From Counts to Observables

The response layer of a finite record substrate: a bridge for physicists, information scientists, and engineers

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Abstract

Every measurement chain an engineer has ever calibrated divides an indication by a transfer function to recover an invariant. Since the 2019 redefinition of the SI, the invariants at the bottom of every such chain are *counts* — fixed integers — and everything instrument-shaped is transfer. This paper takes that architecture seriously as physics. In a finite record substrate, dimensionless constants arise as exact rational *counts* — shares of a finite service ledger — while experiments only ever read *responses*: in-in (closed-time-path) correlators driven by a probe. The principle is: *records say what can be known; responses say what experiments measure.* We formalise the bridge between the two as five theorems, each verified by a self-asserting computation: (i) the monitored theory splits into a commuting, copyable record algebra and a non-commuting response algebra; (ii) a *collapse theorem* — for a latched record channel the spectral function is an equal-time contact whose residue is exactly the count, so every probe observable factorises as $O = T(\text{probe}; \text{scheme}) \times r$; (iii) *rigidity* — counts have no anomalous dimension: scheme changes move T, never r; (iv) a five-front ledger showing that the observables where bare counting historically stalled (QED, electroweak, black-hole emission, CMB, continuum QCD) are exactly the fronts where $T \neq 1$; and (v) a *reading law* — Born weights are count shares at the latch, with interference confined to the response layer. The classical limit recovers calibration practice (Wheatstone bridges, lock-in detection, Kalman observability) as the commutative special case, which is why engineering developed the split without naming it. We close with a forward path for quantum information theory: latching as a free operation, record capacity as an operational measure of classicality, a conjectured record/response complementarity, and stabiliser codes re-read as engineered record algebras with calibration-free syndrome statistics.

1 Introduction: three audiences, one architecture

An engineer, a physicist, and an information scientist each own a piece of the same idea.

The engineer's piece is *calibration*. A pressure transducer does not read pressure; it reads a voltage, and the voltage equals a transfer function times the measurand, plus noise. The discipline of metrology — reference standards, calibration certificates, traceability chains — exists to measure the transfer function so that it can be divided out. Since the 9th SI brochure came into force in 2019, the quantities at the root of every traceability chain are *counts*: the second is 9 192 631 770 caesium oscillations by definition, the ampere counts elementary charges, the mole is a fixed number of entities [1]. Modern metrology, by its own internal evolution, arrived at a two-layer architecture: invariant counts at the bottom, transfer chains above them.

The physicist's piece is the *in-in correlator*. A real experiment happens in time: a probe drives the system, and a detector reads the reaction. The natural formalism is not the scattering (in-out) amplitude but the closed-time-path (CTP) generating functional of Schwinger and

Keldysh [2, 3], in which influence of an environment enters through the Feynman–Vernon functional [4]. Everything an apparatus can register is a functional derivative of this object — a *response*.

The information scientist's piece is the boundary of the *knowable*. Quantum Darwinism [5, 6] identifies what is objectively knowable about a system with what is redundantly copied into its environment — and no-cloning [7, 8] guarantees that only a commuting, pointer-diagonal sector can be so copied. What latches redundantly is a *record*; what cannot latch can only be *measured*, once, as a response.

This paper assembles the three pieces into a single load-bearing principle for a finite record substrate — the programme in which dimensionless constants arise as exact rational shares of a finite service ledger [9, 10]:

> **Records say what can be known; responses say what experiments measure.** A count is record-layer data: an exact rational. An observable is response-layer data: a probe-dependent, scheme-dependent correlator. The bridge is a factorisation theorem,
>
> $$O = T(\text{probe; scheme}) \times r,$$
>
> transfer times count, with all scheme dependence in T and none in r.

Sections 3–8 state and prove the five bridge theorems at the level of finite monitored systems, in a form that is checked line-by-line by a self-asserting computation (the programme's standing verification discipline; every quantitative claim below cites its gate). Section 2 first gives the engineering on-ramp: the classical limit in which every theorem is true but trivial, which is exactly why a working discipline could use the split for a century without needing to name it. Section 7 assembles the physics ledger — five fronts, five counts, five transfers, with live experimental comparators. Section 9 offers the forward path for quantum information theory, ending in five concrete open problems.

