as a global consistency condition, rather than as a mysterious instantaneous update.

As an evaluation, the transactional approach can appear conceptually clarifying because it makes explicit use of time-symmetric structures that classical electromagnetic theory already tolerates in certain absorber-style treatments. It can also appear metaphysically heavy because it adds a distinct ontology of advanced and retarded waves and treats the completed transaction as the primitive event. Extensions into relativistic contexts have been developed in later work, treating transactions as the basic ontological units from which particle-like phenomena emerge (Kastner, 2013).

A central critique concerns empirical equivalence. If the interpretation reproduces standard quantum predictions without adding distinguishing tests, then its status remains interpretive rather than confirmatory. Still, interpretive work can count as scientific progress if it unifies domains, resolves conceptual tensions, or clarifies how locality and covariance may coexist

with quantum statistics.

## **The Two-State Vector Formalism and Weak Values**

The two-state vector formalism (TSVF) describes quantum systems between preparation and measurement using both a forward-evolving state from preparation and a backward-evolving state from post-selection. The framework gives a mathematically precise way to treat pre- and post-selected ensembles symmetrically. This approach underpins the concept of weak values, quantities obtained from weak measurements on such ensembles that can lie outside eigenvalue ranges.

Weak values have a well-established mathematical basis, and they have generated extensive experimental and theoretical work. The conceptual controversy concerns what weak values represent. Some accounts treat them as merely statistical features of conditioned ensembles, while others treat them as revealing something ontological about systems between measurements. TSVF becomes relevant to retrocausality because it places future measurement outcomes in the formal description of intermediate states, encouraging a picture where future boundary conditions constrain earlier descriptions.

A critique here targets interpretive inflation. A formalism that conditions on future outcomes does not automatically entail physical backward causation. It entails that conditional descriptions depend on both endpoints, which can be read epistemically or ontologically. Whether TSVF supports retrocausality depends on additional commitments about the status of the state vectors and the nature of hidden variables.

## **Philosophical Arguments for Retrocausality from Time Symmetry**

A prominent philosophical route argues that time symmetry plus the discreteness of quantum outcomes makes retrocausality natural or even unavoidable, if one also maintains a realist stance about underlying states. An influential formulation contends that physicists often cite thermodynamic asymmetry to justify forward-causal interpretations, but that thermodynamic asymmetry itself arises from contingent boundary conditions, not from fundamental dynamics. On this view, importing macroscopic causal intuition into microscopic quantum processes lacks justification.

This line of argument has been formalised in work connecting time symmetry and quantisation, emphasising that classical continuous states permit time-symmetric stories without backward constraints, while quantum discreteness restricts those stories. A key question then becomes whether one can preserve time symmetry in an “ontological” model

while maintaining certain screening-off conditions without admitting retrocausal dependence.

### **The Leifer–Pusey Result and the Status of a “Retrocausal Theorem”**

Leifer and Pusey ask whether a time-symmetric interpretation of quantum theory remains possible without retrocausality under a set of modelling assumptions, including a screening-off condition on hidden variables (Leifer and Pusey, 2017). Their analysis strengthens the sense that, given particular commitments, retrocausality is not merely a narrative preference but a structural consequence.

This is not a universal proof that nature is retrocausal. It is a theorem about classes of models: if one insists on time symmetry in a certain ontological sense and accepts certain causal-structural assumptions, then retrocausality follows. The critique is therefore targeted. One can reject time symmetry in the relevant ontological form, reject the screening-off condition, reject hidden variables, or adopt a wavefunction-realist ontology that avoids the relevant constraints. The significance lies in making clear that retrocausality can become forced inside certain modelling frameworks rather than remaining a stylistic gloss.

The appropriate evaluation treats such results as narrowing the space of options. They clarify which combinations of desiderata cohere and which do not. They do not, on their own, pick out a unique ontology.

