Anchored Causality Theory: A Record-History Ontology for Open Quantum Systems

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Abstract

Quantum mechanics describes a wave that spreads and interferes; a detector records a particle at one place and time. Anchored Causality Theory (ACT) accounts for both: the electron is a stable wave-mode structure of one composite field, never a particle on a path. A detector's bath of photons and atoms keeps a record that tells the alternatives apart, say the two lobes of a wave behind two slits. The record is released, beyond recall, when nothing the system will actually undergo can restore interference. One alternative becomes an event: a mark in the one actual history. No observer is needed; Schrödinger evolution is never modified.

Four thought experiments, each performed in the laboratory, carry the argument. An unread lossy slab removes the fringes; a tunable coupling sets their fading rate; a reversible filter sorts the field's components, producing no event; and single marks build fringes with no path recorded, a particle pattern once a path record is released. For an event of ACT's kind, eraser and recovery experiments exclude every earlier moment tested; release is the earliest allowed.

ACT changes no quantum prediction and adds one commitment: one history of released records is actual. No event leaves two marks: proved where the bath returns no record, assumed beyond. Given refinable records, two requirements force Born weights: a record's chance here is unchanged by whether records are made elsewhere and continuous in the wave. A covariant release criterion is open. The wave is what exists; the particle is what happens.

Keywords: Measurement problem · Quantum events · Decoherence · Quantum Brownian motion · Interpretations of quantum mechanics · Wave–particle duality

1 The ontology in one page

Send electrons through two slits, one at a time. Each lands as a single dot on the screen. Slowly the dots build up fringes, the pattern a wave makes. So one and the same electron has been asked to be two things: a wave that spreads and interferes, and a particle that lands in one place. The request has a name, wave–particle duality, and its puzzles are famous. Which slit did the electron go through? Does a cat's fate wait for someone to open the box? Can a choice made after a photon has passed the slits reach back and decide which way it went? Can erasing a record bring back fringes already lost? Every interpretation of quantum mechanics is a way of living with the request. Anchored Causality Theory (ACT) refuses it.

The main accounts keep a particle somewhere, at the detector or on a hidden path, or they keep every outcome, each in a world of its own. ACT does neither. The electron is a wave from start to finish. The particle is the mark a bath makes: the detector's own surroundings of light

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and vibrating atoms keep the record, and no one has to look. One history of marks is actual. Other interpretations ask how a superposed quantum state yields a definite result. ACT begins with a real wave and asks how the environment produces a definite event.

The wave is what exists. The particle is what happens.

COMPOSITE FIELD ⟶ A BATH CARRIES A RECORD ⟶ AN ANCHORED MARK

A quantum system is one real, composite wave: a field with internal structure, the way a sound wave contains its harmonics. Its superposition is the composition of that one wave. A particle is not a second kind of thing the wave turns into. It is an event: the mark a detector makes when it anchors one mode of the field, one of its harmonics. A track is a chain of such marks. The history of anchored marks, not the wave alone, is the definite, temporal, causal world.

With the particle gone, the puzzles have nothing left to stand on. Which slit? The wave went through both; there was never a particle to go through one. Does the cat's fate wait for a look? No. In any real box the Geiger counter's bath makes the mark, whether or not anyone looks. Does a later choice reach back in time? There was no particle path for it to decide, and it changes no mark already made (Section 8.3). Are there copies of you in other worlds? One mark, one history, one of you (Section 8.4).

The rest of this section says what each part of the picture is: what exists, what happens, what never changes, and what ACT adds. Anchoring also supports a reading of time. That reading is a layer on top of the mechanism, set out in Section 3.2, and nothing else in the paper depends on it.

What exists. One field, with composite structure. Take a single photon that is said to be "in two places". It is one excitation of one mode with two lobes:

$$\tfrac{1}{\sqrt{2}}\big(|1_A, 0_B\rangle + |0_A, 1_B\rangle\big) = b^\dagger|0\rangle, \qquad b^\dagger = \tfrac{1}{\sqrt{2}}\big(a_A^\dagger + a_B^\dagger\big). \tag{1}$$

Here $a_A^\dagger$ and $a_B^\dagger$ put a photon at the two places, and $b^\dagger$ puts one in the mode that spans both. In the mode basis $\{b, b_\perp\}$ the state is one photon in one mode. The photon is not in two places. It is in one mode that has two lobes. Nothing here is two of anything. A detector placed at A couples to a_A, the lobe at A, and that lobe is the mode it can anchor. Which decomposition of the wave matters is not a human choice. The dynamics decide it: when a field meets an apparatus, they select the alternatives the interaction can hold stable (Section 3; a theorem in the model of Appendix D). Quantum field theory already says that an electron is a quantum of a field, not a small body. ACT carries that to the detector and says how a wave leaves one mark.

What happens. Every detector sits in a bath: photons, phonons and the motions of its own parts, all present before any measurement. When a mode of the field couples to that bath, the bath begins to keep a record: an imprint in its own state that tells the alternatives apart. That is decoherence. While the record can still be undone, no event has occurred. Then the bath carries the record off for good: nothing the system will actually go on to meet can recover the phase between the alternatives. The record is now *released*. ACT says that at that point one of the record's values obtains: an event is *anchored*. One record, one fact, now in causal time. Anchoring does not reduce the wave. It adds a determination. Which record obtains was undetermined; now it is determined, and it stays so.

What never changes. "The Schrödinger evolution is never modified" means one specific thing. The whole closed system—the field, the detector and the bath around it—obeys the

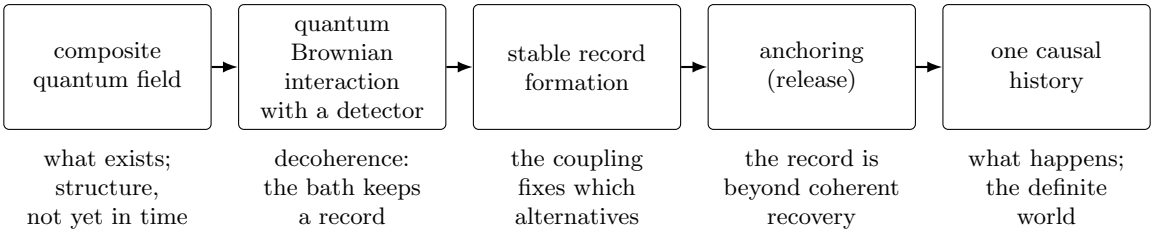


Figure 1: The backbone chain of ACT. Every statement in the theory is about one link of this chain. The first two links, and the physics of the third, are measured in the laboratory and are shared with every interpretation that keeps unitary quantum mechanics. The selection theorem (Appendix D) is ACT's statement of the third link. The event law places the event at the fourth. The fifth is the one commitment.

Schrödinger equation at every moment, during a measurement included. Nothing is added to the equation or applied to the state of the whole: no collapse term, no noise field, no projection. What changes at an event is not the wave but which history is actual. A different state does jump: the state of the system alone, conditioned on the records made so far (Section 7). That state is a description relative to the actual record, not a second dynamics. Average it over the histories that could have occurred, with Born weights, and it returns the ordinary evolution of the open system, the master equation. It never returns the state of the whole. The whole is never conditioned, and the interference between the components the records tell apart, which no average of conditioned states contains, is still there as structure of the one wave. The event law of Section 4, which says when an event happens, among what alternatives and with what chance, reads all three off the Schrödinger evolution and adds a fact. It never feeds anything back into the equation.

What is added. Beyond unmodified quantum mechanics, ACT adds one commitment: one record history is actual. One further statement is needed, that an event leaves one mark and never two. For the networks of Appendix B, a system with a bath that carries each record away and never brings it back, it is a theorem: their released records all commute, like classical variables, so the histories they define exclude one another. Beyond those networks it is a further commitment. No new field, constant, threshold or noise is introduced. Probability is ordinary: one outcome occurs, with a Born-weighted chance. Given one actual history and records that can always be refined, two requirements on the chance of a record, which Section 4 states, force the weights (Appendix A).

The physical picture is the single chain of Fig. 1. In one line: *quantum mechanics describes the real structure of possibility; anchoring describes the production of fact.*

What this paper does. The sections follow the order a reader needs. Section 2 says what "measurement" means. Section 3 states three principles. Section 4 states the event law: what, when and which. Section 5 says what is derived and what is postulated. Section 6 tells the four experiments. Section 7 gives the formal backbone. Section 8 takes up Bell, Wigner's friend and the single history. Section 9 sets ACT beside the other interpretations, and Section 10 states its scope and open problems. The proofs the argument rests on are in the appendices: the Born weights (Appendix A); records, release and exclusivity (Appendix B); the event law (Appendix C); and the selection theorem (Appendix D). Two further papers, one on the quantum Brownian motion case in two exactly solvable models and one on the record algebra in full, extend them [106, 107].

2 The Rock: remove the observer, and the record remains

The double slit is usually told in two versions, without an observer and with one. Without an observer, the marks on the screen build up fringes. With one, the fringes vanish. The word "observer" has complicated the experiment's interpretation for decades, because it joins two things: a body that keeps a record telling the two paths apart, and someone who reads that record. The Rock removes that complication. It keeps the body that records and takes away anyone who reads.

> Send electrons through a double slit and they build fringes. Take away the detector at the slits and put a plain slab beside one path, with nothing reading it. The fringes die anyway. A resistive slab kills them. A good conductor barely touches them. An ideal superconductor should leave them alone. Nothing observed anything. The slab's own electrons, stirred by the passing charge, carried a record of the path off as heat. That is the bath. For a slab, the record follows the dissipation: no dissipation, no record.

The laboratory has done the silicon and the gold. Electrons in a biprism interferometer, the electron analogue of the double slit, pass a few micrometres above a plate of doped silicon. They lose their fringes as the height shrinks and the path separation grows, to zero near the surface [110]. Beside gold, whose resistivity is about a million times lower, the loss in the same geometry is far weaker; macroscopic quantum electrodynamics fits the data without a fit factor and excludes three competing models [78]. Atoms passing a nanograting pick up van der Waals phase shifts and keep their fringes [95]: an interaction that keeps no record leaves coherence alone.

Three things follow, and together they are what ACT means by measurement.

1. **A detector is any body that keeps an irreversible record of the mode it couples to**, whether or not anything reads it. A laboratory detector is a device built to couple a signal into a continuum, with amplification. But what makes it a detector is not that it is read. Detectors and observers anchor events because they are coupled to the bath, not because they observe. The detector/observer effect is the bath's effect.
2. **Interaction is not the criterion; a record is.** The gold slab interacts as the silicon slab does. It keeps almost no record, and the fringes largely stay. What destroys interference is which-path information held irreversibly by something else, not disturbance of the system.
3. **Which record is written is fixed by what is physically coupled**: the slab actually present, the magnet actually in the beam. No one's choice fixes it. The physicist can exploit that coupling; the physicist does not fix it.

This is also the sense in which decoherence is built into ACT rather than added to it. In the Rock the dissipative response that keeps the record is the decoherence. Read run by run, each electron is anchored at the slab or not yet anchored, and the contrast that remains is the share of runs not yet anchored (Section 4, Eq. (5); Section 6, the Mark). In general it is the coupling that keeps the record, whether or not energy is exchanged. A theory whose mechanism is a bath does not need to add decoherence; it cannot avoid it. The Rock places the first link of the chain in Fig. 1 on measured ground.

3 Three principles

The picture rests on three principles. Each is stated, then given its physical content. Together they say what the mark is: the bath anchors one mode of the field. On the interpretive layer of Section 3.2, that is also where the mode enters time.

3.1 The field and its modes

A quantum system is one composite field, and its superposition is its mode structure. "One composite field" means one state of the field the system excites, with its mode structure. It is not a new species of field, and not one field for everything. Equation (1) is the simplest case. In general a superposition is a decomposition of one state into components. Three things that discussions of measurement run together must be kept apart:

- *components*: the terms of the one wave in a given decomposition. They are relative to a basis, and they are not objects present side by side;
- *alternatives*: what a detector, with the records it can keep, is able to register. ACT calls such a detector a record-supported instrument. Exclusivity, one outcome and never two, attaches here and only here;
- *the actual history*: the one sequence of anchored records.

Once a mode is coupled to a detector and its environment, the state becomes

$$\Big(\sum_k c_k \,|o_k\rangle\Big) \otimes |D_0\rangle \otimes |E_0\rangle \;\longmapsto\; \sum_k c_k \,|o_k\rangle \otimes |D_k\rangle \otimes |E_k\rangle. \tag{2}$$

Here the $|o_k\rangle$ are the alternatives, the $|D_k\rangle$ are the detector states that register them, and the $|E_k\rangle$ are the states of the environment. Unitary evolution, by itself, goes no further. Every component on the right has the status it had on the left; nothing has been selected. The terms on the right are no longer modes in the strict sense, because entanglement between separate systems cannot be undone by choosing modes differently. They are still terms in the decomposition of one state. And the dynamics, not a choice, fix which decomposition matters: for a free, translation-invariant field the Fourier modes, and not always Fourier. Spin is the reminder.

Two senses of "real" are used in this paper, and they are kept apart. The components of the wave are real in the first sense: they are the structure of the one wave, which is what exists. They carry amplitude. While no record is released they can still interfere. And an observable a record leaves unrecorded can still anchor later. An alternative is real in the second sense when it is the case: when a released record has made it actual. After an event, the alternatives the record did not select keep the first kind of reality and never acquire the second. They are not destroyed, and they are not things. They are structure of one wave in which no event has occurred. Before an event, the components are the possibilities for a mark that the one wave holds. On the one actual history, a released record makes one of them a mark, and only marks make the history (Section 8.4).

3.2 Not yet in time

Before anchoring, the wave has structure but no temporal causal history. The Schrödinger parameter t orders the global state throughout, unanchored components included. But what t orders there is a trajectory of structure, not a sequence of events. The laboratory shows the difference directly. An atom in a cavity gives its excitation to one mode and takes it back [18]. Which-path information held by a single scattered photon can be regained by selecting on the photon [26]. Which-path information carried by an entangled twin can be erased, so that the conditioned fringes return [79, 119, 83]. In each case nothing has been anchored yet. Once the bath has taken the record irreversibly, an event has been anchored, and it has a place in causal order.

Mass belongs to this principle, as the enabler rather than the gateway. A massive excitation's phase turns at its rest-energy rate $mc^2/\hbar$, de Broglie's internal periodic phenomenon, and an atom interferometer has been operated as a clock on that rate [81]. Mass is present before

anchoring. Matter-wave fringes are spaced by $\lambda = h/mv$ out to 172 kDa [4, 39, 94], and neutrons in an interferometer feel gravity on their mass while still in superposition [28]. Mass gives the field a clock; anchoring gives the clock its readings. Because entering time happens at anchoring and not at mass, a massless photon's detection still creates a temporal fact.

This principle is the interpretive layer of the theory. It motivates the name, and the physics it points to is the difference between evolution that can be undone and evolution that cannot. No derivation in this paper depends on it. The paper uses it in three places, each marked as optional: the opening of Section 3, the first paragraph of Section 8.4, and the remark on time in the conclusion. A reader who declines it loses nothing else.

