# TBCN-P: TEMPORAL BOUNDARY-CONDITION NETWORKS WITH POSTSELECTED RETROCAUSAL CHANNELS

*A detailed scientific and theoretical framework for conditional future-to-past communication, capacity, falsification, and three buildable experimental platforms*

Revision: 5 September 2026

Scientific status: speculative/conditional theory with experimentally testable consequences. This manuscript adopts the working premise that published evidence supportive of retrocausal descriptions is valid evidence for retrocausal structure. It does not equate postselected simulations with a demonstrated physical time machine. A true past-directed information channel is claimed only if an earlier sealed record becomes statistically informative about a later freely generated message without later conditioning.

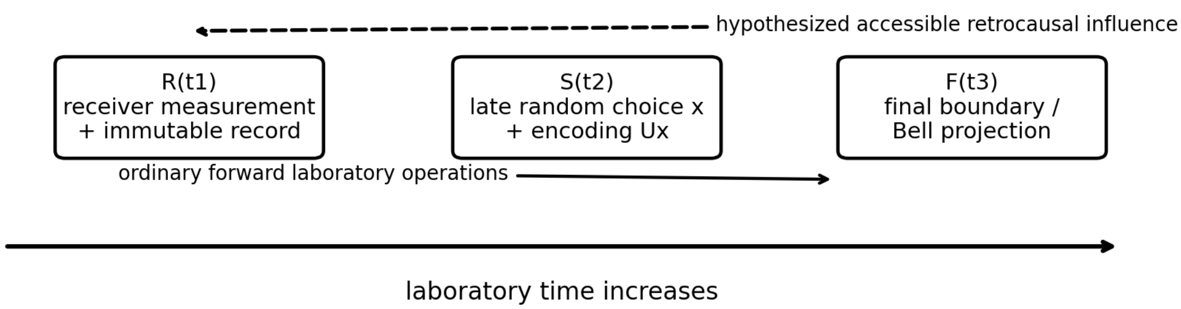


*Figure 1. TBCN-P separates laboratory time from the hypothesized direction of accessible information. The key empirical target is a record at R(t1) that is already informative about a sender intervention at S(t2), t2 > t1.*

# Abstract

Temporal Boundary-Condition Networks with Postselected retrocausal channels (TBCN-P) are proposed as a resource-theoretic extension of time-symmetric quantum mechanics. The construction begins with a conservative boundary: ordinary entanglement, delayed-choice measurements, quantum memories, and completely positive trace-preserving dynamics do not supply controllable information to an already fixed past record. The theory then introduces one explicit nonstandard resource - a physically guaranteed postselected closed timelike curve (P-CTC) or equivalent initial-and-final boundary condition - and asks what follows if such a resource is real. In this enlarged model, the normalized state update is nonlinear, and a later sender can in principle induce distinguishable states at an earlier receiver. This creates a well-defined backward communication problem rather than an interpretive statement about quantum correlations.

The framework is motivated by the P-CTC model of Lloyd and collaborators, the experimental simulation of postselected CTC consistency, delayed-choice entanglement swapping, causal-model analyses of delayed choice, process-matrix approaches without predetermined global causal order, and especially the 2026 result of Ji, Lloyd, and Wilde that characterizes retrocausal classical and quantum capacities of noisy P-CTC channels. It is also informed by a 2026 experimental simulation on Quantinuum and IBM quantum processors in which postselection allows future-to-past recovery of scrambled quantum information within an ordinary forward-time laboratory experiment. These results establish a rigorous simulation and information-theoretic base, but not yet an operational time telephone.

To distinguish a true past-directed channel from retrospective sorting, TBCN-P introduces the Pre-Registration Criterion (PRC): the earlier record must be measured and irreversibly committed before the future message is chosen, and the complete earlier record must contain nonzero accessible information about that later choice without using a success flag, basis disclosure, coincidence list, or any other later variable. The paper develops the mathematical channel model, trace-distance and mutual-information criteria, a nonlinear witness, noise and cascade laws, a temporal-displacement metric, and three buildable experimental platforms: a photonic P-CTC/PRC bench, a superconducting or trapped-ion P-CTC capacity emulator, and an isolated dual-station sealed-record search for an operational backward channel. Standard quantum mechanics predicts that the first two can reproduce conditional P-CTC behavior under postselection while the third yields zero pre-registered information unless new physics supplies a genuine final-boundary resource.


# 1. Scope, claims, and non-claims

TBCN-P is deliberately constructed in layers. This prevents evidence for one layer from being silently promoted into evidence for a stronger layer. The weakest layer is time symmetry: standard quantum theory admits time-symmetric formulations of conditional probabilities for pre- and postselected ensembles. The second layer is retrocausal modeling: some delayed-choice data can be efficiently represented using future boundary conditions or models that are incompatible with restricted nonretrocausal hidden-variable descriptions. The third layer is postselected CTC simulation: ordinary forward-time quantum experiments can simulate the logical map of a P-CTC after conditioning on a future outcome. The strongest layer, and the only layer that would justify the phrase signal into the past, is operational accessibility: an observer at t1 must possess a record that contains information about a later intervention at t2 before any data from t2 arrive by ordinary means.

| Level | Meaning | Present status |
|---|---|---|
| I. Time-symmetric formalism | Future boundary conditions participate in conditional probability assignments. | Established as a reformulation/useful formalism; does not imply signaling. |
| II. Retrocausal explanatory model | Some correlations are modeled with backward-in-time influence or global boundary constraints. | Supported in selected foundational models; interpretation dependent. |
| III. P-CTC simulation | Postselection reproduces a nonlinear CTC-like map after later conditioning. | Experimentally demonstrated in photonics and quantum processors. |
| IV. Operational backward channel | Earlier sealed data are readable as a function of a later free intervention. | Not demonstrated; this is the TBCN-P discovery target. |

The main theoretical claim of this paper is conditional: if a physical process implements the P-CTC/final-boundary transformation rather than merely simulating it by discarding failed trials, then backward classical and quantum communication capacity can be nonzero. The main experimental contribution is to state a test that ordinary postselection cannot fake.