### **Relativity, the Block Universe, and the Non-Universality of “Now”**

Special relativity provides a powerful reason to treat the present as observer-dependent. If simultaneity varies across inertial frames, there is no global foliation of spacetime into universal “nows” that all observers share. Minkowski’s 1908 address famously expresses the unification of space and time into spacetime as a physical consequence rather than a philosophical taste (Minkowski, 1908). This supports a block-universe or eternalist picture in which past, present, and future events all reside within a four-dimensional structure.

Einstein’s letter after the death of a close friend has often been quoted in this context, emphasising the persistence of the past, present, and future distinction as an illusion for those committed to physics (Einstein, 1955). Whatever the emotional context, the philosophical thrust aligns with relativity’s denial of a universal present.

A critique of block-universe rhetoric targets an equivocation. From the fact that no universal simultaneity exists, it does not straightforwardly follow that time does not “pass” in any sense, or that temporal becoming is entirely illusory. It follows that becoming cannot correspond to

a global, frame-independent physical slicing of spacetime. Philosophers of physics disagree on how much metaphysics one can extract from relativity alone.

### **Agency and the Phenomenology of Choice in a Block Picture**

Even if the block picture holds, it does not automatically eliminate agency. One can treat deliberation as a physical process within spacetime that produces decisions. On this view, agency is not an intervention from outside physics. It is part of the physical architecture. The question changes from “Do choices exist?” to “In what sense do choices remain open?”

Ismael develops a compatibilist-friendly approach that reframes freedom in terms of the internal organisation of deliberating systems, rather than in terms of metaphysical openness of the future (Ismael, 2016). A key evaluative point follows. If deliberation is itself a causal process in the world, then agency can remain real, even if the outcomes of deliberation sit fixed within a completed spacetime history.

Callender emphasises that the conflict between manifest time and physical time can be understood by examining how cognitive architecture and evolutionary pressures shape temporal experience, including the feeling of passage (Callender, 2017). This supports a naturalistic account of why “now” feels privileged and why time feels like a flow, regardless of whether fundamental physics contains a moving present.

The critique here targets overreach. One should not infer that because temporal experience can be explained naturalistically, it therefore lacks all metaphysical significance. A psychological genealogy of an experience can coexist with the claim that the experience tracks some real structure. The point remains that relativity constrains what that structure can be.

### **Retrocausality Inside a Block Universe**

Retrocausality meshes smoothly with block-universe thinking because both treat boundary conditions as globally constraining. If the spacetime structure is fixed as a whole, then causal explanations that refer only to past-to-future propagation may represent a perspective-bound storytelling device rather than a fundamental asymmetry.

Lagrangian and variational principles provide a useful analogy. In classical mechanics, Hamilton’s principle can be formulated using boundary conditions and action extremisation. One can describe the path as “selected” by a global constraint rather than generated step-by-step from initial conditions alone. In such a view, a retrocausal influence becomes less like an

intervention travelling backward and more like a constraint relation spanning the temporal extent of a process.

The major critique concerns explanatory gain. A block plus retrocausality can risk becoming a redescription of consistency: events cohere globally, so any local slice must match the whole. That can feel like explaining correlations by asserting global consistency. The standard defence insists that global constraints can have explanatory power when paired with specific mathematical structures that limit possible histories and recover observed statistics without superluminal influence.

### **The Delayed-Choice Quantum Eraser in Popular Narratives**

A recurring pattern in public-facing discussions treats the delayed-choice quantum eraser as proving that future interventions change an earlier, already-registered outcome. The rigorous assessment points in a narrower direction. The decisive phenomenon involves correlations revealed by coincidence counting, not a macroscopic rewriting of a recorded past. The unconditioned distribution lacks interference, while conditional subensembles can show fringes (Kim et al., 2000). This result warrants claims about entanglement and conditional statistics. It does not warrant claims that a past classical record transforms under later choices.

