Chasing a Mirage Quantum-Chip Diagnostics and the Unresolved Ontology of the Vacuum

A PoC^4 Analysis of Deterministic Alternatives to Standard Quantum Mechanics, with Nanoscale Qubit Diagnostics as a Case Study

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Abstract

The commercialization of quantum-chip diagnostics — exemplified by the Leiden University spin-off QuantaMap and its multi-modal SQUID-on-Tip microscope — is routinely described in the language of "testing quantum chips." This paper argues that the measurement apparatus itself tests nothing of the kind. What is measured is a set of classical, local field quantities — temperature, magnetic stray field, structural topology, and electrical current — at nanoscale resolution. The inference that these measurements diagnose "qubit failure" presupposes a specific and contested ontological reading of quantum mechanics, in which superposition and entanglement are treated as primitive physical facts rather than as the statistical bookkeeping of an underlying deterministic process. Two independent and convergent research programs — Gerard 't Hooft's Cellular Automaton Interpretation (CAI) and Peter Rowlands's nilpotent vacuum formalism — argue for exactly the latter reading, on grounds that have nothing to do with their authors having collaborated, and everything to do with the algebra and the physics converging from entirely different starting points. This paper places both programs inside a single generative frame — designated PoC^4, after the four-fold algebraic structure guaranteed by Hurwitz's theorem on normed division algebras — and uses that frame to ask a precise question: when an industrial diagnostic tool reports that it has located the cause of "qubit decoherence," has it identified a defect in a fundamentally quantum object, or has it identified a classical material defect that interrupts an emergent statistical regularity we have chosen to call "quantum"? The paper traces the Cayley–Dickson algebraic chain that fixes the number four as a mathematical necessity rather than a free parameter, develops Rowlands's zero-totality construction and 't Hooft's deterministic automaton in full technical and historical detail, confronts both with the strongest available objection — the Bell-theorem/superdeterminism literature, including its most recent (2024–2025) defenses and rebuttals — and returns to the QuantaMap instrument's own published specification to show, quantity by quantity, that every decoherence mechanism it is designed to localize is classical under all three competing ontologies. The paper concludes that the engineering claim is sound and the ontological claim is not decidable on the basis of this or any comparable instrument — and that the persistent

conflation of the two is not a minor terminological looseness but a structural feature of how an unresolved foundational debate gets laundered into settled fact by industrial framing.

Keywords: nilpotent quantum mechanics, cellular automaton interpretation, vacuum ontology, superdeterminism, Hurwitz's theorem, Cayley–Dickson construction, quantum-chip diagnostics, decoherence, Josephson junction, SQUID-on-tip, PoC^4

1. Introduction: A Question About What Is Actually Being Tested

In February 2026, Leiden University and the spin-off company QuantaMap announced a new microscope, informally nicknamed "Tortilla," capable of imaging four physical quantities simultaneously at the nanoscale: temperature, magnetism, structure, and electrical behavior — the first industrial-grade tool capable of simultaneously imaging these four critical material properties with nanoscale precision in a single scan. The instrument's core component is a nanoscale Superconducting Quantum Interference Device (SQUID) mounted on an atomic force microscope tip, with tapping-mode feedback allowing stable operation even on the highly corrugated surfaces of fully fabricated quantum chips.

The stated purpose of the instrument is diagnostic. As the company's founder and CEO, Johannes Jobst, frames it: "Current chip testing relies mainly on electrical characterization of fully finished chips inside quantum computers — a process that takes weeks per chip and if the performance of some qubits is reduced, it cannot reveal the underlying reason." The new platform is presented as a solution to this diagnostic gap, enabling root-cause analysis at any fabrication stage and allowing developers to pinpoint why specific qubits underperform — whether due to thermal dissipation, magnetic impurities, or structural defects.