# 2. Physical and theoretical background

## 2.1 Time-symmetric conditional quantum mechanics

The two-state-vector and Aharonov-Bergmann-Lebowitz traditions make future and past boundary conditions mathematically symmetric in the conditional description of measurements. For an initial state psi_i, final state psi_f, and intermediate projective alternatives P_k, the conditional probability may be written as Equation 1. This formula is time-symmetric in the sense relevant to pre- and postselection, but it does not by itself give an observer at the earlier time access to the final boundary condition. Thus it is foundation, not a signaling protocol.

$$P(a_k|\psi_i,\psi_f)=\frac{|\langle\psi_f|U_{f,t}P_kU_{t,i}|\psi_i\rangle|^2}{\sum_j|\langle\psi_f|U_{f,t}P_jU_{t,i}|\psi_i\rangle|^2}$$

*Equation 1. ABL time-symmetric conditional probability.*

## 2.2 Delayed-choice evidence

Delayed-choice entanglement swapping has experimentally placed the choice of joint measurement after the registration of the photons whose correlations are later classified, a situation described by the authors as quantum steering into the past. Causal-model work has also identified delayed-choice variants whose statistics are incompatible with restricted nonretrocausal hidden-variable models of matching dimension. These are strong reasons to treat future boundary conditions seriously, but the experimentally accessible marginal at the earlier station remains independent of the later freely chosen setting until the data sets are compared.

## 2.3 Indefinite causal order

Process-matrix theory relaxes the assumption of a predefined global causal order while preserving ordinary quantum operations locally. For local instruments represented by completely positive maps M_A and M_B and a process matrix W, joint probabilities take the bilinear form of Equation 2. This shows that a global causal structure is an assumption that can be generalized. TBCN-P borrows this resource-theoretic attitude but focuses on a more demanding phenomenon: accessible information at an earlier time about a later intervention.

$$p(a,b|x,y)=\mathrm{Tr}[(M_A^{a|x}\otimes M_B^{b|y})W]$$

*Equation 2. Process-matrix probability rule.*

# 3. TBCN-P axioms

Axiom A1 - Local quantum validity. Inside each laboratory, preparations, measurements, and controlled dynamics are described by ordinary quantum mechanics to the accuracy of the experiment.

Axiom A2 - Explicit resource accounting. Entanglement, coherent memory, postselection, feedforward, and any nonstandard final-boundary process are distinct resources. No temporal displacement is inferred merely from memory duration.

Axiom A3 - Free late intervention. The sender variable X at t2 is generated after the earlier record has been committed and is statistically independent of all variables in the causal past except through the hypothesized temporal resource.

Axiom A4 - Pre-registered accessibility. A backward signal exists only if the receiver at t1 could in principle decode information using variables already available at t1. Later conditioning is excluded from the primary signal definition.

Axiom A5 - Self-consistency. If a final-boundary process is physical, histories with zero boundary amplitude do not occur. TBCN-P therefore treats paradox avoidance as a boundary-consistency constraint rather than as unrestricted overwriting of an independently fixed past.

Axiom A6 - Empirical separability of capacity and displacement. A channel can have positive information capacity but negligible temporal separation, or large separation but negligible capacity. Both quantities must be measured.

# 4. Postselected-CTC resource

Begin with the maximally entangled Bell resource in Equation 3. A chronology-respecting system S interacts with one member A of the pair through a unitary U. The future boundary projects A and B onto the same Bell state. Contracting the loop degrees of freedom gives the effective operator C in Equation 4.

$$|\Phi^+\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

*Equation 3. Bell resource state.*

$$C = \langle \Phi^+|_{AB}\, U_{SA}\, |\Phi^+\rangle_{AB}$$

*Equation 4. Effective P-CTC contraction operator.*

If the projection is simply a laboratory event that succeeds on a random subset of trials, the unnormalized branch has probability given by Equation 6. The experimenter may condition on that branch after the fact, but the earlier observer cannot know which branch survived. The P-CTC proposal becomes qualitatively different only if the boundary condition is enforced rather than selected. The normalized map is Equation 5.

$$\mathcal{P}_C(\rho) = \frac{C\rho C^\dagger}{\mathrm{Tr}(C\rho C^\dagger)}$$

*Equation 5. Normalized P-CTC map.*

$$p_{\mathrm{post}}(\rho) = \mathrm{Tr}(C\rho C^\dagger)$$

*Equation 6. Ordinary postselection success probability.*

The denominator depends on the input state. Therefore the transformation is generally nonlinear in density operators. This is the mathematical point at which the standard no-signaling resource theory is enlarged. TBCN-P does not hide this step: the existence of a physical mechanism that realizes this nonlinear normalization is the core unknown.

# 5. Operational backward channel

Let X be a classical bit selected at the future sender S(t2). The encoding produces a quantum state rho_S^(x), and the putative temporal resource maps it to an earlier receiver state rho_R^(x), as shown in Equation 7. A backward channel is operational only if the two receiver states are distinguishable before ordinary information from t2 can reach t1.

$$\rho_R^{(x)} = \mathcal{N}_{\mathrm{back}}(\rho_S^{(x)}), \qquad x \in \{0, 1\}$$

*Equation 7. Binary retrocausal channel states.*

$$D(\rho_0, \rho_1) = \frac{1}{2}\|\rho_0 - \rho_1\|_1$$

*Equation 8. Trace distance.*

$$P_{\mathrm{guess}} = \frac{1}{2}\left(1 + D(\rho_R^{(0)}, \rho_R^{(1)})\right)$$

*Equation 9. Helstrom binary success probability.*

Equation 9 is the Helstrom optimum for equally likely binary messages. If the trace distance is zero, no measurement can distinguish the messages. If the distance is positive, the receiver has above-chance guessing probability. This turns the central question into a laboratory observable.