3.3 The bath

The quantum Brownian bath explains the detector effect, and decoherence is its first act. A bath is a continuum of modes coupled to a system. Whatever the coupling, dissipative as in Brownian motion or pure dephasing, the bath acquires information about the variable it couples to, and superpositions of that variable lose coherence. The same coupling does three things at once. It decoheres: the relative phase of the alternatives passes into the bath. It gives the dynamics a direction. In the Markov regime, when the bath keeps no memory of the mode, a mode coupled to a bath evolves by a semigroup: an evolution that runs forward only and has no physical inverse [82, 55]. And it keeps what it takes: what passes into a continuum does not come back, and a large finite bath returns it only after an astronomically long time.

When the bath also damps, the decoherence is fixed by the damping. In the Caldeira–Leggett model of quantum Brownian motion [23], in its high-temperature Ohmic regime, both come from one quantity, $m\gamma$, in the bath's spectral density. The spectral density is the function that says how strongly the bath's modes at each frequency couple to the system. Their ratio is therefore fixed:

$$\frac{\Gamma_{\mathrm{dec}}}{\gamma} = \frac{1}{2}\Big(\frac{\Delta x}{\lambda_{\mathrm{th}}}\Big)^2, \qquad \lambda_{\mathrm{th}} = \frac{\hbar}{\sqrt{2mk_BT}}. \tag{3}$$

Here γ is the rate at which the bath damps the motion, in the convention of the quantum Brownian motion paper [106], Δx is the separation of the alternatives, and λ_{th} is the thermal de Broglie wavelength. One cannot dial the decoherence rate without dialling the damping. For a gram displaced by a centimetre at room temperature the decoherence is about 4×10^{40} times faster than the damping. The laboratory has watched this. A cavity-field superposition lost its coherence progressively, faster for larger separations [19]. The fading was later filmed snapshot by snapshot [29]. In trapped ions, classical noise standing in for a hot bath gave the same growth with the square of the separation [91, 115].

Here ACT parts company with the accounts whose postulates were fixed before decoherence theory existed and took it in afterwards. Copenhagen's cut was placed by hand in 1927, with Bohr's "irreversible amplification effects" left without a dynamical account [24]. Everett's 1957 postulates had decoherence brought in later for the preferred basis [123, 129, 130]. Bohm's positions are always definite, with the empty-packet argument Bohm himself gave in 1952 doing the work decoherence theory later formalized. The collapse models' noise was given its damping partner afterwards, with an extra parameter [105]. Decoherent histories and quantum Darwinism put decoherence first, but neither has a bath that produces an event. ACT is an interpretation whose mechanism is the bath. Its nearest neighbour on this point is the ETH approach, whose events are grounded in radiation escaping to infinity [20] (Sections 9 and 10). Decoherence is therefore presumed, not added: the bath's decoherence is the phase in which a mode enters causal time, and once irreversible it ends in an anchored event. This is a claim about structure, not a new prediction. The decoherence data are the same for every interpretation that keeps unitary quantum mechanics.

4 The event law: what, when, which

The Schrödinger equation is a law of continuous evolution. What it does not supply is a law of events: when a definite occurrence happens, among what alternatives, and with what probability. ACT's event law answers the three questions in the bath's own terms. This section states the law. Its proofs, each in a stated class, are in the appendices: the alternatives in Appendix D, release and exclusivity in Appendix B, the rate in Appendix C, the weights in Appendix A. What matters for the ontology is where each answer comes from.

What: the alternatives the record architecture supports. The *record architecture* is the set of ways the detector and its bath can carry a record off, fixed by their physical coupling. It fixes which alternatives a record can register, and never the outcome. A Stern–Gerlach magnet fixes the axis. A change of reservoir changes the pointer basis, the set of alternatives the coupling leaves stable. In one and the same ion, a dissipative coupling makes coherent states the pointer states and a phase reservoir makes number states the pointer states [115]. That phase reservoir was classical noise: it shows which states a coupling leaves stable, though noise of that kind records nothing (Section 6). This is einselection [129, 130, 131]. ACT adds one theorem to it (Appendix D). In a model where the record forms faster than the probe, the bath quantum that carries it, disperses, the environment's fragments, the parts of it that can be read separately, can condition the system only on where it is. They can never give it a coherent momentum kick. In words: the environment keeps records of position only. The records can tell the actual history where the system was marked. They can never act on the system as a measurement of its momentum would. A record channel is a distinct route, such as a scattered photon, by which the bath carries a record off. The record algebra, the set of records the channels can make and everything built from them, is selected by the coupling and by the record channels the detector that is present supports, before any event (Section 7). Selection is unitary and reversible; anchoring is not selection.

When: release. A record is *released* when nothing the system still does reaches it. The system's *accessible future* is everything the system will still do and every record it will still make, as the network actually runs (Section 7). A released record is beyond coherent recovery by that future: no later observable of the system, and no later record it makes, acts on it by any path along which the network of couplings actually lets a carrier, the photon or phonon that holds the record, return. The *network* is the system together with everything it couples to—the detector, the bath, and any mirror or cavity that can send a carrier back—and the pattern of who interacts with whom, and when. Release is the condition for anchoring. Anchoring is release together with the commitment of Section 5 that one of the record's values obtains. Until release the record is not yet a fact, because it can still be undone. A cavity returns the excitation it took. A scattered photon's which-path information can be erased. Light sent back by a mirror alters the decay of the atom that emitted it. After release the record commutes with everything the system still does, and attaching actuality to it changes no accessible prediction, for any state (Appendix B). Attach it earlier and the actual history is conditioned on a record while interference with the unselected alternatives is still accessible, so that its predictions depart from quantum mechanics'. The recoherence experiments have tested three such earlier placements and found no departure (Section 6).

The rate at which released records form is read off the same coupling that draws the decoherence curve, with no free constant. In the simplest nondemolition case, one rate for every alternative, the two curves are one. Nondemolition means that recording an alternative does not disturb it, as when the bath takes which-path information without disturbing the paths. The probability that no event has yet occurred is then the fraction of the alternatives' relative

phase that can still be recovered:

$$S(t) = e^{-\Phi_{\mathrm{irr}}(t)}, \qquad \Phi_{\mathrm{irr}}(t) = -\ln \frac{\mathcal{D}(t)}{\mathcal{D}(0)}. \tag{4}$$

Here $\mathcal{D}(t)$ measures how well two preparations that differ only in the relative phase of the alternatives can still be told apart, using only the physically accessible algebra (Section 7), and Φ_{irr} is the phase that has been lost for good. The event rate per unit time, the hazard, is $h = g\,\dot{\Phi}_{\mathrm{irr}}$. This scalar law is the case of the general event law, Eq. (8) of Section 7, in which the record channels are nondemolition and share one rate; the general law covers released records of any coupling. The factor g is a gate. It is one when the environment holds a released record that distinguishes the alternatives, and zero when it holds none. Phase can leave the accessible algebra for good with no such record: classical dephasing noise injected from outside, which is not correlated with which alternative holds. Then $g = 0$. Dephasing that records nothing creates no actuality, however fast it is. A record scrambled across many parts of the environment is the other case. It is a record still, released though no fragment can read it, and the gate is open (Section 7). Where the gate is open the hazard is $\dot{\Phi}_{\mathrm{irr}}$, the form Appendix C derives for record-forming channels; the gate is this paper's statement of that restriction. The survival probability is $S(t) = \exp[-\int_0^t g\,\dot{\Phi}_{\mathrm{irr}}\,dt']$, which is Eq. (4) wherever the gate is open.

Which: Born weights. Given an event, which alternative is actual is a matter of chance, with Born weights. The weights are not postulated. They are forced by what the ontology supplies, together with two requirements on the chance of a record, which the theory states and does not derive. What the ontology supplies: one wave, with one law of chance for a record whatever the basis; one actual history, so that the chance of "this record or that one" is the sum; no record where the wave has no component, for joint records as for single ones; and records that a further apparatus can always refine, as a finer detector splits an alternative in two. The two requirements: a record's chance here does not change when a record is made elsewhere, for every division of the world into here and elsewhere, of which the Bell requirement of Section 8 is the spacelike case; and a record's chance changes continuously with the wave. From these the weights are the squared amplitudes, by an argument due to Zurek [132, 133] in the no-signalling form Barnum gave it [6]. Appendix A states the premises and proves the theorem. The only noncontextuality the argument uses is the one no signalling supplies.

The argument has been contested on two grounds [101, 89, 127]. The first is that where every outcome occurs, what a chance is comes first. That does not arise here, since one record is actual and its chance is a chance. The second is that the argument takes the chance of a record to be one function of the wave, the same under every unitary relabelling and depending on the record only through the sector it selects, the part of the wave the record picks out. ACT takes that as premise (i) of Appendix A: one wave with one law, stated and not derived. One more fact keeps WHEN and WHICH separate. Surviving without an event does not shift the alternatives' populations. That is a corollary of the record channels being nondemolition with one common rate (Appendix C), and Eq. (5) uses it. Nondemolition alone is not enough: with unequal rates, surviving without a click shifts the odds toward the slower channel, and the general law applies. In the pure-dephasing model of Appendix C the same weights also descend from the ensemble to single histories, because the conditioned weights form a martingale, a process whose expected value never drifts. That descent is a consistency check, not the ground of the weights.

In the nondemolition case with one common rate the three answers combine into one identity, and it is the centre of the account there. Take that case, in which each run is a sequence of jumps in the record channels the detector supports (the jump unravelling). Then the ensemble's decoherence is exactly a mixture of two kinds of run, those not yet anchored, which are still

coherent, and those already anchored:

$$\rho_S(t) = S(t)\,\rho_S^{\mathrm{coh}}(t) + \big[1 - S(t)\big] \sum_k P_k\,\rho_S(0)\,P_k. \tag{5}$$

Here $\rho_S^{\mathrm{coh}}(t)$ is the system's state evolved with no event, still coherent, and the P_k are the projectors onto the alternatives. This holds for sharp, nondegenerate pointer alternatives whose populations the coupling preserves and whose coherences all decay with the one factor $S(t)$, as they do for two alternatives. With several alternatives and pair-dependent rates the same identity holds in the instrument form of Appendix C, not with one survival factor. The first term is the surviving fraction, still coherent. The second is the anchored fraction, already in one alternative or another. The event ontology imposes no additional dephasing term, and nothing is double-counted. For nondemolition record-forming channels of one common rate, then, decoherence is anchoring seen in the ensemble: the measured decay curve is the ensemble face of a process in which one run after another acquires a released record. The Mark shows it on a screen (Section 6): the band is the anchored fraction, the fringes the surviving one, and a rock that records weakly lays the one over the other in the proportion S.

What decoherence does not decide. The bath sets when an event can occur, among which alternatives, and at what rate. Which alternative occurs is the anchoring, with Born weights. Decoherence alone does not solve the measurement problem, and ACT does not say that it does. After decoherence every entry of the reduced state is still there, and the full system and bath stand at the right-hand side of Eq. (2), in which nothing has been selected. Three independent facts separate decoherence from anchoring: a finite bath gives back what it took; an erasable record is not yet a released record; and dephasing that records nothing of the alternatives, classical noise injected from outside, loses coherence and anchors nothing. What ACT adds to decoherence is the event law, and one commitment about it.

5 What is derived, and what is postulated

Actuality is primitive, and the ledger below shows exactly what rests on it.

> **The ontic postulate.** One record history is physically actual: one point of the joint spectrum of the released-record algebra of the network is the case.

Three points about the ledger need saying plainly.

First, the count. ACT posits an exclusive outcome register and one actual record history. In the record-algebra class of Appendix B the first is a theorem: once actuality is attached to a point of the spectrum of a commutative algebra, the points are exclusive by construction. The theorem says that the alternatives exclude one another. That one of them is the case is the commitment, and the two are never run together here. Within that class one commitment remains. Outside it exclusivity is a second, and the ledger records both. Either way, everything else is standard open-system physics, arranged. The count in one sentence: one commitment, that one history is actual; a second, exclusivity, where the theorem of Appendix B does not reach; two requirements on the law of chance, no signalling and continuity, stated and not derived; and nothing else. The commitment is a postulate in the ordinary sense, and Section 9 calls it one.

Second, the weights. They are forced by the ontology and its one commitment, together with two requirements on the chance of a record, stated in Section 4 and Appendix A: no signalling, for every division of the world into here and elsewhere, and continuity. Both are requirements on the chance law, not commitments about what exists, and neither is derived. Bohmian mechanics fixes its weights by the quantum-equilibrium hypothesis, a typicality postulate [35].

A no-signalling argument is open to it too, in a different form: Valentini showed that $|\psi|^2$ is the only distribution of its configurations that forbids signalling, given the guidance law [117]. The difference is where the forcing acts. In Bohmian mechanics the complete state is the wave and the configuration, parameter independence fails at that level, and no signalling constrains a distribution over the added variables. In ACT the complete state is the wave together with the actual history, the history is the outcome of the chance and not a variable averaged over, and the same principle lands on the chance of a record itself. What ACT leaves is the question every stochastic theory faces: why there is chance at all.

Third, the empirical standing, in four senses, from the strongest down. The physics the mechanism runs on is measured: decoherence rates set by which-path distinguishability, coherence recoverable until records spread, pointer information copied redundantly across environments. The event law is built from those facts. The mechanism can be refuted at the level of its supports. A definite outcome in a configuration whose complete record remains accessibly reversible would refute it. So would anchoring statistics decoupled from calibrated irreversible dephasing where the regime conditions hold. What is not claimed is a deviation from the predictions of unmodified quantum mechanics; the equivalence is by construction. And what is not available is a direct test of the one-history postulate itself. On those last two rungs ACT stands where every interpretation that keeps quantum mechanics intact stands.

Table 1: The postulate ledger. "Theorem" means proved in the stated class, in the appendices of this paper; "commitment" means added to the formalism and defended by its explanatory work.

item	status	where it comes from
one record history actual	**commitment**	the sole primitive; Section 8 says what follows from it
exclusive outcome register	theorem in the released-record class; commitment outside it	the algebra generated by the released records of a Markov network is commutative, for arbitrary system Hamiltonian and coupling; its spectrum is the set of histories; the joint spectral projectors are orthogonal (Appendix B)
the alternatives (WHAT)	theorem in the model of Appendix D; otherwise einselection	the selection theorem (Appendix D); in general einselection, which is approximate and not a theorem; the apparatus-free case is open (Section 10)
the event rate (WHEN)	standard, applied to released records	the instrument path measure of quantum-trajectory theory (Appendix C); $h = \dot{\Phi}_{\mathrm{irr}}$ is its corollary for nondemolition record-forming channels of one common rate, and the gate g, zero for dephasing that records nothing, is this paper's statement of that restriction; ACT's part is the release criterion and the ontic reading
release as the gate	definition + bound	commutation with the accessible future; the recoverable phase any accessible observable can reach is bounded by a commutator, for networks whose couplings are fixed in advance (Appendix B)
Born weights (WHICH)	**forced**, given two stated requirements	the ontology and its one commitment, plus no signalling for every division into here and elsewhere, and continuity; Zurek's argument in Barnum's form (Appendix A); the martingale descent is a consistency check
global dynamics	unmodified	no noise field, no collapse term, no new constant or threshold
energy	conserved exactly	the total system–bath dynamics is unitary with a time-independent Hamiltonian; for a thermal bath the fluctuation–dissipation pairing is what makes the reduced dynamics thermalize rather than heat; the per-event ledger is open (Section 10)
atemporality	interpretive layer	no proof depends on it

6 Four experiments, told as thought experiments

The experimental record bearing on ACT is best told as four thought experiments, one for each link of the chain in Fig. 1. Together they establish the three things ACT is built from: a composite field (the Filter, and the Mark when no record is kept), a well-characterized bath (the Rock and the Valves), and a mark (the Mark). Each of the four has been performed. One hundred experiments, from 1922 to 2026, bear on them: seventy-six corroborate the four, two controls show the no-record limit, eleven set the constraints every account must meet, and eleven are the collapse searches ACT could have failed. None conflicts with the mechanism. The full registry, with what each experiment corroborates and what it does not establish, accompanies this paper [108]; Table 2 is its summary.