Two scope fences, stated before anything else. First, SI counts are integers *by convention*: humanity chose to nail the second to a caesium integer. The substrate programme's counts are claimed to be *derived* rationals — a strictly stronger and strictly more falsifiable claim, and nothing in this paper hides the difference. Second, in classical engineering the unobservable sector of a state space is contingent — add sensors and it shrinks. The quantum unknowable sector is absolute. The engineering limit is the *commutative special case* of the bridge, not an independent instance of it.

2 Calibration as response theory: the engineering on-ramp

Consider the working vocabulary of measurement engineering and control theory:

- *State versus output.* A plant has an internal state x; the sensor suite reads $y = Cx + \text{noise}$. Nothing guarantees C is invertible; Kalman's observability theory [11] characterises exactly which functions of the state can ever be reconstructed from outputs. The unobservable subspace is ledger content the response layer cannot reach.
- *Calibration chains.* The instrument's T is not computed from first principles; it is *measured against a standard*, and the standard against a better one, terminating (since 2019) in a count [1].
- *Ratiometric practice.* Wheatstone bridges, four-wire resistance measurement, lock-in detection, differential pairs: the craft of arranging for the *same* imperfect hardware to touch both the quantity and the reference, so that the transfer cancels in a ratio. This is precisely the operational form of the rigidity theorem below (Theorem 2): $r = O/T$ with O and T taken through the same probe.

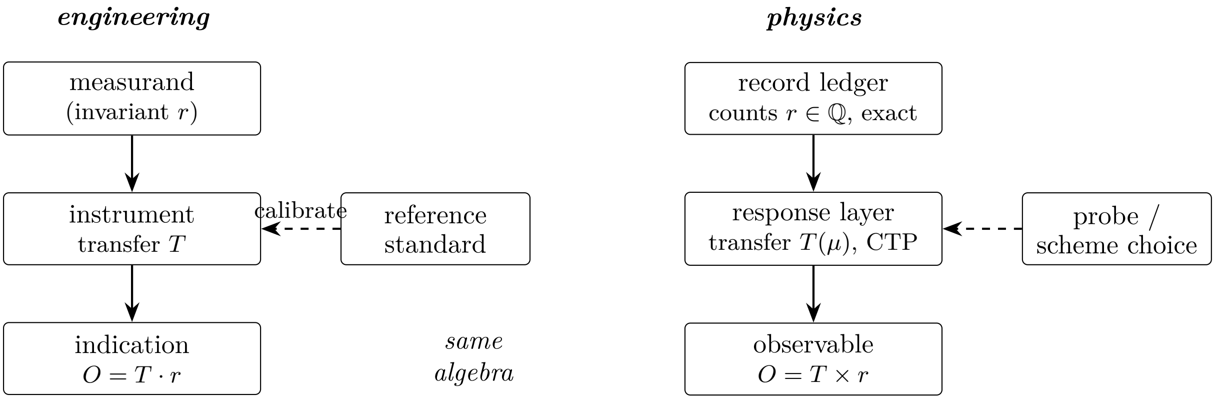

Figure 1: One architecture, two dialects. Left: every calibrated measurement chain recovers an invariant by dividing an indication by a measured transfer function; since SI-2019 the root invariants are counts. Right: the bridge of this paper — exact rational counts in the record ledger, all probe and scheme dependence in the response transfer, observables as their product (Theorem 1).

- *Uncertainty bookkeeping.* The GUM [12] separates Type A (statistical scatter — noise the measurand's records legitimately carry) from Type B (systematic — error in the transfer estimate). The CTP formalism makes the same cut: the symmetric (Keldysh) channel carries classical noise; the retarded channel carries what a probe can extract.

Each item is a shadow of one bridge theorem. The reason engineering never needed the theorems is the classical limit: when everything commutes, *every* channel is latched, every observable factorises, and conflating the ledger with its readout costs nothing. You may pretend the sensor reads the state and stuff the discrepancy into "calibration". The split becomes load-bearing exactly where copying fails — no-cloning draws by theorem the boundary engineering drew by practicality. That is the content of the next three sections.