For many trials, the primary classical communication measure is mutual information, Equation 10. If the channel is effectively binary symmetric with decoder error p_e, Fano's inequality provides the lower bound in Equation 11. Thus a small but reproducible decoding advantage can be translated into bits per trial without assuming a microscopic model of the resource.

$$I(X;Y) = \sum_{x,y} p(x,y) \log_2 \frac{p(x,y)}{p(x)p(y)}$$

*Equation 10. Mutual information.*

$$I(X;Y) \geq 1 - h_2(p_e), \quad h_2(p) = -p\log_2 p - (1-p)\log_2(1-p)$$

*Equation 11. Binary information lower bound.*

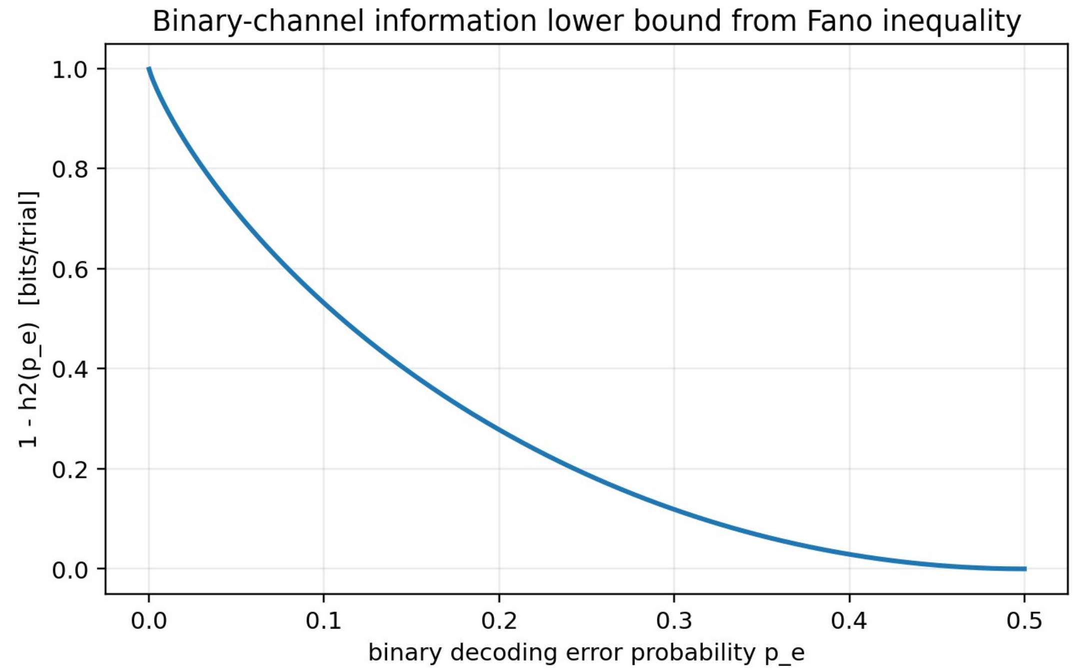


*Figure 2. For a binary symmetric effective channel, the Fano lower bound 1 - h2(p_e) approaches zero as the decoding error approaches 1/2. A statistically significant deviation from chance is necessary but not sufficient; the PRC and leakage controls must also be satisfied.*

## 6. The Pre-Registration Criterion (PRC)

The PRC is designed to eliminate the most common category error in retrocausal discussions: confusing a conditional correlation visible after both time points with a message available at the earlier time. Let Lambda_t1 denote every classical variable physically available to the receiver at the time its record is sealed. A genuine signal requires Equation 12, with no conditioning on variables produced after t1.

$$I(X_{t_2}; Y_{t_1} \mid \Lambda_{t_1}) > 0, \qquad t_1 < t_2$$

*Equation 12. Pre-Registration Criterion.*

The intervention language makes the requirement even sharper. Instead of merely testing correlation between X and Y, TBCN-P asks whether an externally randomized intervention on the later variable X changes the earlier outcome distribution. A useful total-variation effect measure is Equation 13. Hidden common causes cannot satisfy this criterion when the intervention is genuinely randomized after the earlier record is committed.

$$\Delta_{\text{back}} = \frac{1}{2}\sum_{y} |P(y|\text{do}(X=0)) - P(y|\text{do}(X=1))| > 0$$

*Equation 13. Interventional backward-effect statistic.*

In a conventional postselected experiment, P(Y|X,F=success) can depend strongly on X even while P(Y|X) does not. TBCN-P therefore forbids F, a future success flag, from the primary decoder. Secondary conditioned analyses are still useful for verifying the P-CTC simulator, but they are never counted as evidence for Level IV operational signaling.

## 7. Nonlinearity witness

A physical P-CTC resource should not merely produce an unexplained correlation; it should exhibit the nonlinear structure that motivated the claimed channel. A particularly direct test uses different preparation ensembles that correspond to the same density operator under ordinary linear quantum mechanics. Equation 14 shows two such decompositions. For a linear channel, the output depends only on rho, not on its decomposition. The normalized P-CTC map can violate this affine property, as indicated by Equation 15.

$$\rho = \sum_i p_i |\psi_i\rangle\langle\psi_i| = \sum_j q_j |\phi_j\rangle\langle\phi_j|$$

*Equation 14. Equivalent ensemble decompositions.*

$$\mathcal{P}_C(\rho) \neq \sum_i p_i \mathcal{P}_C(|\psi_i\rangle\langle\psi_i|) \text{ in general}$$

*Equation 15. Nonlinearity witness condition.*

Operationally, the experiment alternates between two preparation procedures with the same reconstructed input density matrix. A single CPTP process matrix is fit to all data. TBCN-P requires the claimed final-boundary model to improve the fit in a preregistered model comparison and to predict the same parameter values that explain the backward-information test. This joint requirement reduces the chance that a detector artifact is misidentified as new causal physics.

## 8. Noise, capacity, and coding

A real temporal channel, if one exists, will be noisy. The 2026 work of Ji, Lloyd, and Wilde is important because it defines one-shot and asymptotic retrocausal capacities for noisy P-CTC channels and extends the framework to completely positive maps with arbitrary initial and final boundary conditions. TBCN-P does not need to duplicate their complete capacity theorems; instead it uses experimentally accessible lower bounds from state discrimination and mutual information, and treats the published retrocausal capacity as the ultimate resource limit for a specified map.