I. The Rock: remove the observer; the record remains. Section 2 stated it. A slab that nothing reads destroys the fringes in proportion to its loss: strongly when it is resistive, hardly at all when it conducts well [110, 78]. The source of the decoherence is the slab itself. Its electrons, stirred by the passing charge, carry a record of the path off as heat. That is the bath, and the Rock gives its first property: for a slab, the record follows the dissipation. Other baths are rocks too. A gas carries the record off in its molecules [68]. A hot molecule's own thermal radiation carries it off as light [62]. An interaction that keeps no record leaves the fringes alone [95]. And the fringes themselves say that mass is present before anchoring: no cut set by mass or size has been found out to 172 kDa [94], and ACT, which has no isolated-system collapse, predicts none.

II. The Valves: tune the bath, and the rate follows. Keep the rock and add a valve: the pressure of a gas, a laser that heats the molecules, the current in a detector beside one path, the leak of a cavity, the gap between the paths. Turn it, and the fringes fade faster or slower, smoothly, and by one rule in every kind of bath: faster for a stronger coupling, a hotter bath and, until the record saturates, a wider gap [19, 91, 115, 29, 68, 62, 21]. The bath has a rate, and the laboratory can dial it. Quantum Brownian motion, the bath's exactly solvable model, writes the rule in one line for small separations at high temperature, Eq. (3): the decoherence rate is the damping rate times half the square of the separation measured in thermal wavelengths. So, at a given gap and temperature, the decoherence cannot be dialled without dialling the damping. In a cavity, the decoherence has been seen to quicken as the separation grows, as the theory that ties it to the damping predicts [19]. One valve is a fake. Classical noise injected from outside, like the random-field reservoirs of the trapped-ion experiments, dims the fringes in the average but records nothing [91, 115]. A static spread of frequencies does the same, and an echo brings it back [64]. ACT counts both as no events. This is what the exhibit forces. ACT's event law counts only phase that can no longer be recovered. So a dephasing an echo undoes was never a record, and a dephasing that records nothing of the alternatives opens no gate (Section 4).

III. The Filter: the apparatus picks out components; only a record picks the outcome. An FM radio does not create the station it plays. The air carries one electromagnetic field, the sum of every broadcast at once. The tuner, a resonant circuit, picks out one frequency and leaves every other station on the air. The quantum field is a composite in the same way, a sum of modes, as a Fourier series is a sum of frequencies, and an apparatus can pick out its components.

A cavity is the tuner for an atom's light. An atom can emit only into a mode the field offers. In a cavity tuned to its transition it emits faster [56]. Between plates that leave no mode at its frequency, its emission is suppressed [70]. What leaves the atom is an excitation of a mode, not a projectile.

Table 2: The four thought experiments. "Could have failed if" states what the experiments would have had to show for the link to fail.

exhibit	link in the chain	could have failed if	representative experiments
The Rock	bath interaction → stable record	interaction without a record had killed fringes, or a lossy body with no readout had left them intact	Sonnentag & Hasselbach 2007; Kerker et al. 2020; Perreault & Cronin 2005
The Valves	the rate of record formation	the rate had been fixed, all-or-nothing, or independent of the coupling	Brune et al. 1996b; Myatt et al. 2000 and Turchette et al. 2000 (laser cooling); Hornberger et al. 2003; Deléglise et al. 2008; the fake valve: their random-field reservoirs, and Hahn 1950 (control)
The Filter	composite field → which mode can be recorded	the apparatus had fixed the outcome, or a separation had been irreversible, or emission had ignored the modes on offer; or, where the event can sit, coherence had failed to return while a record could	Gerlach & Stern 1922; Phipps & Taylor 1927; Goy et al. 1983; Hulet et al. 1985; Margalit et al. 2021; where the event can sit, Table 3
The Mark	anchoring → one causal history	one event had ever left two marks, or the marks had built fringes after a record of the path was released, or the frequencies had failed Born	Tonomura et al. 1989; Sonnentag & Hasselbach 2007; Grangier et al. 1986; Nagourney et al. 1986; Kimble et al. 1977; Diedrich & Walther 1987; Guerlin et al. 2007

A Stern–Gerlach magnet sorts the same way. A beam of silver atoms splits in two along the magnet's axis [49]; so does a beam of hydrogen atoms, whose magnetism is the spin of a single electron [96]. Turn the magnet and it sorts along the new axis, as a new setting of the dial brings in a new station. The magnet has found nothing out: in a full-loop Stern–Gerlach interferometer the two beams are brought back together, and they interfere [85]. Which beam a detector finds the atom in is settled only when a record is released, with Born's weights.

So neither the atom nor its electron is a small body that takes one path or the other. Each is a wave whose components can be separated and brought back together, and the particle is the mark left when a record of one component is released. Which alternatives a record can register is set by the coupling, not chosen: a magnet sorts by spin along its axis, a cavity by frequency. The environment copies records of only the alternatives its coupling selects across its fragments, the parts of it that can be read separately [27, 116, 128]. The apparatus picks out components; only a record picks the outcome.

IV. The Mark: the wave is what exists; the particle is what happens. Send electrons one at a time through an electron biprism, the two-slit analogue. Each arrives as a single mark, one dot on the screen, and the dots build up fringes, the pattern of a wave [86, 113]. Bring the rock close under the two paths and the fringes wash out [110]: the dots build up a plain band, the pattern particles would make. Every dot is the same kind of mark either way. The record changes how the marks add up because it changes when the first event of the run happens: at the rock, or at the screen. Every detection is one mark. Send one photon at a beam splitter with a detector on each port. One of them clicks, and the coincidences fall far below the classical bound, while the same photons interfere [57]. Watch one trapped ion. Its fluorescence goes

on and off in steps [92], and after each click the clock restarts, which is antibunching, seen first in an atomic beam and then in a single stored ion [80, 32]. Single photons are born and die in a cavity as jumps in hundreds of nondemolition readings [54]. Repeated nondemolition probes record a cavity field's photon number, reading by reading, until the records settle on one number, with Born-distributed outcomes [59]. And the conditioned history of a single qubit is an observable, manipulable object [90]. The event is discrete, it carries Born weights, and it comes one mark at a time: no event has ever left two marks. That these marks are the events, and their history the one actual history, is ACT's one commitment (Section 5). Every detection is one mark, as every account that keeps quantum mechanics unmodified predicts, and ACT takes that mark at face value.

Two kinds of run make the two patterns. With no rock, nothing records the path before the screen. The dot is the first event of the run: the wave reaches the screen with both components, and the dot falls with the weight of their interference. With the rock, the path is recorded and released before the screen, since the rock's heat is a record nothing can bring back. The run already has one event, the path, and the dot is its second: two events in one history, each leaving one mark. The dot follows the component that record selected; the other component no longer enters the run's history, though the wave is untouched. A rock that records weakly anchors some runs and not others, and the screen shows the proportion: the fringes of the runs not yet anchored laid over the band of the runs anchored, with the contrast equal to the surviving fraction S of Eq. (5). So decoherence before the screen is anchoring before the screen whenever the record has been released. A record that is held but can still come back, a scattered photon's for one, decoheres the reduced state just as fully and anchors nothing; the dot is then the first event of the run (the next paragraph, and Table 3).

Where the event can sit. The Filter's magnet anchors nothing, and the laboratory has gone further. Here the experiments decide something outright: which event rules survive. Read each candidate rule as an event rule of ACT's kind. That means: the coupled variable becomes actual at the moment the rule names, and the actual history proceeds from that record, the unselected alternatives no longer entering it, while the global wave is untouched. Under that reading an early event changes what the actual history predicts. A history conditioned on a record while interference with the unselected alternatives is still accessible predicts that the interference does not return. That is the only reading these experiments test. A rule that assigns values at all times and lets the unselected alternatives keep entering the actual history, as the whole wave keeps guiding a Bohmian configuration, is not of this kind. It is not tested here, and it survives, as the last row of Table 3 says.

Three earlier placements of the event, three earlier moments at which a rule could put it, have been tested, and each fails. An event at first interaction: an atom in a cavity takes its excitation back [18]. An event at decoherence of the reduced state: which-path information carried by a scattered photon can be regained by selecting on the photon [26]. Carried by an entangled twin, it can be erased by choices made late or at spacelike separation, so that the conditioned fringes return [79, 119, 83]. In those erasers the interference reappears only after the signal detections are sorted by the corresponding idler outcomes, and the unsorted signal distribution contains no interference and permits no signalling. A partial measurement of a superconducting qubit can be undone by a matched second measurement [74, 75], and a quantum jump already under way can be caught and reversed in flight [88]. An event at the first appearance of a record carrier: light returned by a mirror enhances or inhibits an ion's own spontaneous emission [37], and a qubit whose phonons return decays non-exponentially [2]. In Wheeler's delayed-choice experiments no environmental record is involved and the result follows the final configuration [71, 84]: no record, no event until detection.

The data rule out every single-history rule of this kind that makes a record actual while the record can still coherently return, and ACT's rule sits at the earliest placement consistent with

Table 3: Where an event could be placed, and what the laboratory says. Each rule is read as an event rule of ACT's kind: the coupled variable becomes actual at the moment named, and the actual history proceeds from that record, the unselected alternatives no longer entering it, while the global wave is untouched.

when an event would happen	what that implies	contradicted by	status
at first interaction	an atom exchanging a photon with a cavity mode has "emitted or not" fixed at once; a magnet that splits a beam has decided the spin; a surface that shifts a phase has recorded a path	Brune 1996a; Margalit 2021; Perreault & Cronin 2005; Kerker 2020 (gold)	ruled out
when the reduced state decoheres	which path is fixed, so interference could never be recovered by conditioning on the environment's record	Chapman 1995; Kim 2000; Walborn 2002; Katz 2006, 2008; Minev 2019	ruled out
when a record carrier exists	emission is a finished fact, so a returning field could not alter the source's own emission	Eschner 2001; Andersson 2019	ruled out
at release (ACT)	the record is beyond coherent recovery by the system's accessible future; everything above, as observed	—	survives
later, or never, or always	the same statistics, from interpretations without events, or with definite values at all times	—	survive

them. Each experiment in Table 3 refuted a rule that placed the event at an independently identified earlier moment. ACT's rule places it at the edge of recoverability, where the laboratory has mapped the boundary. The one way it could fail there, coherence returning through an observable that commutes with the record, is a failure of the commutator bound of Appendix B, which is a theorem of quantum mechanics. On this point ACT's placement is as safe as quantum mechanics itself. Rules placed later, and interpretations with no events at all, survive as well, because each reproduces the statistics of unmodified quantum mechanics. The experiments fix ACT's boundary and corroborate its placement; whether anything happens there is the one thing they leave to the postulate.

The reversibility boundary is also relative to what is controlled. Spin dynamics spread through a solid have been time-reversed, and the magnetization has returned as an echo [98]. Information scrambled across 53 superconducting qubits has been refocused [87]. ACT's accessible algebra is therefore fixed by the physics of the coupling and the apparatus, control hardware included, not by convenience; quantum-trajectory theory needs the same specification [122]. Whether an event has occurred is relative to the operations the network actually performs. ACT accepts that relativity, and Section 10 records the one lead that would remove it.

The collapse searches. ACT adds no dynamics, so it predicts none of the heating or radiation that the collapse models predict. Had the excess radiation appeared, it would have refuted ACT together with unmodified quantum mechanics. Underground germanium detectors found none and excluded parameter-free Diósi–Penrose collapse [33]. The XENONnT search excluded, for the first time, continuous-spontaneous-localization parameters in the range Ghirardi, Rimini and Weber originally proposed [3]. On this front ACT is exactly as refutable as quantum mechanics, and it has survived exactly as quantum mechanics has. The one-history postulate

itself is not tested here or anywhere (Section 5).

What the laboratory has settled. ACT places an event only where a record has become irreversibly unavailable to the system's accessible future. That boundary has been mapped independently, by quantum erasers, vacuum Rabi oscillation, and the return of emitted light and sound to their sources: coherence returns exactly when, and only when, the record remains coherently recoverable. Event rules of ACT's kind placed at first interaction, at decoherence of the reduced state, or at the first appearance of a record carrier are already ruled out. No experiment distinguishes ACT from later event laws, or from interpretations that reproduce quantum mechanics without events. What the laboratory has given ACT is a mechanism measured, a boundary mapped, and a placement tested by every recovery experiment and never refuted. What sets ACT apart from the other accounts that keep quantum mechanics unmodified is not a different prediction but the account it gives.

7 The formal backbone

The chain of Fig. 1 has a mathematical spine, and this section states it in the fewest equations that fix the objects. The proofs are in Appendices B and C.

The bath and its record. The environment is modelled as a quantum Brownian bath: a continuum of modes linearly coupled to the system, with a spectral density that fixes both the damping and the decoherence (Eq. (3)). For time-homogeneous Markovian quantum Brownian motion the dynamics can be written exactly, at one particular time step, as unitary evolution interrupted by entanglement-breaking measurements, which leave no entanglement between the system and the slice of bath that has just left [99]. At each step a fresh slice of the bath couples to the system, carries off a record, and never returns. The output of such a process has an old and exact structure. In the quantum stochastic calculus of Hudson and Parthasarathy [69] and the input–output theory of Gardiner and Collett [47], the record observables Y_t commute among themselves and with every later system observable. Belavkin named these two properties self-nondemolition and nondemolition, and proposed that the output record is a classical past [8]. ACT takes that structure as the carrier of actuality.

Irreversibility: recoverable phase. The question is how much of a relative phase can still be recovered. Fix alternatives $|j\rangle, |k\rangle$ and the phase pair $|\psi_\theta\rangle = \frac{1}{\sqrt{2}}(|j\rangle + e^{i\theta}|k\rangle)$, and let $\rho_\theta(t)$ be the global state evolved from $|\psi_\theta\rangle\langle\psi_\theta| \otimes \rho_E$. Let $\mathcal{A}_{\rm acc}$ be the physically accessible algebra: the observables the apparatus and the rest of the network can actually measure or act on. It is fixed by the detector architecture, causal locality, the division of the environment into parts that can be read separately, and the operations the network actually performs, and not by an agent's choices. Let $\mathcal{E}_{\rm acc}$ be the restriction of a state to it, the state as seen through those observables alone. Then

$$\mathcal{D}(t) = \tfrac{1}{2}\big\|\mathcal{E}_{\rm acc}[\rho_{\theta=0}(t)] - \mathcal{E}_{\rm acc}[\rho_{\theta=\pi}(t)]\big\|_1, \qquad \Phi_{\rm irr}(t) = -\ln\frac{\mathcal{D}(t)}{\mathcal{D}(0)}. \tag{6}$$

The quantity $\mathcal{D}(t)$ is how well the two preparations can still be told apart by accessible means, and $\Phi_{\rm irr}$ is the accessible irreversible phase loss. Because the two preparations differ only in a relative phase, $\mathcal{D}$ cannot be inflated by rotating populations. When the accessible dynamics is CP-divisible, that is, when it can be cut at any time into a sequence of physical maps with no information flowing back, $\Phi_{\rm irr}$ never decreases, since each map can only reduce distinguishability, and there the hazard $h = \dot{\Phi}_{\rm irr}$ is defined. Where divisibility fails, in a single mode, a recurrent finite bath or an eraser, $\Phi_{\rm irr}$ may decrease and the hazard is undefined. In those regimes phase

can come back, so no event should be assigned there; the hazard is undefined there, and none is. Where a carrier returns and then exits, the general law below assigns the event to the exit record, the record made when the carrier finally leaves (Section 8.3).