3 The record layer: what can be known

3.1 Records

A *record* is a degree of freedom that has *latched*: its value has been written, redundantly and irreversibly, into many subsystems. Three properties characterise record-grade data, and each is checkable:

1. **Pointer-diagonal, $\{0, 1\}$ spectra.** A record readout is a projector: an event either latched or it did not. There are no fractional records.

2. **Mutual commutativity, at equal and unequal times.** Latched values are classical data; reading one does not disturb another. In particular a record variable commutes *with its own past*: once written, its history is a consistent classical trajectory.

3. **Copyability.** Records clone perfectly — that is what "redundantly written" means, and it is exactly the sector no-cloning permits: a CNOT copies the record basis with fidelity 1, while a superposition copies with fidelity $\frac{1}{2}$ [7]. Quantum Darwinism promotes this to a definition of objectivity: what is knowable about a system is what the environment holds many copies of [6].

The bridge gate verifies all three on explicit finite models (basis-copy fidelity 1.0 exactly; superposition fidelity 0.500; record–record commutators 0 to machine precision) [13].

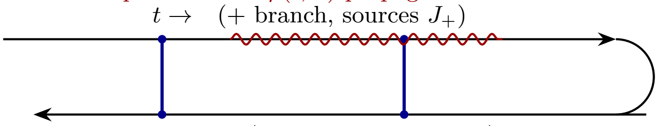

Figure 2: The closed time path. Correlators live on a forward (+) and backward (−) branch. A *latched record* interacts with the contour only through equal-time ties — its unequal-time commutators vanish — so its spectral function is a pure contact with residue equal to the service count (Theorem 1). An *open* quantum channel propagates between different times and does not factorise.

3.2 Counts

The substrate's record layer is a *finite service ledger*: a fixed alphabet of record channels serviced by a scheduler. A *count* is a share of that ledger — necessarily an exact rational. The programme's worked example: a sixteen-letter record alphabet admits $\binom{16}{2} + 16 = 136$ symmetric record pairs; with the idle channel the service alphabet has 137 channels, and the bare service rate is

$$\alpha_0 \;=\; \tfrac{1}{137},$$

one channel's share, exactly [9]. Other ledger shares appearing below: the depth-4 formation register's busy exposure $\frac{15}{16}$ (all states bill except the completed one — a $2^4 - 1$ combinatorial), the service-clock shares $\frac{27}{28}$ and $\frac{1}{28}$, and the composite $\frac{3}{4}\alpha_0^4$. The reader does not need the substrate's derivations to follow this paper; the point is architectural. Counts are rationals because ledgers are finite — and, critically, they stay rationals because of Theorem 2.

One more record-layer fact matters for what follows: parts of the ledger are *unknowable*. The non-commuting remainder of the algebra never latches; no environment holds copies of it; it is measurable (once, destructively, as a response) but never knowable in the Darwinism sense. Classically the unobservable subspace is an engineering budget line — add sensors and it shrinks. Here it is structural.

4 The response layer: what experiments measure

An experiment prepares, drives, and reads — all in time. The generating object is the closed-time-path functional [2, 3, 14]: fields live on a contour that runs forward with sources J_+ and back with sources J_-, and correlators come in four Wightman blocks,

$$C_F = \langle \mathcal{T}\,\phi\phi \rangle, \quad C_B = \langle \bar{\mathcal{T}}\,\phi\phi \rangle, \quad C^> = \langle \phi(t)\phi(t') \rangle, \quad C^< = \langle \phi(t')\phi(t) \rangle,$$

obeying the normalisation identity $C_F + C_B = C^> + C^<$. Two combinations organise everything:

$$\rho \;=\; C^> - C^< \qquad \text{(spectral function: what propagates, what a probe can kick)},$$

$$C_K \;=\; C^> + C^< \qquad \text{(Keldysh/statistical function: the noise the state carries)}.$$

The retarded kernel $K_R(t,t') = \theta(t-t')\,\rho(t,t')$ is the response proper: Kubo's linear-response coefficient, the thing every driven measurement actually reads. When part of the world is traced out — an environment, or a monitoring apparatus — its entire effect on the rest enters as the Feynman–Vernon influence functional [4], quadratic in the sources with exactly these kernels. Monitoring is therefore not an interpretational afterthought; it is an addend in the action.