For a chain of independently characterized temporal links, ordinary data-processing reasoning gives the bottleneck bound in Equation 16. No cascade can transmit more reliable information than its weakest link. If links can be approximated as independent binary-symmetric channels with crossover probabilities p_k and the output of each is hard-decoded into the next, the composite crossover probability is Equation 17. Unless each p_k is small, repeated links rapidly drive p_eff toward one half.

$$C_{\text{cascade}} \leq \min_k C_k$$

*Equation 16. Serial temporal-channel bottleneck.*

$$p_{\text{eff}} = \frac{1-(1-2p_1)(1-2p_2)\cdots(1-2p_n)}{2}$$

*Equation 17. Effective crossover for serial independent binary-symmetric links.*

Consequently, the original notion of obtaining decades of temporal displacement by simply adding long-lived memories is rejected. A memory is not a negative-time channel. A multi-link architecture becomes meaningful only after each individual link has independently demonstrated both positive backward capacity and a measured negative temporal displacement under PRC.

## 9. Temporal displacement

Define temporal displacement Delta t = t_sender - t_receiver for a verified backward link. Positive Delta t means the sender choice occurs later in laboratory time than the receiver record. In a physically composed cascade, verified displacements may add according to Equation 18. The phrase verified temporal links is essential: a quantum memory that stores a qubit for a year contributes storage time, not retrocausal displacement, unless it is part of a channel that has separately passed PRC.

$$\Delta t_{\text{total}} = \sum_{k=1}^{n} \Delta t_k \quad \text{only for verified temporal links}$$

*Equation 18. Composable temporal displacement.*

This factorization of capacity and displacement gives a disciplined route to the previously proposed 50-year objective. Phase 1 is to demonstrate a nonzero capacity at any nonzero Delta t. Phase 2 is to determine how the effect scales with Delta t and resource quality. Phase 3 is to demonstrate composition of two links. Only after those steps would extrapolation to macroscopic temporal baselines be scientifically meaningful.

# 10. Three falsification tests retained in the full theory

## 10.1 Falsification A - postselection-only explanation

Null model: every apparent future-to-past effect can be reproduced by conditioning the earlier data on a later event. Test: analyze the full earlier stream with the later success variable withheld. A Level IV signal must remain. If it vanishes, the system is a P-CTC simulator, not a physical past-directed channel.

## 10.2 Falsification B - common cause or forward leakage

Null model: X and Y share information through ordinary causal paths, including clocks, deterministic pseudorandomness, RF pickup, optical reflections, network packets, power-supply modulation, thermal signatures, file metadata, or experimenter scheduling. Test: generate X after the t1 commitment, physically isolate stations, inject deliberate conventional leakage to calibrate sensitivity, rotate hardware roles, and perform blinded permutations. A claimed effect must survive only when the candidate temporal resource is enabled.

## 10.3 Falsification C - ordinary linear quantum channel

Null model: one CPTP map plus detector/systematic errors explains all observations. Test: jointly fit process tomography, the PRC signal, and the nonlinear ensemble witness. The physical P-CTC hypothesis must provide a reproducible improvement that cannot be eliminated by adding realistic drift parameters to the CPTP model.

# 11. Experimental Example 1 - Photonic P-CTC / PRC bench

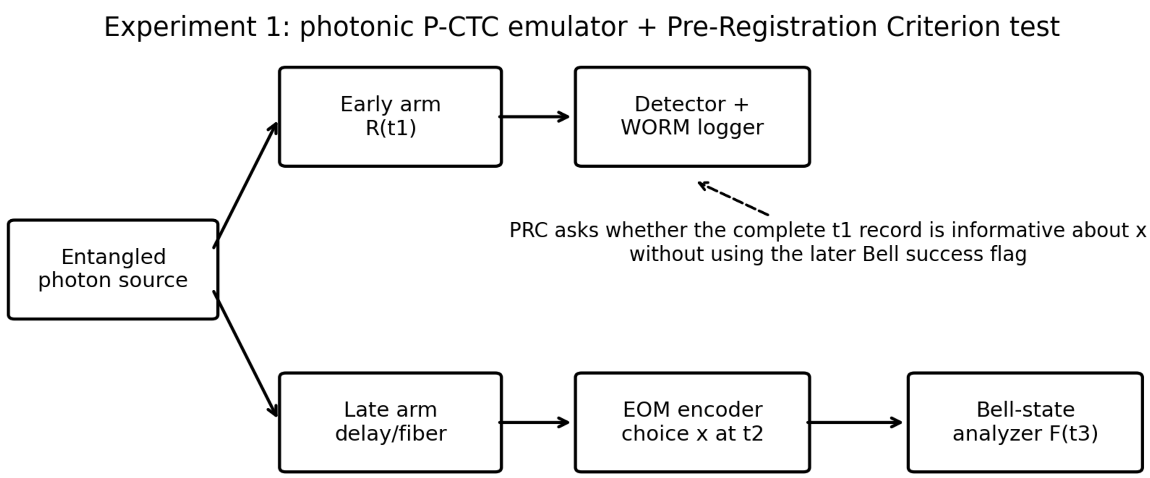


*Figure 3. A buildable optical platform. The upper branch creates the early receiver record; the lower branch carries the late encoding to the Bell-state analyzer. Ordinary postselection predicts conditioned retrocausal-looking correlations but no PRC signal in the unfiltered early record.*

## 11.1 Objective

Build a laboratory system that reproduces postselected-teleportation P-CTC behavior and, in the same apparatus, tests the stronger PRC. The experiment is explicitly bifurcated: the conditioned analysis validates the simulator, while the unconditioned early stream tests for any anomalous operational backward capacity.