Release. Let R be a record observable formed at time s. Let $\mathcal{F}_s^S$ be the system's accessible future: the algebra generated by all later Heisenberg system observables and all later fresh records. It is computed with the actual dynamics of the network, including every path by which a carrier returns. Then

$$R \text{ is released} \quad \Longleftrightarrow \quad [R, F] = 0 \ \text{ for every } F \in \mathcal{F}_s^S. \tag{7}$$

In words: a record is released when nothing the system still does, as the network actually runs, reaches it. When the output never returns, release is exactly nondemolition. When it can return, release does work that nondemolition alone cannot (Proposition B.7). Under time-delayed return the in-flight record is nondemolition but not released, and anchoring waits for the exit record. Under scrambling inside the environment a record leaves the centre of the whole future algebra, since something in the environment can still act on it. It remains central relative to the system, since nothing the system does reaches it. The event stands even as the number of copies of the record in the environment falls. A bound ties release to Eq. (6) (Theorem B.5). For a binary record with gap Δ between its two values, let the phase distinguishability any one observable A can reach be $\frac{1}{2}|\mathrm{Tr}[(\omega - \omega_\pi)A]|$, with ω_π the state with the alternatives' relative phase flipped. It is at most $\|\omega_{\mathrm{off}}\|_1 \|[R, A]\|/\Delta$, where ω_{off} is the part of the state that is off-diagonal between the record's two eigenspaces. Phase can be recovered only through observables that fail to commute with the record, and the bound caps how much.

One idealization should be stated here. Exact commutation holds only in the continuum-bath limit; a large finite bath gives it to exponential accuracy. To place the event where the commutator bound falls below any accessible resolution is therefore an idealization of the same kind as the thermodynamic limit. It is stated as such, and not as a theorem about finite closed systems; exact recurrence of the whole closed system lies outside the scope of the construction. What the ontology needs is this: if R is released, attaching actuality to it with the Born weights changes no accessible prediction, for any state; if R is not released, some accessible observable and some state show the difference (Corollary B.6). A rule that makes a record actual before release conditions the actual history on that record while some accessible observable can still show the difference. The history's predictions then depart from quantum mechanics'. Table 3 is the laboratory's test of exactly such rules. No constant is introduced, and no threshold of the theory's own: the resolution in question is the apparatus's, not nature's. In the continuum limit the event time is exact. In a finite closed system it is defined to that resolution, an idealization Section 10 lists as such.

What fixes the accessible future. Three readings of $\mathcal{F}_s^S$ should be told apart, because they are different ontologies. It could be generated by the couplings in place at s alone. It could be generated by every operation the apparatus could perform after s, whether or not it does. Or it could be generated by the dynamics that actually unfold after s: every intervention that is actually made, and none that is merely possible. ACT means the third, and Appendix B defines it so: $\mathcal{F}_s^S$ is computed with the actual total dynamics of the network. The first reading is refuted by the laboratory. Light returned to its emitter by a mirror alters the emitter's own decay [37, 2], so a record that a return path will reach is not beyond recovery, whatever was in place when it formed. The second would let almost nothing release, since some hardware could always be built. The third is well defined along the actual history, because the dynamics of the network is one definite history of couplings. Which interventions occur is a fact about the apparatus and what is done with it. A later intervention may itself be set by an anchored outcome: an erasure basis chosen by a quantum random number [83], or feedback conditioned

on a monitoring record [88]. Then the network's later dynamics is conditioned on that outcome, and the release status of the record at s inherits the dependence. Release is then adapted to the actual history: settled by outcomes already anchored when the intervention is set, never by outcomes not yet anchored. A formulation in which the event time is a stopping time, a time decided by what has happened so far and never by what has not, is listed in Section 10 as still to be written.

A mirror installed tomorrow, before the light arrives, is part of that dynamics, so today's emission was not a released record. A mirror that could have been installed but never is does not belong to it, and the emission was. Release is therefore a property of a record relative to the dynamics as a whole, like escape to infinity, and not a property fixed by what is in place at s. Nothing travels backward, and no information does. What a later intervention settles is the classification of an earlier record as released, not the record and not any outcome. The in-flight carrier is never a released record; the event is at its exit record, when the light is absorbed or has passed beyond every return path the dynamics actually contain. This dependence on the future dynamics is the feature ACT shares with the other record-based accounts (Section 8.3). The relativity to control hardware of Section 6 is the same reading applied to the accessible algebra, what the apparatus actually reads or acts on; the research lead that would ground it is in Section 10.

Exclusivity and the event law. Released records commute with one another, and that is the whole of the mathematics behind exclusivity. The algebra generated by the released records of a Markov network, a system with a bath that carries each record away and never brings it back, is commutative, for arbitrary system Hamiltonian and coupling (Theorem B.3). Its spectrum, the set of joint values the records can take, is the set of histories $r = (r_1, \dots, r_N)$, and the joint spectral projectors Π_r are mutually orthogonal and sum to the identity. The probability of a history is the instrument path measure, the chance of its records made in order, each conditioned on the ones before,

$$\mathbb{P}(r) = \mathrm{Tr}[\rho_0\, \Pi_r] = \mathrm{Tr}\big[\mathcal{I}_{r_N} \circ \cdots \circ \mathcal{I}_{r_1}(\rho_S)\big], \tag{8}$$

with ρ_0 the initial state of system and bath, ρ_S the system's part of it, and $\mathcal{I}_r$ the instrument a single released record induces on the system: the map that takes the system's state before the record to its unnormalized state after it, for the value r (Theorem B.4). Exclusivity is a theorem in the class because the points of the spectrum of a commutative algebra are exclusive by construction: a history is one point, and two points are never both the case. The event law is Eq. (8) itself. In the continuous case, for a released counting record with jump operator L_r, the operator that describes one record of kind r being made, the event intensity and the conditioned update are

$$\lambda_r(t) = \mathrm{Tr}\big(L_r^\dagger L_r\, \rho_c(t)\big), \qquad \rho_c \;\longrightarrow\; \frac{\mathcal{I}_r(\rho_c)}{\mathrm{Tr}\,\mathcal{I}_r(\rho_c)}. \tag{9}$$

Here ρ_c is the conditioned state, the Belavkin filter. Its ensemble average reproduces the unconditioned Lindblad dynamics for every initial state (Theorem C.1). The first expression is the rate at which records of kind r are made. The second is what the conditioned state becomes when one is. The jump operators are the record channels the environment physically supports, read by the detector that is present. The generator alone does not fix them: it is invariant under mixing of the jump operators, and the same dephasing generator is unravelled equally well by phase kicks that never collapse a population [122]. That choice lives in the record architecture, and the no-free-constant claim is relative to it: given the record channels, the rate is the bath's. When the record channels are nondemolition with one common rate, $L_\pm = \sqrt{\Lambda}\, P_\pm$, the total intensity is $\Lambda = \dot{\Phi}_{\mathrm{irr}}$, independent of the conditioned state. The no-event evolution is then outcome-neutral, that is, surviving without an event does not shift the alternatives'

populations, and Eqs. (4) and (5) follow (Corollary C.2). Outside the nondemolition window the extrapolated hazard $h = \dot{\Phi}_{\mathrm{irr}}$ is wrong: for a driven atom with a photodetected output it gives the wrong lifetime and no antibunching. Eq. (9) with $L = \sqrt{\gamma}\,\sigma_-$ gives Carmichael's delay function, the waiting-time distribution between clicks, with $w(0^+) = 0$ [25]. The general law is Eq. (8); the scalar hazard is its case of nondemolition channels with one common rate.

The actual history. Along the actual history the conditioned state jumps at each anchoring. The unrealized components cease to be part of that history, and remain in the global state as structure. The ensemble is untouched. The results of Appendix B are verified to machine precision in a finite collision model, the discrete bath of that appendix, with the system Hamiltonian chosen not to commute with the coupling; the verification scripts are deposited [109].

8 Bell, Wigner's friend, and the single history

A theory that says one history is actual owes three answers: what it says about Bell's theorem, what it says about an observer inside a quantum system, and what the rest of the wave is. Each is given here plainly.

8.1 Entangled records and Bell nonlocality

ACT is nonlocal in Bell's sense. It keeps parameter independence, admits no retrocausal influence on outcomes or signals (Section 8.3 says what a later intervention does settle), and violates outcome independence. An entangled pair is one structure. When one end's record is anchored, the other end anchors from what is left of that structure consistent with the record. So its outcome depends on the first, while nothing of the first detector's setting alone reaches it: the far marginal does not depend on it. Records far apart have no time order, and it makes no difference which end is taken first.

The Bell experiments violate the Bell–CHSH inequality [9], as loophole-free tests confirm [66, 52, 102, 112], and ACT neither correlates the measurement settings with the source nor admits influences running backward in time. In Jarrett's decomposition [72], with the names Shimony gave its two halves [103], the record history violates outcome independence and satisfies parameter independence. Parameter independence is not read off the weights. It is one of the two requirements the theory places on the chance of a record (Section 4), stated for every division of the world into here and elsewhere. The weights that requirement forces then satisfy it, as the marginal below shows. When one end's record a is anchored with setting x, the other end anchors from the conditioned state,

$$\rho_{B|a} = \frac{\mathrm{Tr}_A\big[(P_a^x \otimes \mathbb{I})\,\rho_{AB}\big]}{\Pr(a \mid x)}, \qquad \Pr(b \mid a, x, y) = \mathrm{Tr}\big[P_b^y\,\rho_{B|a}\big], \tag{10}$$

while the marginal $\sum_a \Pr(a, b \mid x, y) = \mathrm{Tr}[P_b^y\,\rho_B]$ does not depend on the distant setting x, so nothing can be signalled. Shimony called this passion at a distance [104]. Textbook quantum mechanics with the projection rule and the collapse models share it. Bohmian mechanics, whose outcomes depend on the distant setting, violates parameter independence as well. The joint statistics do not depend on which end is conditioned first, $\Pr(a \mid x)\Pr(b \mid a, x, y) = \Pr(b \mid y)\Pr(a \mid b, x, y) = \Pr(a, b \mid x, y)$, so records at spacelike separation need no time order between them. In the covariant measurement theory of Fewster and Verch [40] their instruments commute and their composition is independent of order, and that is what "no time order" means here. The covariant form of the release criterion itself is open (Section 10). Nothing is removed from the field: what is left over is what is still available to the actual history. The interpretive layer of Section 3.2 is not offered as a way around this nonlocality; its role here is only that no preferred order is required.

8.2 Wigner's friend

Wigner's friend measures a qubit inside a sealed laboratory. Wigner, outside, describes the laboratory unitarily and can in principle interfere its two components. Does the friend have a definite outcome? On this account a measurement is a released record, and the accessible future is the network's actual dynamics (Section 7). Three cases follow. If Wigner actually runs the laboratory coherently and acts on the friend's record, so that the interference measurement is part of the network's dynamics, then the record is within the system's accessible future. No record is released and no event is assigned: during that interval the friend's record is a possibility for a mark, not yet a mark. If the laboratory leaks, as every real laboratory does, through a photon, a phonon, or a thermal record that nothing in the network returns, the record is released at the leak. The friend's outcome is then a fact for everyone, and Wigner's interference measurement fails at exactly the rate the leak sets. And if Wigner never acts on the laboratory's record at all, nothing reaches it after it forms, and it is released when it forms.

Three consequences follow.

1. *Absoluteness of observed events holds for released records.* An anchored record is a fact for every observer and is never undone by a later record. What ACT denies is that an unreleased "measurement" is an observed event.

2. *The extended Wigner's-friend arguments are consistent with this, and ACT states which of their assumptions it gives up.* The Frauchiger–Renner argument [41] chains inferences across agents, some of whose laboratories are later measured in a basis incompatible with their records, which requires those laboratories to have stayed coherent. On ACT such an agent has made no released record. The premise that its outcome is a fact available for inference fails for that agent, and no contradiction is reached. The no-go theorems for observer-independent facts [15, 13], and the experiments that violate their inequalities, with photons [97, 13] and with entangled states of up to 17 qubits [125] as "friends," involve no released record inside the friend's system. So ACT assigns the friend no event. In the Local Friendliness classification of Wiseman, Cavalcanti and Rieffel [121], which sorts accounts by the assumption of the no-go theorem each gives up, ACT gives up Friendliness. It keeps universal quantum theory, so it predicts that the violation will be observed with such a friend. And it denies that a friend whose laboratory is kept coherent has an observed event, because ACT assigns none where there is no released record. Any account that denies Friendliness for such a friend shares that cell, one-history unitary readings such as Steane's among them. What is ACT's own is the reason, release, and its application to a human friend whose laboratory is kept coherent. That is a definite position, stated here as one.

3. *A one-history reading of quantum theory needs exactly this criterion.* Steane has argued that such a reading, a single-world reading in his terms, is sustainable without modifying the dynamics, provided certain outcomes are not quantum-erased in the future [111]. Release is the physical criterion for when erasure does not occur in the network's actual dynamics, rather than when it is merely impractical.

8.3 Is ACT retrocausal?

Whether a record is released depends on the system's accessible future: on the couplings and return paths the interaction network provides after the record forms. In the delayed-return model (Proposition B.7) an atom's emission comes back from a mirror. The in-flight record is nondemolition now but not released, and anchoring waits for the exit record, as the laboratory shows [37, 2]. But release depends on the future *dynamics*, not on outcomes not yet anchored. Which return paths the network actually comes to contain, including those an intervention makes, is a fact about the apparatus, and where an intervention is set by an anchored outcome the dependence runs through the actual history (Section 7). Nothing later alters an anchored

record, and no information travels backward. In the delayed-choice eraser the later record on the idler side never changes the earlier detection of its partner but decides which subset that detection belongs to, and the unsorted signal distribution carries no interference. ACT shares this reference to the future with Kent's late-time records [76, 77], with the ETH approach's algebra of the future [43], and with Gell-Mann and Hartle's permanent records [48]; it is a family feature of record-based one-history accounts. A formulation in which release is a stopping time of a filtration generated by the coupling structure is open, and is listed with the covariant criterion in Section 10.

8.4 What the rest of the wave is

After an event the wave still holds the components the record did not select. On ACT they are what they were before: the structure of one real wave, holding possibilities for a mark. Every component carries its own records, but only one history of them is actual, and only its records are marks. On the reading of time in Section 3.2, which a reader may set aside, causal order is made by events, so nothing is lived through in the rest of the wave.