5 The collapse theorem: how a count enters an observable

Theorem 1 (Collapse)**.** *Let $R(t)$ be a latched record channel with service count r per tick: $[R(t), R(t')] = 0$ for $t \neq t'$, with the service event contributing the only equal-time antisymmetric content. Then the spectral function is a pure contact,*

$$\rho(t,t') \;=\; C^{>} - C^{<} \;=\; r\,\delta_{tt'},$$

and for any probe with transfer kernel G the measured observable factorises exactly:

$$O \;=\; G\,\rho\,G^{\dagger} \;=\; r \times GG^{\dagger} \;=\; T \times r.$$

The count is the entire retarded content of a record channel; everything else in O is the probe's own dressed propagation.

Proof sketch. (i) Unequal-time commutativity kills every off-diagonal element of ρ: for $t \neq t'$, $C^{>}(t,t') = C^{<}(t,t')$ because the operators commute — a latched history is classical, so ordering does not matter. (ii) The remaining support of ρ is the equal-time diagonal, where the antisymmetric content is the service event itself; its weight per tick is by definition the count r. (iii) The retarded kernel is then $\theta\rho = r \times$ (contact), and convolving a contact with the probe's kernels gives the factorised form. The classical (Keldysh) channel C_K meanwhile retains the record's full autocovariance — records carry statistics; they are what can be known — but C_K sources nothing: a latched ledger does not radiate. □

The verification gate builds both channels explicitly on a 24-tick contour [13]: for the latched channel with $r = \frac{15}{16}$ held as an exact fraction, $\max|\rho - r\delta| = 0$ identically and $\max|O - rT| = 8.9 \times 10^{-16}$; for an open channel (a positive spectral bath of six modes, the same kernels used in the QED endpoint reconstruction [15]), ρ has off-diagonal magnitude 6.6 and the best scalar fit $O \approx cT$ leaves a 100% residual. The factorisation is not approximate for records and is not available for open channels; the theorem is sharp on both sides.

Theorem 1 is the general form of what the QED endpoint-action reconstruction found in the concrete case [15]: monitored (latched) Wilson-line endpoints do not source classical fields — the four Wightman blocks cancel in the classical channel — and couple retardedly only through the service contact. There, the surviving contact is what carries α_0 into electromagnetic response.

6 Rigidity: why counts do not run

Theorem 2 (Rigidity)**.** *Counts have no anomalous dimension. (a) Algebraically: a record readout obeys $P^2 = P$; the rescaled candidate ZP is idempotent only at $Z = 1$, so the record algebra admits no wave-function renormalisation. (b) Operationally: if the same probe (dressed by any scheme factor Z) measures both the observable O and the transfer T, the extracted count $r = O/T$ is Z-invariant identically. All scheme dependence lives in T.*

The gate sweeps $Z \in [0.6, 1.4]$: the idempotence defect is $O(1)$ at every $Z \neq 1$; across the same sweep the transfer moves by 444% while the extracted count varies by 1.7×10^{-18} and equals $\frac{1}{137}$ to machine precision [13].

Part (b) is Wheatstone's principle promoted to a theorem: arrange for the reference and the unknown to share the same arms, and the arms drop out. Every ratiometric technique in the engineer's kit — bridge circuits, four-wire sensing, lock-in detection, chopper-stabilised amplifiers — is a scheme for enforcing the hypothesis of Theorem 2(b) in hardware. The physics translation is worth stating plainly: *a count is a calibration-free observable.* A transfer is not: it runs, it renormalises, it depends on scheme and scale, and computing it to the needed order is real work — which is the subject of the next section.