## 11.2 Hardware

| Subsystem | Example implementation | Purpose |
|---|---|---|
| Entangled-pair source | SPDC source or entangled quantum-dot source; polarization or time-bin qubits | Prepare Bell-pair resource. |
| Early receiver arm | Polarization analyzer + single-photon detector + | Generate Y at t1. |

| | | |
|---|---|---|
| | FPGA counter | |
| Immutable logger | WORM medium or append-only hardware logger with externally witnessed hash | Freeze the complete t1 record before X exists. |
| Late encoder | Electro-optic modulator or fast waveplate controlled by QRNG | Apply U0/U1 after commitment. |
| Bell analyzer | Linear-optical Bell-state analyzer with coincidence detection | Create ordinary P-CTC postselection branch. |
| Isolation controls | Separate power, RF shielding, optical baffling, independent clocks | Suppress conventional forward leakage. |

### 11.3 Sequence

1. Generate an entangled pair. Measure the early arm at R(t1), record detector output and all auxiliary channels, and commit the record. 2. After the commitment acknowledgement, generate X from an independent QRNG and drive the late-arm encoder. 3. Perform the Bell-state analysis at F(t3). 4. Run two analyses. Simulator analysis conditions on the designated Bell result and should reproduce postselected correlations. PRC analysis ignores the future success flag and compares the complete t1 stream against X. 5. Repeat with the Bell analyzer removed, the entangled source replaced by a classical source, and intentionally injected forward leakage.

### 11.4 Predicted outcomes

Standard quantum mechanics predicts that conditioned data can show the P-CTC simulation while the complete earlier marginal is independent of X. TBCN-P with no physical guaranteed boundary gives the same prediction. A Level IV anomaly would be a reproducible nonzero Delta_back in the unfiltered t1 record, appearing only when the full candidate resource is active and accompanied by the predicted nonlinear signature.

### 11.5 Why this experiment matters

The optical platform is the cleanest bridge between the 2011 photonic P-CTC consistency experiment and a genuine signaling test because its chronology can be enforced at the hardware level. It is also relatively transparent: the future Bell success event can be physically withheld from the t1 decoder, making it difficult to mistake retrospective filtering for a signal.

## 12. Experimental Example 2 - Digital P-CTC capacity emulator on a quantum processor

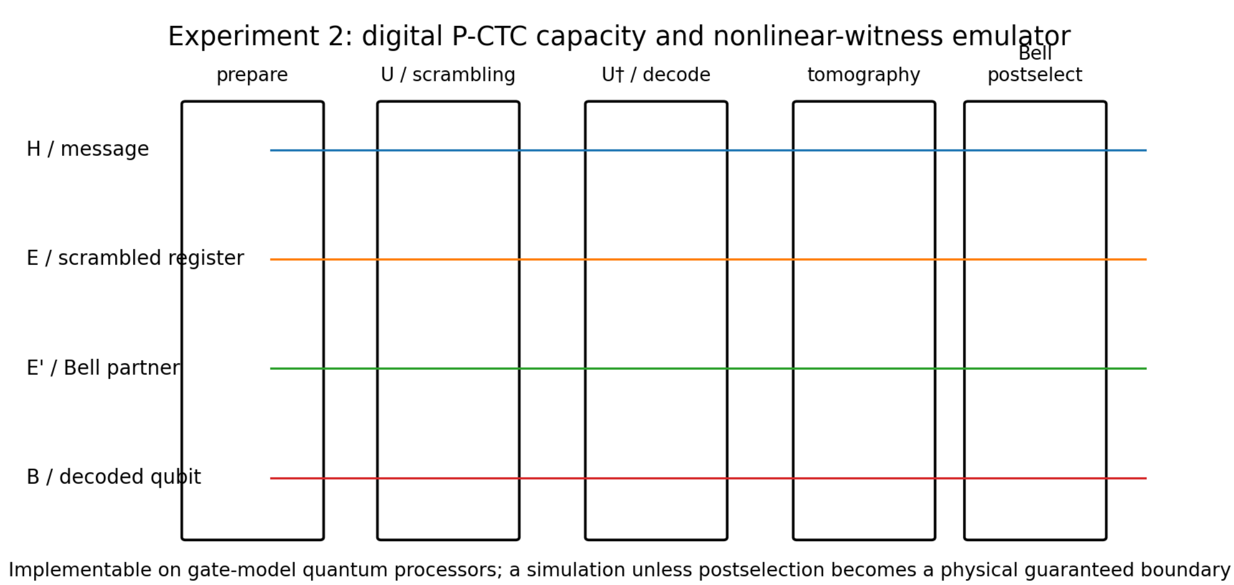

*Figure 4. A gate-model quantum computer can emulate the P-CTC map, scrambling, decoding, tomography, and final Bell postselection. The 2026 Huang et al. experiment demonstrated this class of future-to-past information-recovery simulation on Quantinuum and IBM processors.*

## 12.1 Objective

Construct a controllable digital twin of the TBCN-P resource to test capacity formulas, nonlinear postselection behavior, error models, and temporal-link composition before any claim of physical retrocausality. This experiment is buildable on current gate-model hardware and provides a calibration environment for analysis code that will later be applied to the PRC experiment.

## 12.2 Minimal circuit

A four- to six-qubit circuit is sufficient for a proof-of-principle. Prepare a Bell pair E,E'. Encode or scramble a message with unitary U. Apply an inverse or decoding circuit to the appropriate subsystem. Perform tomography on the nominally early decoded qubit. Finally perform a Bell measurement and postselect the specified result. Huang et al. experimentally implemented a related four-qubit P-CTC decoding protocol on both Quantinuum and IBM quantum processors in 2026, while explicitly stating that it is a controlled simulation rather than physical time travel.

## 12.3 Scrambling and OTOC

For scrambling-based variants, the out-of-time-order correlator in Equation 19 quantifies the spread of initially localized information. The P-CTC decoding success probability can be studied as a function of scrambling strength, gate noise, and postselection rate. State fidelity, Equation 20, supplies an experimentally standard performance measure.

$$F(t) = \langle W^{\dagger}(t) V^{\dagger} W(t) V \rangle$$

*Equation 19. Out-of-time-order correlator.*

$$F(\rho, \sigma) = \left(\mathrm{Tr}\sqrt{\sqrt{\rho}\,\sigma\sqrt{\rho}}\right)^2$$

*Equation 20. Quantum state fidelity.*

## 12.4 Capacity sweep

Run a family of circuits in which dephasing, depolarization, amplitude damping, or readout noise is deliberately varied. For each channel, estimate the receiver-state trace distance, optimal binary discrimination, and mutual information after the designated postselection. Compare the measured trend with the theoretical noisy P-CTC capacity bounds. This creates a benchmark map from physical hardware error rates to effective retrocausal-simulation capacity.