The sharpest objection to any one-history theory over unmodified unitary dynamics is the one Brown and Wallace pressed against Bohmian mechanics [14]. After decoherence the unselected components hold everything the selected one holds, so calling the selected one actual is only a label. It applies to ACT no less than to Bohm: both leave the unselected components in place. Where Bohm's beable is present at every moment, ACT has events only at anchorings; GRW with flashes [114] suppresses those components by a new dynamics. ACT's answer is its primitive ontology, the stuff in spacetime the theory is about, in the sense of Allori, Goldstein, Tumulka and Zanghì [1]. On ACT that stuff is the anchored events. A component holds possibilities for events, weighted by its amplitude, and no events. Whether a component with no events in it could still hold someone who sees an outcome is a substantive question. ACT answers no, as flash-ontology theories do. That answer is a commitment, defended, not derived.

What the commitment buys is explanatory. It says which history is actual, and it says what the components of a superposition are: the structure of one real wave, holding the possibilities for anchoring. It makes probability ordinary, one outcome occurring with a chance, and that is what lets the weights be forced. Where every outcome occurs, what a chance is has to come first, and the Everettian derivations of the Born rule have been contested for more than twenty-five years [30, 5, 120, 101]. ACT runs Zurek's argument with its premises supplied by the ontology and by two stated requirements (Section 5). The difference is not where an assumption sits but which assumptions are needed.

9 Relation to the other interpretations

Section 1 drew the line. Other interpretations ask how a superposed quantum state yields a definite result. ACT begins with a real wave and asks how the environment produces a definite event. The difference is in the question, and it has two parts: what a superposition is, and what produces a definite event.

First, the wave is not a superposed particle. A superposition is the structure of one wave (Section 3). It is not a particle holding two classical properties at once. So ACT needs no further worlds, no continuously definite particle trajectory and no spontaneous collapse to say what a wave with several lobes is. To say which lobe is anchored it needs one commitment: one record history is actual (Section 5).

Second, measurement is a physical process, not an act of observation. The detector is not passive. It couples the system to the bath, and the bath keeps a record. That coupling, together with the irreversible release of the record, is what ACT calls anchoring. No conscious observer is required, and no specially designated measurement. The Rock (Section 2) anchors with nothing

reading it.

The main accounts answer both questions by keeping a particle somewhere, or by keeping every outcome. Copenhagen brings the particle back at the detector, through a measurement rule, and leaves the designation of a measurement primitive. Bohmian mechanics keeps it all along: definite particle positions on a path the wave steers through a guidance law [12]. The collapse models squeeze the wave down to one place, with stochastic dynamics and new constants [50, 93, 51, 114]. Everett keeps no particle, but every outcome, one mark to a world [38, 120]. Those who say plainly that there are no particles, only fields, part ways with ACT at the detector. Hobson lets the field collapse there and leaves the cause open [67]. Zeh gave up the collapse as well as the particle, and was left with every outcome [124]. ACT takes the third road: no particle, no collapse, one history, and the bath makes the mark. The event ontologies below come nearest to it.

Of the remaining accounts, QBism holds, by design, that the event is the agent's experience, and gives no physics of its production [45]. Relational quantum mechanics makes every event relative to the system it interacts with. It posits no boundary of ACT's kind, which is relative to the physical record architecture and to no observer [100, 31]. The modal interpretations give the system possessed values at all times [118]. Decoherent histories assign probabilities within a framework and name no mechanism that realizes one history [58, 48, 34]. Several of the main accounts predate decoherence theory and incorporated it afterwards (Section 3). Quantum Darwinism makes environmental decoherence central from the outset [131, 134], and leaves open why one outcome is actual. Two rules govern the comparison. Age and familiarity earn nothing. And an experiment counts for an account's distinctive content only if a rival lacking that content would have predicted a different result.

Many Worlds needs a paragraph of its own. It shares ACT's equation and a real wave that never collapses. The two part at the outcome, and there they are opposites. In Many Worlds every outcome happens, each in a world of its own, with a copy of the observer in each. The bath only draws the borders between those worlds, and decoherence was brought in later to say where the borders fall [123, 129, 130]. In ACT the bath makes the mark, and one history of marks is actual, with an ordinary chance. No experiment decides between the two: every detection is one mark, as both predict. ACT takes that mark at face value. Many Worlds counts every other outcome as a world of its own, which no experiment can reach, and where every outcome happens, what a chance is has to be rebuilt (Section 8.4).

Occam's razor. Every account in Table 4 but the collapse models reproduces the statistics of quantum mechanics exactly; the collapse models depart from them, and survive the experiments only where the radiation searches have left their constants open (Section 6). Where the experiments cannot choose, a third rule decides: Occam's razor. The table counts what each account adds to the physics already measured, the Schrödinger equation and the bath whose decoherence the laboratory has mapped, and what the addition costs. Many Worlds is said to win the count, since it adds nothing to the equation. But the razor counts what must be assumed to account for what is observed. What is observed is one outcome in every run, with Born frequencies. Many Worlds accounts for it by holding that every outcome occurs, each in a world of its own with a copy of the observer, and no experiment in one world can reach another; and it has to rebuild what a chance is (Section 8.4). ACT accounts for it with one postulate, that one history of marks is actual, so the outcome a run shows is the only one that occurs. Outside the record-algebra class, the networks of Appendix B, exclusivity is stated as a second (Section 5). Every account fixes its weights by an assumption of its own: the Born rule postulated, the quantum-equilibrium hypothesis of Bohmian mechanics, the decision-theoretic axioms of the Everettians. ACT's, given refinable records, are two requirements on its law of chance, no signalling and continuity. Its open problems (Section 10) are parts of the law still to be written, not added entities.

Table 4: Occam's razor: what each account adds to the Schrödinger equation and the measured bath, and what the addition costs.

account	what it adds	what it costs
Copenhagen	a measurement rule, applied at a measurement it never defines; a line between quantum and classical	no account of where the line falls
Bohmian mechanics	a particle with a position at all times; a guidance law; the quantum-equilibrium hypothesis; for relativity, a preferred foliation, which the wave function may itself fix [36]	individual paths, and in relativistic versions a foliation, that no experiment can observe
collapse models	new stochastic dynamics, with new constants (two in GRW and CSL)	constants chosen by hand, steadily narrowed by the radiation searches
Many Worlds	nothing in the equation	every outcome counted as a world, with a copy of the observer in each and none reachable from another; probability rebuilt
QBism; relational quantum mechanics	nothing in the equation; outcomes relative to an agent, or to a system	no outcome that is a fact apart from an agent or a system
ACT	one postulate, that one history of marks is actual (exclusivity a second, outside the record-algebra class); two requirements on its law of chance, given refinable records	a postulate defended, not derived; release not yet stated covariantly

ACT and Many Worlds both keep the whole wave. The Everettian reply is that the worlds are only its decohered components, which ACT keeps as well. The difference is what a component holds. On ACT, it holds possibilities for events and no events, and no one who saw another outcome (Section 8.4). On Many Worlds, it holds a copy of the observer who did. No run can reach another component to check, and where no run can, the razor counts against positing observers no experiment can find. Where Bohmian mechanics adds a particle with a path at every moment, ACT adds no particle, only the fact of which marks were made: an event where a record is released, and nothing between. QBism and relational quantum mechanics add nothing to the equation either, and pay with outcomes that are facts only for an agent, or relative to a system. Among the accounts in which an outcome is a fact apart from any agent or system, the count comes down to one comparison. ACT asserts, of each run, one outcome, the one the run shows. Many Worlds asserts that outcome and every other besides, the others in worlds no run can reach.

ACT begins with the environment rather than adding it afterwards. The bath's dynamics fix the recordable alternatives and the condition for anchoring. The one-history commitment makes one released record history actual. The unitary evolution of the whole is not modified. The nearest accounts are the event ontologies, from Heisenberg's *potentia* to Haag, Blanchard and Jadczyk, Kastner, Belavkin, Kent, the ETH approach of Fröhlich and collaborators (events, trees and histories) and Zhang [65, 60, 61, 11, 73, 8, 76, 77, 44, 10, 43, 42, 126], which also place the event in a physical irreversibility. ACT joins that lineage rather than founding it, and differs within it in three things. The Schrödinger evolution is left exactly as it is, where ETH makes the state's stochastic reduction a law. The boundary is stated against the system's accessible future, rather than ETH's full future algebra or Kent's final hypersurface. And the event rate is the jump intensity of the record channels the bath physically supports, where the event-enhanced quantum theory of Blanchard and Jadczyk postulates a detector coupling of its own.

The open piece Zhang's account names, single-outcome event generation, ACT answers by its one postulate, with the release criterion fixing when: answered, not derived.

The distinction between ACT and all of these lies in a physical ontology of how definite events arise from quantum waves. The decoherence phenomena themselves are the same for every account that keeps unitary quantum mechanics (Section 6). ACT does not treat superposition as a paradox to be resolved. It treats it as the natural structure of a wave. The problem is then not why a particle seems to occupy contradictory states. It is how physical interactions give rise to one definite, irreversible event. ACT's answer is environmental record formation, irreversible release, and the anchoring of one actual history.

10 Scope and open problems

The ontology is proposed generally. The derivations are regional, and the regions are stated. The scalar hazard $h = \dot{\Phi}_{\mathrm{irr}}$ is established where record formation is nondemolition with one common rate for the alternatives (Corollary C.2) and the reduced dynamics is CP-divisible: where it can be cut at any time into a sequence of physical maps with no information flowing back. In practice that means the approximately quantum-nondemolition (QND) and linear–Gaussian windows, the couplings that keep Gaussian states Gaussian. The general event law, Eq. (8), covers released records of any coupling in the Markov class, with one non-Markovian case worked through, delayed return (Proposition B.7; the model is computed in full in [107]). The following are open, in the order the program ranks them. Each is a place where the law is not yet written in full, not a place where it has failed.

1. **A covariant release criterion.** Release is defined against a time-slice's accessible future, and "central relative to the accessible future" has no covariant statement yet. Fewster–Verch instruments give a partially ordered record history [40], so the ontology needs no preferred foliation. Kent's construction [76] shows that a one-history ontology over unmodified unitary dynamics can be Lorentz covariant. What is open is a covariant criterion, not covariant statistics, which ACT has. The delayed-choice eraser at spacelike separation is where this bites. ACT's verdict on when release occurs there is frame-dependent until the criterion is covariant, though its statistics are not.

2. **Release as a stopping time.** Related to the covariant criterion, and not the same question: a stopping-time construction in one frame would settle this item and leave the covariant criterion open, and a covariant criterion would still need the construction. Release is adapted to the network's actual couplings. The theorems of Appendix B are for networks whose couplings are fixed in advance, the two networks of Proposition B.7 included. Where a later coupling is set by an anchored outcome, the dependence runs through the actual history (Section 7); that is stated, not proved, and a formulation of the event time as a stopping time of a filtration generated by the coupling structure is not yet written.

3. **Selection without an apparatus.** The selection theorem is proved with a record architecture in place. What fixes the accessible algebra for a dust grain decohering in the thermal photon bath, where nothing was built to record, is not yet derived. The conjecture ACT states is alignment: the alternatives the records select coincide with the pointer states the dynamics make robust. It is exact in the nondemolition class. Coherent-state pointers in quantum Brownian motion are the candidate answer, and a regime with small nondemolition-breaking and large misalignment would refute it. A levitated particle in a natural thermal bath, with the recorded observable reconstructed from environment fragments as in the quantum-Darwinism experiments, asks exactly this question.

4. **Non-Markovian release.** The delayed-return model defers anchoring to the exit record. Its continuum limit is open, and so is release in a structured environment that hands phase back

late. So is the exact event time in a finite closed system, where release holds to exponential accuracy only: the theory states that idealization and does not remove it.

5. **The per-event energy ledger.** Energy is conserved exactly, because the total system–bath dynamics is unitary with a time-independent Hamiltonian. The fluctuation–dissipation pairing of a modelled bath is what makes the reduced dynamics thermalize rather than heat. A bath-conditioned event map that keeps the books along a single history is not yet constructed.

6. **The general mode-to-alternative map.** How the component structure of the pre-event state is related to the distinct alternatives of the record-supported instrument is obtained here from environmental selection. Whether Fourier or normal-mode structure plays a more fundamental role in it is open, and is the picture's research frontier.

7. **The accessible algebra, grounded.** Irreversibility is relative to accessible operations. ACT ties the accessible algebra to the physics of the coupling and the apparatus, as quantum-trajectory theory does. The partition into system and environment, which under scrambling decides whether a record is central relative to the system, is fixed here by the record architecture and not derived. One research lead would make the criterion objective: grounding accessibility in outgoing massless radiation, as the ETH approach does through Huygens' principle [20], at the cost of moving ACT toward ETH.

11 Conclusion

The wave is what exists. The particle is what happens. Between them stands a bath that every laboratory already has, and ACT's claim is that the bath, plus one commitment, is enough. The bath decoheres. It keeps a record. It carries the record beyond recovery. At that point one mark joins the one causal history. The Schrödinger equation is left exactly as it is. The event law is read off the coupling, with no free constant. The alternatives are fixed by the record architecture. The weights are Born's, and they are forced, not postulated: by the ontology with its refinable records, by no signalling for every division of the world into here and elsewhere, and by continuity. One commitment is added, that one history is actual. Where exclusivity is not yet a theorem, it is stated as a second. The two requirements on the chance law are stated as well.

The laboratory has placed almost the whole of this mechanism on measured ground. It has mapped the boundary at which a record can no longer be recalled. For event rules of ACT's kind it has eliminated each of the three earlier placements that has been tested. And it has watched single quanta leave single marks with Born frequencies. What sets ACT apart from the other accounts that keep quantum mechanics intact is not a different prediction but the account it gives. Other interpretations ask how a superposed quantum state yields a definite result. ACT begins with a real wave and asks how the environment produces a definite event. The case for ACT is explanatory. It says where definiteness lives: in released records. It makes probability ordinary. On the interpretive layer of Section 3.2, it makes time something events do. And it lists what it adds, for Occam's razor to count (Table 4). The one history it holds actual is the one the runs show; Many Worlds counts every other outcome as a world no run can reach.

Quantum mechanics is still spoken in the language of particles and probability clouds: an electron pictured as a small body whose position is spread, somehow, across the alternatives. Everett removed the collapse and kept the wave; the language stayed, and so did the observer, now copied into every branch. ACT says its picture outright. The electron is the wave-mode structure of the composite field; the probabilities are chances of records, not positions of a body; the particle is the mark a released record leaves. The puzzles of Section 1 have nothing left to stand on once the particle is gone and the released record stands in its place. Which slit?

The wave went through both, and there was never a particle to go through one. The cat's fate waits for no one: in any real box, which leaks, the Geiger counter's bath releases the record of the decay (Section 8), and the cat's fate follows that one record whether or not anyone looks. A choice made after the wave has passed the slits changes no mark already made. There was no particle path for it to decide, and in the eraser the later choice decides how the marks are sorted, never which marks were made (Section 8.3). An erased record was never released: it could still be undone, and the pattern it seems to restore appears only in the sorted subsets (Section 6). And no observer is copied into other worlds: one mark, one history (Section 8.4). What the laboratory has measured is a composite field that interferes, a well-characterized bath that keeps records, and marks, one at a time and never two from one event. Together with what the ledger of Section 5 adds, that is all the explanation needs. The apparent mysteries resolve into one causal history of composite field, bath and mark.