Read carefully, this is a precise and modest engineering claim. The instrument measures four classical field quantities with high spatial resolution. It correlates spatial variation in those quantities with spatial variation in a separately measured electrical performance metric. It does not measure a wavefunction, a superposition amplitude, an entanglement witness, or any quantity that requires the formalism of quantum mechanics to define. It measures heat, magnetic stray fields, lattice structure, and current — exactly the quantities a classical condensed-matter physicist would have measured in 1965, executed at a spatial resolution that 1965 instrumentation could not achieve.

And yet the framing throughout the announcement, and in nearly every secondary report of it, is that the instrument "tests quantum chips" and diagnoses "qubit failure." This is not a minor rhetorical issue. It encodes a specific philosophical commitment: that whatever a qubit fundamentally *is*, in the deepest ontological sense, is something the classical measurements can be read as diagnosing the malfunction of. That commitment is not obviously true. It is, in fact, one of the most actively contested questions in the foundations of physics, and two serious, technically worked-out research programs — one by a Nobel laureate, one by a career theoretical physicist whose work has been continuously developed and peer-reviewed since the 1990s — argue that it is false in a specific and well-defined sense.

This paper takes that tension seriously rather than treating it as a curiosity to be footnoted and dismissed. Its structure is as follows. Section 2 sets out the algebraic frame, PoC^4, within which the rest of the argument is conducted, tracing the Cayley–Dickson construction from the real numbers through to the octonions and showing precisely why the count of normed division algebras terminates at four and not five, six, or eight. Section 3 presents Rowlands's nilpotent vacuum formalism as the primary generative chain, in full technical detail, including its historical development and its explicit dependence on the Hurwitz constraint. Section 4 presents 't Hooft's Cellular Automaton Interpretation as an independently derived, convergent deterministic account, tracing its origin in the black-hole information paradox and its subsequent generalization into a full interpretation of quantum mechanics, together with recent (post-2020) numerical work claiming experimental-style validation of its central predictions. Section 5 confronts both programs with the strongest available objection — the Bell-theorem/superdeterminism literature — in its most recent and most adversarial form, without softening either side of the argument. Section 6 returns to the QuantaMap case in technical detail, using the instrument's own published specification (Rog et al., 2026) to examine, channel by channel, what is and is not settled when such an instrument reports a diagnostic result. Section 7 concludes, with explicit recommendations for how the language of quantum-chip diagnostics should be revised to track what is actually known rather than what is conventionally assumed.

2. The Algebraic Frame: PoC^4, Hurwitz, and the Cayley–Dickson Construction

2.1 Why a single algebraic foundation, not a menu of interpretations

Before engaging the physics, it is necessary to be precise about what kind of foundation this paper reasons from, because the temptation in this literature is to treat every framework — Copenhagen, Bohmian mechanics, many-worlds, CAI, nilpotent QM — as freestanding *alternatives to be compared on roughly equal footing, as if the choice between them were a matter of taste, or worse, a matter of which philosophical temperament one happens to have. PoC⁴ rejects that framing entirely. The starting point is not a menu of interpretations; it is a single algebraic fact, proven in pure mathematics independently of any physical hypothesis, and everything else in the argument is examined for whether it is consistent with, derivable from, or in conflict with that fact. This is a deliberately narrower and more falsifiable approach than typical foundations-of-physics writing, which tends to proliferate vocabulary (Bohmian "pilot waves," many-worlds "branching," QBist "personalist probabilities," relational "perspectives") faster than it resolves anything. The wager of this paper, following the broader PoC⁴ program, is that beneath this proliferation of vocabulary lies a single, comparatively simple algebraic constraint, and that the various interpretations are, to varying degrees of fidelity, different natural-language translations of what that constraint permits.*

2.2 Hurwitz's theorem, precisely stated

The fact in question is Hurwitz's theorem (1898): there exist exactly four normed division algebras over the real numbers — the reals (ℝ, dimension 1), the complex numbers (ℂ, dimension 2), the quaternions (ℍ, dimension 4), and the octonions (𝕆, dimension 8) — and no more. This is a closed, proven result in pure mathematics, not a physical hypothesis, and it has stood without revision or exception since its original publication in Hurwitz's 1898 paper to the Göttingen Academy of Sciences.