## 12.5 Nonlinear witness

Prepare two ensembles with the same reconstructed density matrix but different decompositions. Apply the emulated normalized P-CTC transformation separately to the labeled ensembles and measure whether the postselected output statistics depend on preparation context. Because the emulator uses an explicit later filter, such effective nonlinearity is expected conditionally. The same analysis pipeline can then be used as a template for the physical-resource search, where the later filter is forbidden from the PRC decoder.

## 12.6 Two-link temporal repeater simulation

A particularly useful extension concatenates two independent P-CTC emulators. Measure each link's effective binary crossover probability and verify Equation 17. Test error-correcting codes across the simulated cascade. This does not create a two-step trip into the past, but it validates the information-engineering layer required if physical temporal links are ever found.

# 13. Experimental Example 3 - Sealed-record operational retrocausal channel search

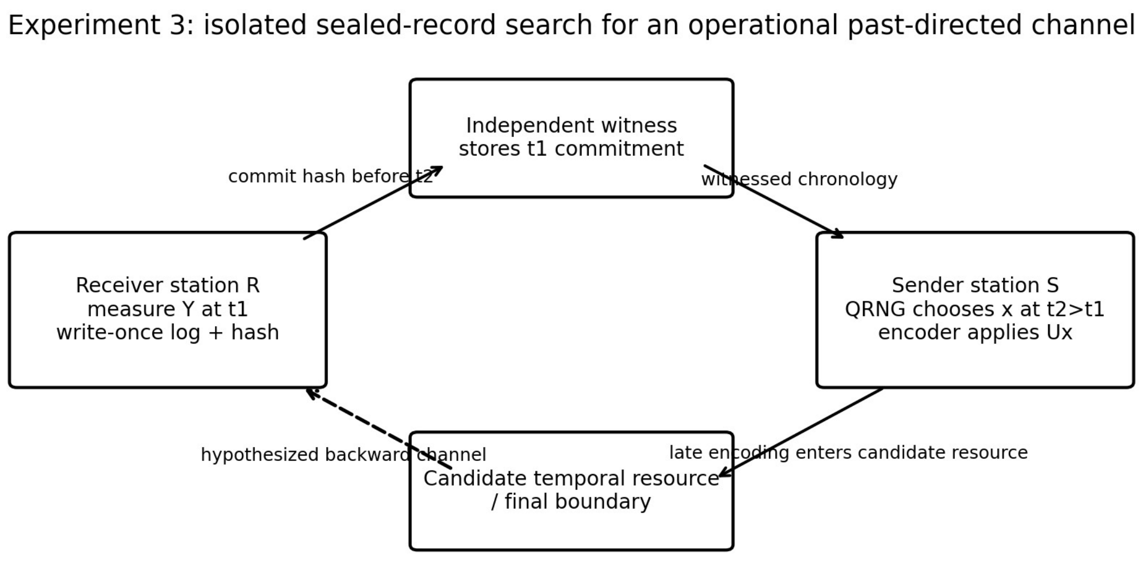


*Figure 5. The decisive experiment isolates an earlier receiver from a genuinely later randomized sender choice. The early record is committed to an independent witness before X exists. Any claimed channel must survive without future success information.*

## 13.1 Objective

This experiment is the strongest and most important of the three. Its purpose is not to reproduce known postselection effects but to search for the missing physical ingredient: a process that makes a final boundary condition operationally effective without retrospective data selection. It is intentionally designed so that a null result is scientifically useful because it constrains TBCN-P candidate mechanisms.

## 13.2 Architecture

Receiver laboratory R measures Y at t1 and writes each trial to local append-only media. A cryptographic hash of each block is transmitted one-way to an independent witness before the sender choice is generated. Only after receipt of the commitment does sender laboratory S obtain X from a hardware QRNG and apply the corresponding encoding. Any candidate final-boundary device lies on a physical path that is present during the trial but does not supply ordinary classical communication from S to R.

## 13.3 Candidate resource insertion

TBCN-P does not currently identify a demonstrated material that supplies guaranteed postselection. The experiment should therefore be modular: the candidate-resource module can initially be the same optical P-CTC simulator used in Experiment 1, which should yield a null PRC result and calibrate the analysis. Future candidate mechanisms - for example, new boundary-condition devices suggested by quantum-gravity or final-state models - can be inserted without changing the chronology or statistical protocol. A device is not promoted to a physical P-CTC unless it passes PRC.

## 13.4 Controls

The receiver and sender should use independent clocks and power supplies; no network path may connect S to R after the t1 commitment except through monitored witness infrastructure that cannot carry X backward in laboratory time. Optical paths must be baffled; RF and acoustic coupling must be monitored; pseudorandom generators are forbidden for the primary X; trial schedules should be jittered; experimenters should be blinded to X during collection; software should be deterministic and preregistered; and the raw data should be independently mirrored before analysis.

### 13.5 Discovery statistic

The primary null hypothesis is independence of X and the complete earlier Y stream. The likelihood-ratio statistic in Equation 21 or an exact permutation test can be used. Because subtle systematic correlations are more dangerous than pure sampling error, the analysis should emphasize replication, role swapping, negative controls, and effect persistence rather than a single p-value.

$$\Lambda = 2\sum_{x,y} n_{xy} \ln\left(\frac{\hat{p}(y|x)}{\hat{p}(y)}\right)$$

*Equation 21. Likelihood-ratio independence statistic.*

### 13.6 Illustrative sample size

For a simple two-outcome receiver near a 50/50 baseline, Equation 22 gives an order-of-magnitude sample size for detecting an absolute probability shift delta. Using a nominal 5-sigma normal threshold and 90% power gives approximately 197,000 trials per arm for delta = 0.02, 789,000 per arm for delta = 0.01, and 3.16 million per arm for delta = 0.005. These calculations ignore drift and multiple testing, so a real discovery program should collect more data and include independent replication.

$$N_{\text{per arm}} \approx \frac{2(z_{1-\alpha/2} + z_{1-\beta})^2}{\delta^2}$$

*Equation 22. Approximate sample size near p=1/2.*

## 14. Data analysis and preregistration standard

A retrocausal claim is unusually vulnerable to accidental information leakage and retrospective flexibility. TBCN-P therefore treats preregistration as part of the apparatus. Before opening the final data set, the collaboration should publish or externally timestamp: the exact sender randomization method, receiver decoder, trial inclusion rule, primary outcome, maximum sample size, stopping rule, calibration exclusions, treatment of detector dead time, synchronization algorithm, and all planned secondary analyses.