A Why the weights are Born's

This appendix proves the WHICH law of Section 4: six stated premises on the chance of a record leave only the squared amplitude. Three of the premises restate the ontology and its commitment, one extends the Bell requirement of Section 8 to every division of the network, one is an assumption about the network, and one is new. The argument is Zurek's [132, 133], in the no-signalling form Barnum gave it [6]. Nothing in the mathematics is new; what is ACT's is that the premises are the theory's own. The argument has been contested where every outcome occurs [101, 89, 127], because there what the probability of an outcome means is itself the open question. Here one record is actual, its chance is a chance, and each contested step is carried by a named premise.

The setting. One global wave Ψ, a unit vector of a separable Hilbert space $\mathcal{H}$, with unmodified unitary dynamics. The network of Appendix B fixes how $\mathcal{H}$ splits into parts: the system, the bath's slices, the pointers. As in that model, the network holds a supply of fresh pointers, each in a fixed initial state and not yet coupled; a *wave of the network* is a unit vector of that form, $\Psi = \Psi_0 \otimes |c_0\rangle \otimes |d_0\rangle \otimes \cdots$. A released record algebra $\mathcal{A}$ is a commutative algebra of released records (Definition B.2) whose minimal projectors $\{P_r\}_{r \in \Omega(\mathcal{A})}$, countably many, are mutually orthogonal and sum to the identity (Theorem B.4); the P_r are the pointer sectors. Records of two parts compose: if $\mathcal{A} = \{P_a \otimes I\}$ and $\mathcal{B} = \{I \otimes Q_b\}$ are released record algebras of parts A and B, their join $\mathcal{A} \vee \mathcal{B} = \{P_a \otimes Q_b\}$ is a released record algebra, because records on distinct factors commute (Theorem B.3). A *law of chance* assigns to every released record algebra $\mathcal{A}$ and every wave Ψ a function $\mu(\,\cdot \mid \Psi; \mathcal{A})$ on $\Omega(\mathcal{A})$: the chance that record r becomes actual. The theorem says what μ must be. Nothing below uses the path measure, the instrument or the conditioned state; those are what the theorem recovers.

The premises.

(i) *One law, one wave.* The chance depends on the wave and the record projectors only, and the same function serves in every basis: for every unitary U on $\mathcal{H}$ for which $U\mathcal{A}U^\dagger$, the algebra with projectors $UP_rU^\dagger$, is again a released record algebra of the network,

$$\mu(r \mid U\Psi; U\mathcal{A}U^\dagger) = \mu(r \mid \Psi; \mathcal{A}). \tag{11}$$

There is nothing else for a chance to depend on: not the Hamiltonian, not the coupling, not a preferred basis. The proof uses only unitaries that map $\mathcal{A}$ onto itself.

(ii) *One history.* For each released record algebra exactly one record is actual, so $\mu(\,\cdot \mid \Psi; \mathcal{A})$ is a probability measure on $\Omega(\mathcal{A})$, countably additive when $\Omega(\mathcal{A})$ is infinite. For exclusive joint records the chance of "a and (b_1 or b_2)" is the sum.

(iii) *Sharp records, with support certainty.* No record is made where the wave has no component: $P_r\Psi = 0$ implies $\mu(r \mid \Psi; \mathcal{A}) = 0$, for the joint records of a composite algebra as for single ones; so if $P_r\Psi = \Psi$ then $\mu(r) = 1$. Anchoring selects among the wave's components and creates none.

(iv) *No signalling, for every division.* The chance of a record here is unchanged when a record is made elsewhere, and unchanged whether one is made: for every factorisation $\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_B$ given by the network and all released record algebras $\mathcal{A}$ of A and $\mathcal{B}$ of B, the marginals of the joint law are the parts' own laws,

$$\mu(a \mid \Psi; \mathcal{A}) = \sum_b \mu(a, b \mid \Psi; \mathcal{A} \vee \mathcal{B}), \qquad \mu(b \mid \Psi; \mathcal{B}) = \sum_a \mu(a, b \mid \Psi; \mathcal{A} \vee \mathcal{B}). \tag{12}$$

The trivial algebra $\{I\}$, no record made, counts among the record algebras of a part. The Bell requirement of Section 8 is the spacelike case, and it gives the rest: any part can be carried away, with its apparatus, by a unitary acting on that part alone; by (i) that unitary changes no chance of a record here (Lemma A.1); once the part is far away the Bell requirement applies; and by (i) again the chances in the far configuration are the chances in the near one. The one further premise this uses is that the division is into systems, each of which can be carried away with its apparatus. This is the only noncontextuality the argument uses: a record's chance does not change when a record is made elsewhere. It is a requirement on the chance law, not something had for free.

(v) *Refinement.* Any released record can be refined by the unmodified dynamics: for every released record algebra $\mathcal{A} = \{P_r\}$ of a part A and integers $m_r \geq 1$, the network supplies a fresh pointer C in a fixed initial state $|c_0\rangle$ and a unitary $W = \sum_r P_r \otimes W_r$ on $A \otimes C$ with $W_r|c_0\rangle = m_r^{-1/2} \sum_{j=1}^{m_r} |c_{rj}\rangle$, the $|c_{rj}\rangle$ orthonormal, such that the projectors $|c_{rj}\rangle\langle c_{rj}|$, completed by their remainder, form a released record algebra $\mathcal{C}$ of C. Then $\mathcal{A} \vee \mathcal{C}$ is a released record algebra of $A \otimes C$ refining $\mathcal{A}$, and on $W\Psi$ its supported records are the $P_r \otimes |c_{rj}\rangle\langle c_{rj}|$. With every $m_r = 1$ this is a copy of the record onto a pointer. In the collision model a fresh slice rotated conditionally on a record, and never returning, is such a pointer (Theorem B.3); a pointer with m_r sectors is m_r such slices or one larger one.

(vi) *Continuity.* For fixed $\mathcal{A}$ and r, $\Psi \mapsto \mu(r \mid \Psi; \mathcal{A})$ is continuous in the norm of $\mathcal{H}$.

Premises (i)–(iii) restate what the paper has already said; (iv) is the Bell requirement of Section 8 in a stronger form, for every division; (v) is an assumption about the record architecture, that any released record can be refined; and (vi) is new.

Three lemmas.

Lemma A.1 (Unitaries that commute with the records)**.** *If $[U, P_r] = 0$ for every $r \in \Omega(\mathcal{A})$, then $\mu(r \mid U\Psi; \mathcal{A}) = \mu(r \mid \Psi; \mathcal{A})$. In particular a unitary acting on a part on which the records of $\mathcal{A}$ act trivially leaves every chance of $\mathcal{A}$ unchanged.*

Proof. $UP_rU^\dagger = P_r$ for every r, so $U\mathcal{A}U^\dagger = \mathcal{A}$ record by record, and (11) reads as claimed. □

Lemma A.2 (Transfer across a perfect correlation)**.** *Let $\mathcal{A} = \{P_a\}$ and $\mathcal{B} = \{Q_b\}$ be released record algebras of parts A and B, let $S_A = \{a : (P_a \otimes I)\Psi \neq 0\}$ and $S_B = \{b : (I \otimes Q_b)\Psi \neq 0\}$, and suppose there is a bijection $f\colon S_A \to S_B$ with $(P_a \otimes Q_b)\Psi = 0$ unless $b = f(a)$. Then $\mu(a \mid \Psi; \mathcal{A}) = \mu(f(a) \mid \Psi; \mathcal{B})$ for every $a \in S_A$, and the records outside S_A and S_B have chance zero.*

Proof. By (12), $\mu(a \mid \Psi; \mathcal{A}) = \sum_b \mu(a, b \mid \Psi; \mathcal{A} \vee \mathcal{B})$, and by (iii) every term with $b \neq f(a)$ vanishes, so the sum is $\mu(a, f(a) \mid \Psi; \mathcal{A} \vee \mathcal{B})$. For $b = f(a)$ the only a' with $(P_{a'} \otimes Q_b)\Psi \neq 0$ is $a' = a$, because f is a bijection; so by (iii) again $\mu(a, f(a) \mid \Psi; \mathcal{A} \vee \mathcal{B}) = \sum_{a'} \mu(a', f(a) \mid \Psi; \mathcal{A} \vee \mathcal{B})$, which is $\mu(f(a) \mid \Psi; \mathcal{B})$ by the second half of (12). The last statement is (iii). □

Lemma A.3 (Equal weights)**.** *Let $\mathcal{D}$ be a released record algebra of a part D, let $S \subset \Omega(\mathcal{D})$ have N elements, let the records $D_r = |d_r\rangle\langle d_r|$, $r \in S$, be rank one, and let*

$$\Psi = N^{-1/2} \sum_{r \in S} |d_r\rangle \otimes \Phi_r, \tag{13}$$

with the Φ_r orthonormal in the complementary factor; since the records of an algebra are mutually orthogonal, every record of $\mathcal{D}$ outside S annihilates Ψ. Then $\mu(r \mid \Psi; \mathcal{D}) = 1/N$ for $r \in S$, and every other record of $\mathcal{D}$ has chance zero.

Proof. For a permutation π of S let S^D_π be the unitary on $\mathcal{H}_D$ with $S^D_\pi |d_r\rangle = |d_{\pi(r)}\rangle$ and the identity on the orthogonal complement of the $|d_r\rangle$, and let S'_π be a unitary on the complementary factor with $S'_\pi \Phi_r = \Phi_{\pi(r)}$ and the identity on the orthogonal complement of the Φ_r. Then $U = S^D_\pi \otimes S'_\pi$ satisfies $U\Psi = \Psi$ and $U(D_r \otimes I)U^\dagger = D_{\pi(r)} \otimes I$ for $r \in S$, and U fixes every record of $\mathcal{D}$ outside S; so $U\mathcal{D}U^\dagger = \mathcal{D}$ with the records of S permuted, and (11) gives $\mu(\pi(r) \mid \Psi; \mathcal{D}) = \mu(r \mid \Psi; \mathcal{D})$. Since π is arbitrary the N chances are equal; by (iii) every record outside S has chance zero; by (ii) the N chances sum to one. □

The theorem.

Theorem A.4 (Born weights)**.** *Under (i)–(vi), for every released record algebra $\mathcal{A} = \{P_r\}$ of the network and every wave Ψ of the network,*

$$\mu(r \mid \Psi; \mathcal{A}) = \langle \Psi | P_r | \Psi \rangle. \tag{14}$$

Proof. Write $w_r = \langle \Psi | P_r | \Psi \rangle$ and $S = \{r : w_r > 0\}$, and for $r \in S$ put $\Phi_r = P_r \Psi / \sqrt{w_r}$; the Φ_r are orthonormal, and Φ_r lies in the range of P_r.

Step 0: copy the record onto a pointer (i, iii, iv, v). The network holds a fresh pointer D in its initial state, so $\Psi = \Psi_0 \otimes |d_0\rangle$ with Ψ_0 on the rest, and by (v) with every $m_r = 1$ a copying unitary $V = \sum_r P_r \otimes V_r$, $V_r |d_0\rangle = |d_r\rangle$, gives

$$\Psi' = V\Psi = \sum_{r \in S} \sqrt{w_r}\, \Phi_r \otimes |d_r\rangle, \tag{15}$$

with the Φ_r now read on the factor complementary to D. Since $[V, P_r \otimes I] = 0$, Lemma A.1 gives $\mu(r \mid \Psi'; \mathcal{A}) = \mu(r \mid \Psi; \mathcal{A})$. The projectors $D_r = |d_r\rangle\langle d_r|$, $r \in S$, with the remainder form the released record algebra $\mathcal{D}$ of D (v), and $\mathcal{A}$ and $\mathcal{D}$ are perfectly correlated on Ψ': $(P_r \otimes D_{r'})\Psi' = 0$ unless $r' = r$, with the identity on S as the bijection. Lemma A.2 gives $\mu(r \mid \Psi'; \mathcal{A}) = \mu(r \mid \Psi'; \mathcal{D})$. It remains to show $\mu(r \mid \Psi'; \mathcal{D}) = w_r$ for a pointer whose supported records are rank one and whose partners Φ_r are orthonormal.

Step 1: equal weights (i, ii, iii). If $w_r = 1/N$ for $r \in S$, Lemma A.3 gives $\mu(r \mid \Psi'; \mathcal{D}) = 1/N = w_r$.

Step 2: rational weights (i–v). Let $w_r = m_r/M$ with integers $m_r \geq 1$ for $r \in S$ and $M = \sum_{r \in S} m_r$. By (v) applied to $\mathcal{D}$ with these integers, a pointer C and $W = \sum_r D_r \otimes W_r$ give

$$\Psi'' = W\Psi' = M^{-1/2} \sum_{r \in S} \sum_{j=1}^{m_r} \Phi_r \otimes |d_r\rangle |c_{rj}\rangle. \tag{16}$$

Since $[W, D_r \otimes I] = 0$, Lemma A.1 gives $\mu(r \mid \Psi''; \mathcal{D}) = \mu(r \mid \Psi'; \mathcal{D})$. Let $\mathcal{C}$ be the released record algebra of C supplied by (v), with records $C_{rj} = |c_{rj}\rangle\langle c_{rj}|$ and their remainder, so that $\mathcal{D} \vee \mathcal{C}$ is a released record algebra refining $\mathcal{D}$; on Ψ'' its supported records are the M rank-one projectors $|d_r c_{rj}\rangle\langle d_r c_{rj}|$, each with weight $1/M$, and their partners Φ_r repeat. By (v) with every integer equal to one, copy the refined record onto a further pointer E:

$$\Psi''' = M^{-1/2} \sum_{r \in S} \sum_{j=1}^{m_r} \Phi_r \otimes |d_r c_{rj}\rangle \otimes |e_{rj}\rangle, \tag{17}$$

with the $|e_{rj}\rangle$ orthonormal. The copy is block-diagonal in the records of $\mathcal{D}\vee\mathcal{C}$ and so commutes with every one of them, supported or not, and Lemma A.1 gives the chances of $\mathcal{D}\vee\mathcal{C}$ the same value on Ψ''' as on Ψ''; on Ψ''' the partners $\Phi_r\otimes|e_{rj}\rangle$ are orthonormal, so Lemma A.3 gives $\mu(r,(r,j)\mid\Psi'';\mathcal{D}\vee\mathcal{C})=1/M$ for the M supported records $(r,(r,j))$ and zero for every other record of $\mathcal{D}\vee\mathcal{C}$. Finally, by the first half of (12) on the division of the network into D and the rest,

$$\mu(r\mid\Psi'';\mathcal{D})=\sum_{(r',j)}\mu(r,(r',j)\mid\Psi'';\mathcal{D}\vee\mathcal{C})=\sum_{j=1}^{m_r}\frac{1}{M}=\frac{m_r}{M}=w_r. \tag{18}$$

Step 3: all weights (vi). For fixed S, $\mathcal{D}$ and partners, $w\mapsto\Psi'(w)=\sum_{r\in S}\sqrt{w_r}\,\Phi_r\otimes|d_r\rangle$ is a continuous map from the closed simplex to the unit sphere, and Steps 1 and 2, applied with the support of w in place of S, give $\mu(r\mid\Psi'(w);\mathcal{D})=w_r$ at every rational point of the simplex. Rational points are dense, and (vi) extends the identity to every w. If S is infinite, let Ψ'_N be the normalised sum over the N largest weights; the finite case gives $\mu(r\mid\Psi'_N;\mathcal{D})=w_r/\sum_{S_N}w_s$, $\Psi'_N\to\Psi'$ in norm, and (vi) gives $\mu(r\mid\Psi';\mathcal{D})=w_r$. With Step 0 this is (14). □

Corollary A.5 (The path measure is forced)**.** *For the record algebra of N slices (Appendix B), Theorem A.4 gives $\mu(r\mid\Psi)=\langle\Psi|\Pi_r|\Psi\rangle$, which is the path measure (8); an initial system state ρ_S that is mixed is the reduction of the one wave on a larger network, and the chance is $\mathrm{Tr}[\rho_0\Pi_r]$ by linearity of the partial trace. The system-level chance of an unsharp record, $\mathrm{Tr}(\rho_S E)$ with E the effect the record induces on the system, follows by the same partial trace: it is a consequence, not a rule. The event law of Appendix C is therefore forced rather than imported: its intensities are the limit of a discrete path measure whose weights the theorem fixes.*

No signalling: premise and check. Section 8 obtained parameter independence from the conditioned pair state. Here the same property, for every division of the network and not only for spacelike separated regions, is the premise (iv), placed on the law of chance before the weights are known; the law it forces, $\langle\Psi|P_a\otimes Q_b|\Psi\rangle$, satisfies (12) identically. The two statements are consistent and not circular: (iv) is the premise, and the no-signalling of the conditioned state is the check that the premise is honoured. Every no-signalling derivation of the weights takes the same order [6].