front	count r (exact)	transfer T	live comparator
QED α	$\alpha_0 = \frac{1}{137}$	endpoint-vertex dressing	inside the Cs/Rb dispute
electroweak v	$C_v \to \frac{15}{16}$	Coleman–Weinberg + RG	pull -0.13σ
CMB primordial	$A_s = \frac{3}{4}\alpha_0^4$; $n_s = \frac{27}{28}$	radiation transfer (external)	$z = +0.97$; $z = -0.15$
BH emission	horizon record structure	greybody flux	conditional grade
continuum QCD	graph-dict record geometry	metric-weighted normalisation	bridge scalar 3.9998

Table 1: The count/transfer ledger. Counts are exact rationals from the record layer; transfers are scheme-dependent response computations; comparators as of July 2026 (see text for values and sources).

7 The observable ledger: five fronts, five transfers

The substrate programme's headline numbers all have the form $O = T \times r$. Table 1 lists the five fronts on which bare counting historically stalled, with the count, the transfer, and the current live comparator on each. The table is *self-verifying* in the programme's repository: a gate recomputes every count as an exact rational in-process, requires every named transfer computation to exist on disk, and requires the live comparators to land [13].

QED. The count is $\alpha_0 = \frac{1}{137}$ (the alphabet share of Section 3); the transfer is the endpoint-vertex dressing chain, whose CTP clauses were derived rather than assumed [15]. The composed landing, $\alpha^{-1} = 137.035999107$, currently sits *inside* the unresolved experimental dispute between the two best atomic-recoil determinations — caesium, 137.035999046(27) [16], and rubidium, 137.035999206(11) [17], with CODATA at 137.035999084(21) [18] — which disagree with each other at the 5σ level. The bridge's reading: the disagreement is a transfer-layer dispute in the metrology, and its resolution is a registered discriminator for the count-layer claim.

Electroweak. The count is the busy-projector exposure $\frac{15}{16}$, characterised by an if-and-only-if theorem (record grade + no self-billing + service completeness select it uniquely among all 65,535 readouts). The transfer is the effective-quartic chain λ_{eff}: Coleman–Weinberg at fixed scheme plus renormalisation-group running, currently computed at full-order running grade with a measured prescription band, giving a required $C_v = 0.93864 \pm 0.00888$ against the count's $\frac{15}{16} = 0.9375$ — a pull of -0.13σ. The remaining distance is explicitly a transfer programme (the two-loop effective-potential integrands of 19), not a search for a new integer.

CMB. The primordial pair is pure count: $A_s = \frac{3}{4}\alpha_0^4 = 2.1290 \times 10^{-9}$ and $n_s = \frac{27}{28} = 0.96429$, against Planck 2018's $A_s = (2.100 \pm 0.030) \times 10^{-9}$ and $n_s = 0.9649 \pm 0.0042$ [20] — z-scores +0.97 and −0.15. Here the transfer (radiation transport from primordial power to observed spectra) is external, classical, and supplied by the standard cosmological pipeline: the bridge's division of labour is visible in how the community already reports "primordial parameters".

Black holes and QCD. The Hawking front pairs horizon record structure with a greybody transfer (conditional grade at the time of writing); the continuum-QCD front pairs the graph-dictionary record geometry with a metric-weighted plaquette normalisation whose lattice-to-continuum bridge scalar computes to 3.9998 against the geometric 4. Both are cited here as ledger rows, with their detailed status held by their own gates in the repository.

The steering rule. The table's pattern is the paper's practical payoff, and within the programme it is now a derived rule rather than an observed habit: *when an observable disagrees with a bare count, compute the transfer to the next grade — never hunt a new integer.* Historically,