The raw chronology must be auditable. For each receiver event, the committed record should contain detector result, local time, trial ID, detector health channels, source status, and hash-chain pointer. For each sender event, it should contain X, the time X became available to the control electronics, the applied physical operation, and health channels. The independent witness should store only commitments, not information that can influence either station.

A positive result should be analyzed in at least four ways: direct contingency-table independence; permutation tests preserving known time correlations; logistic or multinomial models including nuisance channels; and causal analysis testing whether the association follows the randomized future intervention rather than a pre-existing common variable. The effect should be reported both in sigma/p-value units and in operational units such as trace distance, guessing advantage, mutual information, and bits per trial.

## 15. Three experimental devices that follow if PRC is ever passed

The three experiments above can be constructed now as tests or simulations. If Experiment 3 were to establish a reproducible physical backward channel, the same architecture would immediately support three prototype devices. These are conditional engineering consequences, not current capabilities.

### 15.1 One-bit temporal warning register

A future station evaluates a binary condition - for example, whether a later detector crosses a threshold - and encodes the result into the temporal channel. The earlier station displays one bit. The scientific purpose of the first prototype would not be prediction of complex events but repeated closed-loop verification that the bit in the sealed earlier record tracks the later randomized condition with the measured channel error rate.

### 15.2 Retrocausal error-flag coprocessor

A computation at t1 proceeds optimistically while a verifier at t2 checks a costly condition. The future verifier sends a single accept/reject flag through the temporal channel. In a self-consistent model the earlier computation can use that flag to choose between two allowed branches. Such a device would be a powerful test of consistency constraints because deliberate contradictory encodings could be attempted and their suppression measured.

### 15.3 Temporal repeater testbed

Two verified backward links are connected in series with an intermediate decode/re-encode node. The testbed measures whether both information capacity and temporal displacement compose as predicted. This would be the first essential step toward any long-baseline architecture and would directly test the bottleneck and crossover equations in Sections 8 and 9.

## 16. Relation to the 50-year objective

A 50-year operational channel is many scientific steps beyond the present theory. TBCN-P nevertheless specifies what would have to be true. First, one physical link must pass PRC at a nonzero Delta t. Second, the dependence of capacity, error, and resource success on Delta t must be measured. Third, two links must compose without the effect collapsing into ordinary postselection. Fourth, the required physical boundary resource must remain stable or be reproducible across the entire baseline. Fifth, the receiver record must remain independently verifiable for the full time interval.

None of these requirements is satisfied merely by a long coherence time. A fifty-year quantum memory could preserve a state into the future but would not send a newly chosen bit into the past. The long-baseline goal is therefore a temporal-channel problem, not a storage problem.

## 17. Theoretical limitations and open questions

### 17.1 Physical origin of guaranteed postselection

This is the central missing element. Laboratory postselection is an epistemic operation performed after outcomes occur. TBCN-P requires a boundary law that eliminates inconsistent branches physically. Black-hole final-state proposals, quantum-gravity boundary conditions, or other global consistency principles motivate mathematical analogies, but none currently supplies a laboratory component known to satisfy PRC.

### 17.2 Nonlinearity and ensemble dependence

Nonlinear quantum maps create conceptual issues because density matrices can have multiple ensemble decompositions. A physical theory must specify what preparation information the map acts on and how this remains compatible with operational consistency. The nonlinear witness is therefore not merely a diagnostic; it probes whether the proposed map defines a coherent physical theory rather than a post-processing rule.

### 17.3 Relativity and frame dependence

For timelike separated events the sign of t2 - t1 is invariant, so the core PRC experiment is best performed with a clear timelike separation. Spacelike configurations introduce frame-order questions that are interesting for process-matrix physics but unnecessary for the first operational test. TBCN-P therefore recommends a single laboratory rest frame and explicitly timelike event ordering.

### 17.4 Free intervention and superdeterministic loopholes

No finite experiment can logically exclude every conceivable common cause. TBCN-P uses the standard scientific strategy: independent hardware random generation after commitment, physical isolation, source diversity, and replication. The aim is to exclude ordinary causal explanations to the same or stronger standard used in high-quality foundational experiments.

### 17.5 Thermodynamics and computation

A physical nonlinear temporal resource could alter familiar computational and thermodynamic bounds. Those consequences should not be assumed in advance. The first experiments should measure only small-alphabet channel behavior, energy accounting, and consistency. Claims of exotic computation belong after a replicated Level IV channel exists.

## 18. Falsifiability map

| Observation | Interpretation within TBCN-P |
|---|---|
| Conditioned P-CTC correlations only | Confirms simulator; no operational past signal. |
| PRC null, nonlinear conditioned witness present | Consistent with ordinary postselection; physical resource absent. |
| Small PRC correlation explained by leakage | Experimental systematic; not evidence for retrocausality. |
| Replicated PRC correlation, no nonlinear signature | Anomaly, but not specifically P-CTC; seek alternative causal model. |
| Replicated PRC correlation + predicted nonlinear witness + resource on/off control | Strong evidence for the TBCN-P class of physical final-boundary models. |
| Two independently verified links compose in capacity and displacement | Evidence that temporal channels can be engineered as networks. |

## 19. Conclusion

TBCN-P converts a broad retrocausal idea into a resource theory with an explicit experimental fork. Ordinary quantum mechanics, delayed-choice correlations, and postselected P-CTC simulations occupy one side of the fork: they can generate striking retrodictive structure but do not make a future choice readable in an earlier complete record. A physical guaranteed final-state boundary occupies the other side: it changes the state-update rule, can create distinguishable earlier receiver states, and therefore can support a nonzero backward channel in the theory.