This critique matters because it separates two questions. One asks whether quantum theory permits retrocausal models consistent with no-signalling and relativity. Another asks whether specific experiments force such models. Overstatement about the second question can discredit serious inquiry into the first.

### **Penrose, Objective Reduction, and Quantum Measurement**

Penrose has argued that standard quantum theory's measurement postulate reflects an incomplete understanding, and he proposed objective reduction schemes in which collapse occurs when a superposition reaches a threshold associated with gravitational effects. This position appears in popular and technical writings and is frequently discussed alongside consciousness-related proposals (Penrose, 1994). A careful evaluation distinguishes the core gravitational-collapse idea from additional hypotheses that attempt to link such collapse to cognitive processes.

Objective reduction models aim to preserve an observer-independent trigger for collapse, which in turn can stabilise macroscopic classicality without appealing to ill-defined "measurement" primitives. The critique remains that objective-collapse theories must supply clear dynamical rules and match all established quantum results. Many variants exist, and the

experimental landscape remains active in testing departures from unitary evolution in mesoscopic regimes.

Claims that delayed-choice and quantum-eraser experiments directly prove “the past changes” do not become more secure under objective reduction. They remain constrained by the same statistical structure of post-selection and no-signalling. Objective reduction can change the story about when collapse occurs, not necessarily the story about whether later measurement choices rewrite an already-fixed macroscopic past.

### **The Contemporary Research Landscape and the Demand for Distinguishing Predictions**

Retrocausality occupies a position that is neither fringe fantasy nor settled orthodoxy. It persists as a research programme spanning physics and philosophy, with multiple technical approaches exploring time symmetry, boundary conditions, and causal modelling. Work on loophole-free Bell tests continues to refine empirical constraints on local realist pictures, while philosophical analyses continue to clarify which assumptions remain negotiable.

The decisive step for retrocausality would involve either (a) a fully worked theory that reproduces quantum mechanics across domains while providing a clearer reconciliation with relativity and perhaps quantum gravity, or (b) a set of experimentally distinguishable predictions that differ from standard quantum mechanics under testable conditions. Until such predictions mature and experiments adjudicate them, retrocausality remains best regarded as a theoretically motivated interpretive and model-building framework rather than an empirically established feature of nature.

At the same time, the conceptual work has value even under empirical equivalence. If retrocausal models can preserve locality without superdeterministic epistemic collapse, and if they can offer a clean account of Bell correlations under relativistic constraints, they could provide genuine progress in the foundations, even before decisive experimental separation.

### **Conclusion**

Time symmetry in fundamental dynamics and time asymmetry in experience generate a deep structural tension. Quantum theory intensifies this tension by placing irreversible measurement outcomes atop reversible unitary evolution, while Bell’s theorem and its experimental confirmations pressure classical assumptions about locality and realism. Measurement independence emerges as a pivotal assumption. If it fails, locality can be preserved through either superdeterminism or retrocausality. Superdeterminism carries a substantial methodological cost, threatening the reliability of experimental inference.

Retrocausality promises locality-preserving explanations without the same degree of epistemic sabotage, but it must confront challenges of empirical distinctiveness and explanatory non-triviality.

Delayed-choice and quantum-eraser experiments, when treated carefully, do not straightforwardly establish retrocausality. They establish context-dependence and conditional correlations grounded in entanglement and post-selection. Retrocausal interpretations remain possible, but they are not uniquely forced by these demonstrations.

Relativity supports a block-universe-friendly picture by undermining a universal present, while philosophical accounts of agency and temporal experience suggest that deliberation and choice can remain real as physical processes even within a fixed spacetime structure. Retrocausality integrates naturally with block-universe reasoning, framing quantum events as globally constrained by both preparation and measurement boundary conditions.

The open scientific question concerns whether retrocausality can be elevated from a coherent and potentially unifying stance to an empirically discriminable framework. The bar for that elevation remains high. Meeting it would sharpen what physics says about causation, time, and the lived sense of an open present.

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