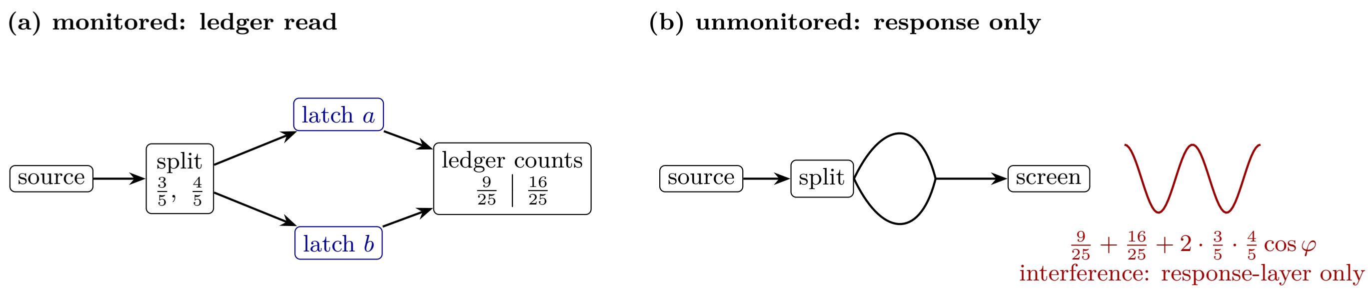

Figure 3: The reading law on a two-path system with exact amplitudes $\frac{3}{5}, \frac{4}{5}$. (a) Monitored: each pass latches a which-path record; the ledger's count shares are $\frac{9}{25}$ and $\frac{16}{25}$ exactly — the Born weights, read as counts. (b) Unmonitored: the screen response keeps the interference term $2ab\cos\varphi$, which lives only in the response correlator — there is no record to read, so there is nothing in the ledger to disagree with it. Records commute; they carry no phase.

counting carried the programme quickly to α_0, A_s, n_s, $\frac{15}{16}$ — and then stalled at precisely the five fronts above. The bridge explains the stall: those are the fronts where $T \neq 1$, and each became tractable the day it was treated as a precision-transfer programme.

8 The reading law: Born weights as count shares

The last theorem closes the loop between the layers.

Theorem 3 (Reading law)**.** *Probabilities are count shares of latched records. At a latch event, the record ledger inherits weights from the response-layer inside score (the coherent squared amplitude); thereafter the weights are counts — exact, commuting, copyable, phase-free. Interference exists only in the response algebra: for unmonitored alternatives there is no record, hence nothing to which a probability, in the counting sense, yet attaches.*

On the two-path example of Figure 3 (amplitudes $\frac{3}{5}, \frac{4}{5}$), the gate confirms the monitored ledger shares equal the Born weights exactly ($\frac{9}{25}, \frac{16}{25}$, summing to 1 as fractions) and that the unmonitored screen response carries the full interference term $2ab\cos\varphi$ with amplitude $2 \cdot \frac{12}{25}$ [13]. The statement is the CTP-language form of the reading law introduced with the programme's parsing formalism (probabilities as the count-reading of coherent inside scores) [21], and it is consistent with, and gives a finite-ledger mechanism for, the decoherent-histories account of when probabilities may be assigned at all [22, 23].

Three familiar puzzles look different from here. The *measurement problem* becomes, in this architecture, a category error: collapse is not a dynamical process in the response layer but the bookkeeping of a latch — the moment content crosses from the measurable to the knowable. The *Born rule's* special status becomes the statement that there is exactly one consistent exchange rate between inside scores and count shares. And the classical world's *objectivity* is Darwinism's redundancy, here counted rather than merely described. None of these observations is a proof of an interpretation; they are what the two-layer accounting makes natural.

9 A forward path for quantum information theory

Quantum information theory already lives on both sides of the bridge without saying so. Its resources — coherence, entanglement, magic — are response-layer objects: precisely the content that cannot latch. Its classical interfaces — syndrome extraction, measurement records, broadcast channels — are engineered record algebras. Making the split explicit suggests a research programme; we state it as one reframing and five problems.

The reframing. Treat *latching* as a free operation and *counts* as invariants. A stabiliser code [24, 25] is then an engineered two-algebra split: the syndrome algebra is a designed record layer (commuting, $\{0, 1\}$, copied into classical control hardware every cycle), and the logical algebra is the protected response layer. Code design is the choice of *where to draw the record boundary* inside a physical substrate. Theorem 2 then makes a concrete, testable claim about fault-tolerant hardware: syndrome *statistics* are calibration-free observables — scheme drift in the readout chain cancels in ratiometric syndrome quantities, while the logical channel's fidelity (a transfer) drifts. Holographic error correction [26] sits naturally here too: bulk operators are response-layer content reconstructable only where the record boundary permits.