It is frequently and incorrectly conflated in adjacent literature with Bott periodicity, a distinct theorem in algebraic topology concerning the periodicity of homotopy groups of the classical (orthogonal, unitary, symplectic) Lie groups — period 2 for complex K-theory, period 8 for real and quaternionic K-theory. The two results are not the same statement, do not share the same proof technique (Hurwitz's theorem is an elementary, finite, purely algebraic argument about composition algebras; Bott periodicity is a deep result in stable homotopy theory requiring the full machinery of algebraic topology), and do not license the same inferences. Confusing them is a specific and identifiable error: a period-8 result (Bott) does not, by itself, generate or imply a privileged four-fold structure, whereas Hurwitz's theorem does so directly and exhaustively. The number four in this paper's framework — designated PoC⁴ — is sourced exclusively from Hurwitz, not from Bott. This distinction is not academic pedantry; it is the difference between a claim that can be checked against a closed, finite mathematical fact (four division algebras, full stop, theorem proven) and a claim that smuggles in an unrelated, more exotic piece of mathematics whose actual content does not support the inference being drawn from it.

2.3 The Cayley–Dickson construction: why the count stops at four

The mechanism by which the four Hurwitz algebras are generated, and by which it becomes visible why the sequence terminates where it does, is the Cayley–Dickson construction: a recursive algebraic process that generates a sequence of hypercomplex number systems by doubling the dimension of the previous algebra at each step, starting from the real numbers.

Concretely, the construction defines a new algebra as a Cartesian product of an algebra with itself, with multiplication defined via an involution (conjugation), so that an algebra of dimension n generates an algebra of dimension 2n. Applied iteratively to the real numbers, the construction yields, consecutively, the complex numbers, then the quaternions, then the octonions — thus all four real normed division algebras — and only then, at the next iteration, the sedenions, which are no longer a division algebra at all.

What is mathematically essential here, and directly load-bearing for the argument of this paper, is that the construction does not fail randomly or for unrelated reasons at each step — it fails by shedding a specific, named algebraic property at each successive doubling, in a fixed and well-understood order: the symmetries of the real field disappear as the Cayley–Dickson construction is repeatedly applied — first losing order (at the complex numbers, where there is no longer a total ordering compatible with the field structure), then commutativity of multiplication (at the quaternions, where ij ≠ ji), then associativity of multiplication (at the octonions, where (ab)c ≠ a(bc) in general, though a weaker property called alternativity survives), and finally, at the very next step, the division-algebra property itself (at the sedenions, dimension 16, where genuine zero divisors first appear — nonzero elements whose product is zero, which is incompatible with being able to define a multiplicative inverse for every nonzero element). Up to the octonions, the reals, complex numbers, quaternions, and octonions are the only finite-dimensional real normed division algebras, a fact the Cayley–Dickson construction does not merely illustrate but structurally explains: the construction systematically strips away algebraic structure at each doubling, and the division-algebra property survives only through the fourth member of the sequence before it is lost for good. This is not an empirical regularity that happens to hold for four cases and might continue if we looked harder; it is a proven, exhaustive, and final classification. There is no algebra after the fourth member of the sequence that is also a normed division algebra over the reals, and this has been known with full rigor since Hurwitz.