What each premise excludes. A rule that squares the weights and renormalizes, $\mu_r\propto|c_r|^4$, meets (i), (ii), (iii), (v) and (vi) and fails (iv): Alice's marginal changes when Bob records, by as much as 0.2 in random trials. A rule that is not the same function in every basis fails (i). The covariant nonlinear rules, the symmetric cubic rule among them, meet (iii) and fail (iv); the no-signalling toy model of Galley and Masanes [46] meets (iv) and fails (iii), since no record in it is ever certain. A rule that treats rational and irrational weights differently fails (vi). Gleason's theorem [53, 22] characterizes the same weights from a stronger premise, that a record's chance is the same whatever apparatus produces it; here that is a consequence. Additivity, which Zhang shows no derivation of the Born rule can do without [127], is supplied by (ii) within an algebra and by (iv) across algebras, a requirement and not something had for free; the paper does not claim that noncontextuality yields it. The derivation is conditional on the six premises. What is not derived: that there is chance at all, which comes with the one commitment, that one history is actual; (iv) beyond its spacelike case, which rests on the carriability of each system with its apparatus; (v); and (vi). In the pure-dephasing model of Appendix C the same weights also descend from the ensemble to single histories, because the conditioned weights form a martingale; that descent is a consistency check, not the ground of the weights.

B Records, release and exclusivity

This appendix proves the three statements of Section 7 that the ontology rests on: released records commute, so the histories they define exclude one another; release is the point at which attaching actuality to a record changes no accessible prediction; and before release some accessible observable shows the difference. The proofs are given in a collision model, the discrete form of the quantum Brownian bath, in which every commutator can be computed exactly; the continuous case is the Hudson–Parthasarathy calculus, where the same statements are the nondemolition theorems of Bouten and van Handel [16, 17].

The model. A system S meets a sequence of fresh slices of the bath $a_1, a_2, \ldots, a_N$, one at each step; each slice is a two-level system in its ground state $|g\rangle_k$, which stands for the vacuum of one bath mode. With $|e\rangle, |g\rangle$ the system levels and $\sigma_- = |g\rangle\langle e|$, step k is

$$U_k \;=\; e^{-iH_S\,\delta t}\; e^{-i\theta_c\,(\sigma_-\otimes a_k^\dagger + \sigma_+\otimes a_k)}, \qquad \theta_c = \sqrt{\gamma\,\delta t}, \tag{19}$$

where $a_k^\dagger = |e\rangle\langle g|_k$ excites slice k: the system hands a quantum to the slice, or takes one back, and the slice then leaves. The chain up to step k is $U_{1..k} = U_k U_{k-1}\cdots U_1$. The record on slice k is an observable Q_k of that slice: $\sigma_z^{(k)}$ (is a quantum present in slice k?) or $\sigma_x^{(k)}$ (a quadrature). Nothing below assumes that H_S commutes with the coupling; the system may be driven between the very levels the record distinguishes. A *Markov record network* is a network of this kind: each slice meets the system once and never returns. Where a slice does return, the statements below apply to the record at the slice's exit (Proposition B.7).

Definition B.1 (Record observables; record algebra)**.** $Y_k := U_{1..k}^\dagger\, Q_k\, U_{1..k}$ is the record observable of slice k, in the Heisenberg picture at the end of step k; Theorem B.3(iii) shows that later steps leave it unchanged. $\mathcal{R}_N := \mathrm{vN}\{Y_1, \ldots, Y_N\}$, the algebra the records generate, is the record algebra.

Definition B.2 (The accessible future; release)**.** For a time s, the system's accessible future $\mathcal{F}_s^S$ is the algebra generated by all later Heisenberg system observables and all later fresh records, computed with the actual total dynamics of the network, including any path by which a carrier returns to the system. A record observable R formed at time s is *released* if $[R, F] = 0$ for every $F \in \mathcal{F}_s^S$: nothing in the system's accessible future can act on it. Released records commute among themselves (Theorem B.3), and the actual history is one point of their joint spectrum.

Theorem B.3 (Commutativity and nondemolition for arbitrary system Hamiltonian and coupling)**.** *In the model (19), for arbitrary H_S and arbitrary coupling operator in place of σ_-: (i) $[Y_k, Y_l] = 0$ for all k, l; (ii) $[\,j_N(X), Y_k\,] = 0$ for every system observable X and every $k \le N$, where $j_N(X) = U_{1..N}^\dagger X U_{1..N}$; (iii) $U_{1..N}^\dagger Q_k U_{1..N} = Y_k$ for all $N \ge k$. In words: the records of a Markov network commute with one another and with everything the system does later, and once formed they never change.*

Proof. Slice k enters the dynamics only at step k. Write $U_{1..N} = U_{k+1..N} U_{1..k}$ with $U_{k+1..N} = U_N \cdots U_{k+1}$. Each factor of $U_{k+1..N}$ acts on the system and the slices after k, and as the identity on slice k, so $[U_{k+1..N}, Q_k] = 0$; this gives (iii): $U_{1..N}^\dagger Q_k U_{1..N} = U_{1..k}^\dagger U_{k+1..N}^\dagger Q_k U_{k+1..N} U_{1..k} = U_{1..k}^\dagger Q_k U_{1..k}$. For (i) with $l > k$, $Y_l = U_{1..k}^\dagger \big(U_{k+1..l}^\dagger Q_l U_{k+1..l}\big) U_{1..k}$, and the bracketed operator acts on the system and the slices $k+1, \ldots, l$, hence commutes with Q_k; conjugation by $U_{1..k}$ preserves commutation. (ii) is the same argument with X in place of Q_l: $j_N(X) = U_{1..k}^\dagger \big(U_{k+1..N}^\dagger X U_{k+1..N}\big) U_{1..k}$, and the bracketed operator does not act on slice k. No property of H_S or of the coupling was used. □

Theorem B.4 (Histories; exclusivity as a theorem)**.** *$\mathcal{R}_N \cong L^\infty(\Omega_N, \mathbb{P})$ with $\Omega_N = \{+,-\}^N$ the set of records, $r_k = \pm$ the two values of Q_k and $P_\pm$ its spectral projectors. The joint spectral projectors*

$$\Pi_r = U_{1..N}^\dagger \left(P_{r_1} \otimes \cdots \otimes P_{r_N}\right) U_{1..N}, \qquad r \in \Omega_N, \tag{20}$$

are mutually orthogonal and sum to the identity, and for a product initial state $\rho_0 = \rho_S \otimes |g\cdots g\rangle\langle g\cdots g|$,

$$\mathbb{P}(r) = \mathrm{Tr}[\rho_0\, \Pi_r] = \mathrm{Tr}\big[\mathcal{I}_{r_N} \circ \cdots \circ \mathcal{I}_{r_1}(\rho_S)\big], \tag{21}$$

where $\mathcal{I}_r$ is the single-step instrument on the system: couple to a fresh slice, project the slice onto P_r, trace it out.

Proof. By Theorem B.3(i), $\mathcal{R}_N$ is a commutative von Neumann algebra generated by N commuting self-adjoint operators with spectra $\{\pm 1\}$, so its spectrum is Ω_N and its minimal projectors are the joint spectral projectors. Since $Y_k = U_{1..N}^\dagger Q_k U_{1..N}$ for all k (Theorem B.3(iii)) and the Q_k act on distinct tensor factors, the joint projector for the record r is Π_r as displayed; orthogonality and completeness are inherited from those of the P_{r_k} under the unitary conjugation. For (21), insert $U_{1..N} = U_N \cdots U_1$ and use that P_{r_k} commutes with U_l for $l > k$ to move each P_{r_k} next to U_k: $\mathrm{Tr}[\rho_0 \Pi_r] = \mathrm{Tr}[P_{r_N} U_N \cdots P_{r_1} U_1 \rho_0 U_1^\dagger P_{r_1} \cdots U_N^\dagger P_{r_N}]$. Tracing out slice k immediately after P_{r_k} is applied, since it is no longer acted on, gives the composition of single-step instruments. □

The points of the spectrum of a commutative algebra are exclusive by construction: a history is one point, and two points are never both the case. That is the whole of the mathematics behind exclusivity, and it is why the ledger of Section 5 counts one commitment within this class. Here $\mathbb{P}$ is the spectral measure of ρ_0 on the record algebra, ordinary quantum probability; that it is the law of chance of the actual record is what Appendix A proves.

Theorem B.5 (Graded release bound)**.** *Let $R = r_+P_+ + r_-P_-$ be a binary record, $P_+ + P_- = I$, $\Delta = |r_+ - r_-|$. For an operator A write $A_{\mathrm{off}} = P_+AP_- + P_-AP_+$, and for a state ω write $\omega_{\mathrm{off}} = P_+\omega P_- + P_-\omega P_+$, the part of the state that is off-diagonal between the record's two eigenspaces. Let $S = P_+ - P_-$ and $\omega_\pi = S\omega S$, the state with the relative phase between the two alternatives flipped, which is the state that Eq. (6) compares ω against. Then: (a) $\|[R,A]\| = \Delta\, \|A_{\mathrm{off}}\|$ in every unitarily invariant norm; (b) for every A with $\|A\| \le 1$, $|\mathrm{Tr}(\omega_{\mathrm{off}} A)| \le \|\omega_{\mathrm{off}}\|_1\, \|[R,A]\|/\Delta$; (c) consequently*

$$\mathcal{D}_{\mathrm{acc}}(\omega, \omega_\pi) := \sup_{A \in \mathcal{A}_{\mathrm{acc}},\, \|A\| \le 1} \tfrac{1}{2}\big|\mathrm{Tr}[(\omega - \omega_\pi)A]\big| \;\le\; \frac{\|\omega_{\mathrm{off}}\|_1}{\Delta} \sup_{A \in \mathcal{A}_{\mathrm{acc}},\, \|A\| \le 1} \|[R,A]\|\,, \tag{22}$$

and in particular, if R is released then $\mathcal{D}_{\mathrm{acc}}(\omega, \omega_\pi) = 0$ for every state ω. In words: phase can be recovered only through observables that fail to commute with the record, and the commutator caps how much.

Proof. (a) Insert $I = P_+ + P_-$ on both sides of A in $[R,A] = r_+P_+A + r_-P_-A - r_+AP_+ - r_-AP_-$. The diagonal blocks $P_\pm AP_\pm$ cancel, and $[R,A] = (r_+ - r_-)(P_+AP_- - P_-AP_+)$. Since $S\,A_{\mathrm{off}} = P_+AP_- - P_-AP_+$, we have $[R,A] = (r_+ - r_-)\,S\,A_{\mathrm{off}}$ with S unitary, whence $\|[R,A]\| = \Delta\,\|A_{\mathrm{off}}\|$ in any unitarily invariant norm. (b) ω_{off} has only off-diagonal blocks, so $\mathrm{Tr}(\omega_{\mathrm{off}} A) = \mathrm{Tr}(\omega_{\mathrm{off}} A_{\mathrm{off}})$: the diagonal blocks of A pair with the vanishing diagonal blocks of ω_{off}. Hölder's inequality gives $|\mathrm{Tr}(\omega_{\mathrm{off}} A_{\mathrm{off}})| \le \|\omega_{\mathrm{off}}\|_1\, \|A_{\mathrm{off}}\|$, and (a) converts $\|A_{\mathrm{off}}\|$. (c) S leaves the diagonal blocks of ω and negates the off-diagonal ones, so $\omega - \omega_\pi = 2\omega_{\mathrm{off}}$ and $\frac{1}{2}|\mathrm{Tr}[(\omega - \omega_\pi)A]| = |\mathrm{Tr}(\omega_{\mathrm{off}} A)|$; take the supremum over the accessible unit ball and apply (b). If $[R,A] = 0$ for all $A \in \mathcal{A}_{\mathrm{acc}}$ every term vanishes. □

Corollary B.6 (Actuality is empirically idle exactly at release)**.** *Let $R = r_+P_+ + r_-P_-$ be a binary record formed at time s, let ω be any state, and let $\omega_{\mathrm{dec}} = P_+\omega P_+ + P_-\omega P_-$ be the mixture obtained by attaching a definite value to R with the Born weights and conditioning on it without reading it. Then for every $A \in \mathcal{F}_s^S$ with $\|A\| \le 1$,*

$$\left|\mathrm{Tr}(\omega A) - \mathrm{Tr}(\omega_{\mathrm{dec}} A)\right| \;\le\; \frac{\|\omega_{\mathrm{off}}\|_1}{\Delta}\,\|[R, A]\|\,. \tag{23}$$

Consequently: (i) if R is released, attaching actuality to it changes no accessible prediction, for every state; (ii) if R is not released, there exist an accessible observable $A \in \mathcal{F}_s^S$ and a state ω for which the two predictions differ.

Proof. $\omega - \omega_{\mathrm{dec}} = \omega_{\mathrm{off}}$, so the left side of (23) is $|\mathrm{Tr}(\omega_{\mathrm{off}} A)|$, and Theorem B.5(b) gives the bound; (i) follows because every commutator on the right vanishes. For (ii), not released means $[R, A] \neq 0$ for some $A \in \mathcal{F}_s^S$, which we may take self-adjoint (if $[R, A] \neq 0$ then R fails to commute with the Hermitian or the anti-Hermitian part of A), and which by Theorem B.5(a) means $P_+AP_- \neq 0$; choose unit vectors $u \in \mathrm{ran}\,P_+$, $v \in \mathrm{ran}\,P_-$ with $a = \langle u|A|v\rangle \neq 0$ and set $\psi = (u + e^{i\varphi}v)/\sqrt{2}$, $\omega = |\psi\rangle\langle\psi|$. Then $\mathrm{Tr}(\omega_{\mathrm{off}} A) = \mathrm{Re}(e^{i\varphi}a)$, which equals $|a| > 0$ for $\varphi = -\arg a$. □

Corollary B.6 is what fixes where a one-history ontology over unmodified quantum mechanics may place its events, and it is the statement Table 3 tests. A rule that makes a record definite before release, in the corollary's sense, changes what the actual history predicts: by (ii), for some preparation and some accessible observable, that history predicts a value that unitary evolution does not, and the observable is one through which the recorded phase can still return. A rule that places the event at release, or later, is empirically idle by (i). The commutation in Definition B.2 is exact in the continuum-bath limit and holds to exponential accuracy for a large finite bath; Section 7 states that idealization.