Problem 1 (Record capacity)**.** *Define the record capacity* $\mathsf{R}(\mathcal{N})$ *of a dynamics* $\mathcal{N}$ *as the optimal asymptotic rate (bits per use) at which Darwinism-grade records — redundancy* $\geq k$ *across specified fragments — can be latched through* $\mathcal{N}$*. Relate* R *to the Holevo and coherent-information capacities [27]; determine whether* R *is additive; exhibit channels with* $\mathsf{R} = 0$ *but positive quantum capacity, and conversely.*

Problem 2 (Complementarity)**.** *Prove or refute: for fixed* $\mathcal{N}$*, record throughput and preserved response coherence obey a trade-off of information–disturbance type — increasing the latched sector's rate necessarily degrades the coherent sector's fidelity, with an equality case characterising ideal syndrome extraction.*

Problem 3 (Latched-sector identifiability)**.** *Characterise the channel families for which the factorisation* $O = T \times r$ *is exactly recoverable from data: when can a finite probe ensemble separate the contact residue (the count) from the transfer, with certified error bars, in the presence of non-latched leakage? This is the quantum version of instrument identifiability in system identification.*

Problem 4 (Rigidity-optimal codes)**.** *Given a noise model, choose the record boundary (the stabiliser group) to maximise count rigidity: syndrome statistics maximally insensitive to readout-chain scheme drift. Does rigidity optimisation coincide with, or trade against, distance optimisation? A positive theory here would make "calibration-free fault tolerance" a design target rather than an accident.*

Problem 5 (Device-independent counts)**.** *Counts are exact rationals; self-testing certifies structure from statistics alone. Can a ledger share (a rational count, e.g.* $\frac{15}{16}$*) be certified device-independently — from observed correlations, without trusting the apparatus — the way singlet statistics self-test the singlet? A positive answer would make count claims falsifiable at the strongest possible (device-independent) grade; quantum metrology's Fisher-information bounds [28, 29] would then apply only to the transfer factor, sharpening what precision is* for*.*

The through-line: quantum information theory has treated classicality as a resource-theoretic *absence* (decoherence as loss). The bridge suggests treating the record layer as a first-class object with its own capacity, its own invariants, and its own engineering discipline — calibration — inherited from two centuries of classical practice.

10 Scope, falsifiability, outlook

What would kill the bridge? Front by front: an observable whose residual against its count *cannot* be absorbed into a computable transfer — a discrepancy that survives every legitimate scheme choice at every computable order — falsifies the factorisation claim for that front. The programme maintains registered discriminators of exactly this type (the α-metrology resolution; a next-generation G measurement; the electroweak two-loop close), each with pre-stated kill conditions [30]. Conversely, the bridge is *not* falsified by transfer disputes as such: the Cs/Rb disagreement is currently a dispute inside the response layer of the metrology itself.

The two scope fences of Section 1 bear repeating at the exit. SI-2019 shows humanity *choosing* a count-rooted architecture for its units [1]; the substrate programme claims nature *derived* one for its constants. The first is precedent, not evidence. And the engineering limit is the commutative special case — the place where the theorems are true, trivial, and therefore invisible. The quantum world is where the split pays rent: aspects of the ledger are unknowable in principle, records and responses genuinely differ, and the difference is where the measurement problem, the Born rule, and the constants question all turn out to live.

For the working reader, one sentence per discipline. To the engineer: your calibration chain is a theorem about nature, and since 2019 your standards bottom out in counts — physics may too. To the physicist: when a clean number misses, compute the transfer to the next order before you reach for a new constant. To the information scientist: the knowable is the copyable; count it, and let everything that cannot be copied be what it is — response.

Reproducibility. Every quantitative claim in this paper is asserted by a self-checking computation in the programme repository (the bridge gate and the gates it imports and cites: endpoint reconstruction, busy-projector characterisation, running-grade prescription band, normalisation theorem) [13, 15]. The programme's published chain, including the registered predictions cited above, is archived on Zenodo [9, 10, 21, 30–32].

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