The 2026 retrocausal-capacity result of Ji, Lloyd, and Wilde supplies a modern information-theoretic foundation for this conditional resource, while the 2026 Quantinuum/IBM P-CTC simulation shows that relevant circuits can be studied experimentally today. The decisive next step is not another retrospective delayed-choice plot. It is a chronology-hardened PRC experiment in which the receiver record is sealed before the future bit exists and the full earlier stream is tested without later selection.

If that experiment remains null across increasingly strong candidate resources, TBCN-P will be correspondingly constrained. If it succeeds and replicates with the nonlinear signature and leakage controls, the result would constitute a qualitatively new physical phenomenon: operational information from a later intervention available in an earlier record. Only then would long-baseline temporal engineering, including multi-link repeaters and ultimately year-scale displacement, become a justified research program.

# Appendix A - Rendered equation reference

All equations are reproduced below as fully rendered mathematics. Raw LaTeX command text is intentionally omitted from the PDF so Linux viewers such as Evince display the appendix exactly as mathematical notation. A separate companion LaTeX source file is provided with the document package for independent re-rendering.

**Equation 1 - ABL time-symmetric conditional probability**

$$P(a_k|\psi_i,\psi_f)=\frac{|\langle\psi_f|U_{f,t}P_kU_{t,i}|\psi_i\rangle|^2}{\sum_j|\langle\psi_f|U_{f,t}P_jU_{t,i}|\psi_i\rangle|^2}$$

**Equation 2 - Process-matrix probability rule**

$$p(a,b|x,y)=\mathrm{Tr}[(M_A^{a|x}\otimes M_B^{b|y})W]$$

**Equation 3 - Bell resource state**

$$|\Phi^+\rangle=\frac{|00\rangle+|11\rangle}{\sqrt{2}}$$

**Equation 4 - Effective P-CTC contraction operator**

$$C=\langle\Phi^+|_{AB}\,U_{SA}\,|\Phi^+\rangle_{AB}$$

**Equation 5 - Normalized P-CTC map**

$$\mathcal{P}_C(\rho)=\frac{C\rho C^\dagger}{\mathrm{Tr}(C\rho C^\dagger)}$$

**Equation 6 - Ordinary postselection success probability**

$$p_{\mathrm{post}}(\rho)=\mathrm{Tr}(C\rho C^\dagger)$$

**Equation 7 - Binary retrocausal channel states**

$$\rho_R^{(x)}=\mathcal{N}_{\mathrm{back}}(\rho_S^{(x)}),\qquad x\in\{0,1\}$$

**Equation 8 - Trace distance**

$$D(\rho_0,\rho_1)=\frac{1}{2}\|\rho_0-\rho_1\|_1$$

**Equation 9 - Helstrom binary success probability**

$$P_{\mathrm{guess}}=\frac{1}{2}\left(1+D(\rho_R^{(0)},\rho_R^{(1)})\right)$$

**Equation 10 - Mutual information**

$$I(X;Y)=\sum_{x,y}p(x,y)\log_2\frac{p(x,y)}{p(x)p(y)}$$

**Equation 11 - Binary information lower bound**

$$I(X;Y)\geq 1-h_2(p_e),\quad h_2(p)=-p\log_2 p-(1-p)\log_2(1-p)$$

**Equation 12 - Pre-Registration Criterion**

$$I(X_{t_2};Y_{t_1}\,|\,\Lambda_{t_1})>0,\qquad t_1<t_2$$

**Equation 13 - Interventional backward-effect statistic**

$$\Delta_{\mathrm{back}}=\frac{1}{2}\sum_y|P(y|\mathrm{do}(X=0))-P(y|\mathrm{do}(X=1))|>0$$

**Equation 14 - Equivalent ensemble decompositions**

$$\rho=\sum_i p_i|\psi_i\rangle\langle\psi_i|=\sum_j q_j|\phi_j\rangle\langle\phi_j|$$

**Equation 15 - Nonlinearity witness condition**

$$\mathcal{P}_C(\rho)\neq\sum_i p_i\mathcal{P}_C(|\psi_i\rangle\langle\psi_i|)\text{ in general}$$

**Equation 16 - Serial temporal-channel bottleneck**

$$C_{\text{cascade}} \leq \min_k C_k$$

**Equation 17 - Effective crossover for serial independent binary-symmetric links**

$$p_{\text{eff}} = \frac{1-(1-2p_1)(1-2p_2)\cdots(1-2p_n)}{2}$$

**Equation 18 - Composable temporal displacement**

$$\Delta t_{\text{total}} = \sum_{k=1}^{n} \Delta t_k \quad \text{only for verified temporal links}$$

**Equation 19 - Out-of-time-order correlator**

$$F(t) = \langle W^\dagger(t) V^\dagger W(t) V \rangle$$

**Equation 20 - Quantum state fidelity**

$$F(\rho,\sigma) = \left(\mathrm{Tr}\sqrt{\sqrt{\rho}\,\sigma\sqrt{\rho}}\right)^2$$

**Equation 21 - Likelihood-ratio independence statistic**

$$\Lambda = 2\sum_{x,y} n_{xy} \ln\left(\frac{\hat{p}(y|x)}{\hat{p}(y)}\right)$$

**Equation 22 - Approximate sample size near p=1/2**

$$N_{\text{per arm}} \approx \frac{2(z_{1-\alpha/2} + z_{1-\beta})^2}{\delta^2}$$

## Appendix B - Experimental build summary

| Experiment | Can be built with present technology? | What it establishes | What it cannot establish alone |
|---|---|---|---|
| 1. Photonic P-CTC/PRC bench | Yes | Reproduces P-CTC postselection and directly tests the no-later-conditioning PRC. | A postselected correlation alone is not a physical time signal. |
| 2. Quantum-processor capacity emulator | Yes; already closely related demonstrations exist | Tests circuit logic, noisy capacity, scrambling, nonlinear conditioned behavior, and cascade coding. | Cloud or laboratory postselection remains a simulation of the temporal resource. |
| 3. Sealed-record operational search | Yes as an experimental architecture; the hypothesized physical resource is unknown | Places the decisive Level IV claim under controlled experimental test. | A null result does not disprove all imaginable retrocausal theories; it constrains the tested resource class. |

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