Proposition B.7 (Two networks whose output is not free)**.** *(a)* Delayed return. *Let slice k interact at step k, return and interact again at step $k + \tau$, and then leave for good: an atom before a mirror, in collision-model form [37, 2]. The in-flight record $Y_k^{(1)} = U_{1..k}^\dagger Q_k U_{1..k}$ is nondemolition at intermediate times, $[Y_k^{(1)}, j_t(X)] = 0$ for $k < t < k + \tau$, but is not released: $[Y_k^{(1)}, j_t(X)] \neq 0$ in general for $t \ge k + \tau$. The exit record $Y_k^{\mathrm{exit}} = U_{1..k+\tau}^\dagger Q_k U_{1..k+\tau}$ is released, and the exit records satisfy Theorems B.3 and B.4 verbatim. (b)* Scrambling. *After the record Y_k has formed, let a unitary W act on slices already emitted and on parts of the environment that never couple to the system, and never on the system or on a slice still to interact. Then Y_k stays released, while it no longer commutes with readouts of the slices W mixed it into, and the system's reduced dynamics is unchanged.*

Proof. (a) For $k < t < k + \tau$ slice k is not acted on between steps k and t, so the argument of Theorem B.3(ii) applies. For $t \ge k + \tau$ the factor $U_{k+1..t}$ contains the second interaction of slice k with the system, which does not commute with Q_k, and the commutator is in general nonzero. After step $k + \tau$ slice k is never acted on again, so Theorem B.3 applies to the exit records with $U_{1..k+\tau}$ in place of $U_{1..k}$, and Theorem B.4 to the enlarged system of the system together with the slices in flight. (b) W acts as the identity on the system and on every slice that has not yet interacted, so it commutes with every later $j_t(X)$ and with every fresh record, and the argument of Theorem B.3(ii) goes through with W inserted into the chain; W entangles slice k with the slices it acts on, so Q_k pulled back through W fails to commute with their observables; and W is traced out of the reduced state. Both networks are computed in full, with the in-flight and exit outcomes of (a) differing with finite probability, in [107]. □

These are the two cases Section 7 describes: anchoring deferred to the exit record, and a record that leaves the centre of the whole future algebra, since something in the environment

can still act on it, while remaining central relative to the system, since nothing the system does reaches it.

C The event law

This appendix proves the WHEN law of Section 4 in its general form, and derives the scalar hazard $h = \dot{\Phi}_{\rm irr}$ as its case of nondemolition channels with one common rate.

Theorem C.1 (The event law, general form)**.** *For released records the law of events is the instrument path measure* (21)*, equivalently the law of the output process under the quantum filter. In the continuous case, for a released counting record with jump operator L_r, the event intensity is*

$$\lambda_r(t) = \mathrm{Tr}\big(L_r^\dagger L_r\, \rho_c(t)\big), \tag{24}$$

where ρ_c is the conditioned state, the Belavkin filter, and its ensemble average reproduces the unconditioned Lindblad dynamics for every initial state.

Proof. This is the content of the filtering theorems [7, 16, 17] together with Theorem B.4: the probability of a history is $\mathrm{Tr}[\rho_0 \Pi_r]$, which is the path measure; the counting intensity is the infinitesimal form of the single-step instrument's outcome probability, $\mathrm{Tr}[\mathcal{I}_r(\rho_c)] = \mathrm{Tr}(L_r^\dagger L_r \rho_c)\, dt + O(dt^2)$; exactness in ensemble is completeness of the instrument, $\sum_r \mathcal{I}_r = e^{\mathcal{L}\, dt}$. □

Corollary C.2 (The nondemolition hazard, one common rate)**.** *If the record channels are $L_\pm = \sqrt{\Lambda}\, P_\pm$ with $\sum_\pm L_\pm^\dagger L_\pm = \Lambda\, I$, then the total intensity is Λ, independent of the conditioned state; the no-event evolution is outcome-neutral, that is, surviving without an event does not shift the alternatives' populations; and $\Lambda = \dot{\Phi}_{\rm irr}$. The scalar law $h = g\, \dot{\Phi}_{\rm irr}$ of Section 4, with the gate open, is this case of Theorem C.1, and Eqs.* (4) *and* (5) *follow.*

Proof. $\sum_\pm \mathrm{Tr}(L_\pm^\dagger L_\pm \rho_c) = \Lambda \mathrm{Tr}\rho_c = \Lambda$. The no-event generator $-\frac{i}{\hbar} H_{\rm eff} = -\frac{i}{\hbar} H_S - \frac{1}{2}\Lambda I$ is proportional to the identity in its non-Hermitian part, so the no-event evolution does not reweight the alternatives. For a nondemolition record the accessible distinguishability of the phase pair decays as $\mathcal{D}(t) = \mathcal{D}(0) e^{-\int_0^t \Lambda}$, so $\dot{\Phi}_{\rm irr} = \Lambda$. The survival probability is then $S(t) = \exp[-\int_0^t \Lambda] = e^{-\Phi_{\rm irr}(t)}$, which is Eq. (4); and since the no-event evolution preserves the populations while the anchored runs sit in one alternative each, the ensemble is the mixture (5). □

Outside the nondemolition window the extrapolated hazard $h = \dot{\Phi}_{\rm irr}$ is wrong, not merely unestablished: for a driven two-level atom with a photodetected output it gives the wrong lifetime and no antibunching, while (24) with $L = \sqrt{\gamma}\, \sigma_-$ gives, for the undriven atom, $\rho_{ee}(t) = \rho_{ee}(0) e^{-\gamma t}$, and, for the driven atom with the drive in $H_{\rm eff}$, the waiting-time density $w(\tau) = \gamma |\langle e| e^{-i H_{\rm eff} \tau} |g\rangle|^2$ with $w(0^+) = 0$, Carmichael's delay function [25]. The scope stated in Section 10, that the scalar hazard is established where record formation is nondemolition with one common rate and the reduced dynamics is CP-divisible, has its reason here. Released records exist for any coupling in the Markov class, and at the exit record where a carrier returns (Appendix B); the general law (24) covers them all. The scalar hazard needs two things more: nondemolition channels with one common rate, $\sum_\pm L_\pm^\dagger L_\pm = \Lambda\, I$, so that the intensity is outcome-neutral (Corollary C.2), since nondemolition alone does not give this: channels $L_\pm = \sqrt{\gamma_\pm}\, P_\pm$ with unequal rates have intensity $\gamma_+ p_+ + \gamma_- p_-$ and a no-event evolution that shifts the populations toward the slower channel; and CP-divisibility, since a time-local jump unravelling with non-negative rates exists exactly when the reduced dynamics is CP-divisible [63].

The pure-dephasing model. In the simplest record-forming channel, a system with two alternatives $|\pm\rangle$ coupled to a bath that reads which alternative holds and disturbs neither, the Lindbladian is $\mathcal{L}\rho = \Lambda(P_+\rho P_+ + P_-\rho P_- - \rho)$, and the conditioned weights $p_\pm(t) = \mathrm{Tr}[P_\pm \rho_c(t)]$ along a run are a martingale: their expected value never drifts, because the no-event evolution is outcome-neutral and each event sends one weight to one and the other to zero with the current weights as chances. Averaging the single-history law over runs therefore returns $\rho_S(t)$, the master equation's solution, with the Born weights as the long-run frequencies of the marks. This descent is the consistency check named in Section 4: the weights are forced by Appendix A, and the model shows the single-history law and the master equation agree.

D The selection theorem

This appendix proves the theorem Section 4 cites for the WHAT law: in a model where records form faster than the probe disperses, the environment's fragment records can condition the system only on where it is, and never give it a coherent momentum kick.

Setup. Let $\hat{\mathcal{O}}$ have eigenbasis $\{|o\rangle\}$, and let a probe prepared in the wavepacket $\varphi(y)$ acquire the value of $\hat{\mathcal{O}}$ through $U = \exp(-i\,\hat{\mathcal{O}} \otimes \hat{p}_E)$, so that

$$|\Psi\rangle = \sum_o c_o\,|o\rangle \otimes |\varphi_o\rangle, \qquad \varphi_o(y) = \varphi(y - o). \tag{25}$$

The probe's position is shifted by the value of the observable. The two rival instruments, one that localizes and one that kicks the momentum, are

$$M_y = \varphi(y - \hat{\mathcal{O}}), \qquad L_q = \tilde{\varphi}(q)\, e^{-iq\hat{\mathcal{O}}}, \tag{26}$$

with $\tilde{\varphi}$ the Fourier transform of φ. Let the environment read the probe through a position-diagonal fanout,

$$V = \int dy\ |y\rangle\langle y| \otimes V_y, \tag{27}$$

acting on the probe's position before free evolution converts momentum information into position information, so that

$$|\Psi'\rangle = \sum_o c_o\,|o\rangle \otimes \int dy\ \varphi(y - o)\,|y\rangle \otimes V_y|E_0\rangle. \tag{28}$$

Theorem D.1 (Selection)**.** *Every conditioned operation on the system that fragment records alone can produce has the form*

$$\rho_S \longmapsto \int dy\ \mu(y)\, M_y \rho_S M_y^\dagger, \qquad \mu(y) \geq 0, \tag{29}$$

a classical post-processing of the localization instrument $\{M_y\}$. Moreover, provided (i) the translated wavepackets are pairwise non-proportional on the spectrum of $\hat{\mathcal{O}}$, that is, $\varphi(y - \cdot)$ and $\varphi(y' - \cdot)$ are not related by a constant factor for $y \neq y'$ in $\mathrm{supp}\,\mu$*, and (ii) $|\varphi(y - o)|$ is non-constant across the relevant eigenvalues o, no nontrivial momentum-kick instrument L_q is realizable by such records.*

Lemma D.2 (Phase-only probe information is absent from fragment records)**.** *For any fragment F of the environment, the reduced state ρ_F depends on φ only through $|\varphi|^2$; hence $\varphi(y) \mapsto e^{iqy}\varphi(y)$ leaves every ρ_F invariant.*

Proof. Tracing Eq. (28) over the system, the probe and the complement of F, and using $\langle y'|y\rangle = \delta(y-y')$,

$$\rho_F = \sum_o |c_o|^2 \int dy\ |\varphi(y-o)|^2\ \rho_F(y), \qquad \rho_F(y) = \mathrm{Tr}_{\bar{F}}\big[V_y|E_0\rangle\langle E_0|V_y^\dagger\big]. \tag{30}$$

Only $|\varphi|^2$ appears, and $|e^{iqy}\varphi(y)|^2 = |\varphi(y)|^2$. □

Proof of Theorem D.1. Let $\{E_r\}$ be any POVM on fragment records, so that $0 \le E_r \le \mathbb{I}$ and $\sum_r E_r = \mathbb{I}$, and let $M_F = E_r$ be one of its effects. The unnormalized conditioned system state is

$$\begin{aligned}\mathrm{Tr}_{P,E}\Big[(\mathbb{I}_S \otimes M_F)\,|\Psi'\rangle\langle\Psi'|\Big] &= \sum_{o,o'} c_o c_{o'}^*\,|o\rangle\langle o'| \int dy \int dy'\ \varphi(y-o)\varphi^*(y'-o')\,\langle y'|y\rangle\,\mathrm{Tr}\big[M_F\,\sigma_{yy'}\big] \\ &= \sum_{o,o'} c_o c_{o'}^*\,|o\rangle\langle o'| \int dy\ \varphi(y-o)\,\varphi^*(y-o')\,\mu(y),\end{aligned} \tag{31}$$

with $\mu(y) = \mathrm{Tr}[M_F\,\rho_F(y)] \ge 0$. Writing $\mu_r(y) = \mathrm{Tr}[E_r\,\rho_F(y)]$ for the weight induced by effect E_r, and noting that each $\rho_F(y)$ of Eq. (30) is a normalized state, the condition $\sum_r E_r = \mathbb{I}$ gives $\sum_r \mu_r(y) = 1$ for every y. The family is therefore a genuine classical post-processing and not merely a nonnegative reweighting. This is exactly (29).

For the second statement we argue by Kraus rank rather than by phase invariance alone, since invariance of the weights does not by itself exclude an accidental coincidence for some special φ. The map $\rho \mapsto L_q \rho L_q^\dagger$ has Kraus rank one. The fragment-conditioned map (29) is a positive mixture $\int dy\,\mu(y)\,M_y \cdot M_y^\dagger$ of operators M_y that are diagonal in the $\hat{\mathcal{O}}$ eigenbasis with entries $\varphi(y-o)$. Its Choi operator is $\int dy\,\mu(y)\,|m_y\rangle\langle m_y|$ with $|m_y\rangle$ the vectorization of M_y; this has rank one if and only if the vectors $\{|m_y\rangle : y \in \mathrm{supp}\,\mu\}$ are mutually parallel, that is, the functions $\varphi(y-\cdot)$ are pairwise proportional almost everywhere on $\mathrm{supp}\,\mu$. That is excluded by hypothesis (i), which holds for any translated localized wavepacket whose support moves with y. Hence for μ supported on more than a single point the conditioned map has Kraus rank greater than one and cannot equal $L_q \cdot L_q^\dagger$. For μ concentrated at a single y the map is $M_y \cdot M_y^\dagger$, of rank one, and the exclusion instead uses hypothesis (ii): $L_q = \tilde{\varphi}(q)e^{-iq\hat{\mathcal{O}}}$ has constant modulus $|\tilde{\varphi}(q)|$ across the spectrum, whereas M_y has entries $\varphi(y-o)$ of non-constant modulus, so no scalar multiple relates them. Lemma D.2 supplies the complementary fact that μ carries no q-dependence with which such a coincidence could be engineered. □

Scope. The proof uses the position-diagonality of the fanout and the fact that it couples to the probe's position before free evolution converts momentum or phase information into position information: record formation fast compared with probe dispersion, $\tau_{\mathrm{rec}} \ll t_{\mathrm{disp}} \sim m_E\sigma^2/\hbar$. Outside that regime the conclusion inverts: free flight converts a momentum displacement into a later position displacement, $\Delta y = \hbar q t/m_E$, so a downstream position-local environment can record momentum, which is how momentum is ordinarily measured, and the selected instrument follows the recorded variable. The theorem constrains fragment-accessible conditioning to the localization class; it does not fix the weight $\mu(y)$, the resolution or the coarse-graining, and claims that the record architecture determines a unique instrument are stronger than it supports. It is derived entirely from standard unitary dynamics, so it is not a new operational prediction: ordinary quantum mechanics, restricted to the same fragment records, issues the same restriction. Its role is to identify, from the physical record architecture, which of the mathematically available unravellings is treated as actual. Model-independent uniqueness, extension to general POVMs and a covariant formulation remain open (Section 10).

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