This matters directly for the physics that follows, for a specific reason: the third member of this sequence, the quaternions (ℍ), is not a mathematical curiosity selected for convenience. It is the unique division algebra of dimension four, sitting at the exact point in the Cayley–Dickson sequence where commutativity is lost but associativity and the division property are still intact — a very particular algebraic "sweet spot." Rowlands's nilpotent formalism, developed independently of any motivation drawn from this paper's framing, builds its representation of the Dirac equation, the fundamental equation of relativistic fermions, directly out of this quaternionic structure. The fact that the algebra available at exactly this point in the Cayley–Dickson hierarchy turns out to be the algebra needed to represent the equation governing the electron is, at minimum, a striking coincidence; PoC^4 treats it as considerably more than a coincidence, and Section 3 develops why.

2.4 Why quaternions specifically: the minimality argument made explicit

To be precise about the scope of the claim, and to avoid a gap that would otherwise weaken everything that follows: PoC^4 does not assert that quaternionic algebra somehow causes *quantum mechanics to take the form it does, in the sense of a metaphysical first-mover. It asserts the narrower and more defensible claim that the algebra available at the relevant dimensional "slot" in the Hurwitz/Cayley–Dickson hierarchy is the minimal sufficient structure for representing the relativistic fermion equation without redundancy. This claim is not free-floating; it can be stated as a concrete counting argument, and it is worth making that argument explicit rather than leaving it as an assertion, since an assertion of this kind is exactly the sort of step a careful reader should refuse to accept on authority alone.*

A relativistic fermion state, in the form Rowlands works with, requires independent algebraic room for four physically distinct quantities: one scalar (energy or mass, depending on frame) and three components of a vector (momentum, or equivalently the three spatial directions). This is not a free choice; it is fixed by the structure of special relativity, in which energy-momentum forms a four-vector (E, p) with three spatial components. The question the algebra must answer is: what is the smallest normed division algebra that can hold one scalar and three independent vector-like generators, with multiplication closed within the algebra (so that products of physical quantities remain physical quantities, not artifacts requiring an enlarged number system)?

The real numbers (dimension 1) plainly cannot hold three independent vector components; there is only one dimension to work with. The complex numbers (dimension 2) provide one scalar (the real part) and only one independent "vector-like" direction (the imaginary part) — insufficient by a factor of three. The quaternions (dimension 4) provide exactly one scalar component (the real part) and exactly three independent vector-like components (the i, j, k imaginary units) — an exact, non-redundant match to the four physical quantities (E, p_x, p_y, p_z) the theory needs to represent, with the added structural benefit that quaternion multiplication of two "vector" parts automatically generates both a scalar part (via the dot product, encoded in the anticommutator) and a new vector part (via the cross product, encoded in the commutator) — which is exactly the algebraic behavior needed to reproduce the relativistic energy-momentum relation and angular-momentum/spin algebra without additional postulates. The octonions (dimension 8) could also hold four such quantities, with four dimensions to spare, but at the cost of losing associativity — meaning that the order in which sequential physical operations are composed would matter in a way with no known physical correlate, and meaning standard operator calculus (on which the entire technical apparatus of quantum mechanics depends) becomes substantially harder to define consistently. The quaternions are therefore not an arbitrary convenient choice among four options; they are the unique point in the Hurwitz/Cayley–Dickson sequence that exactly matches the dimensional requirement of relativistic energy-momentum (four components) while still retaining the associativity that ordinary operator algebra requires. This is the precise sense, stated as a counting and closure argument rather than an appeal to authority, in which the quaternions are the minimal sufficient structure for the task, and it is this specific argument — not a general gesture toward "elegance" — that licenses calling the recovery of the Dirac equation's structure from this algebra a non-redundant fit rather than a coincidence dressed up in mathematical language.

Recognizing this allows a reformulation (Rowlands's nilpotent Dirac equation, detailed in Section 3) in which features of quantum mechanics that appear mysterious or postulated in the textbook formalism (the vacuum, the structure of spin, the Pauli exclusion principle) become visible as direct algebraic consequences rather than additional axioms bolted onto the theory. This is the sense in which PoC^4 *is a generative frame rather than a competing physical postulate: it does not ask physics to adopt a new axiom, but rather asks whether the existing axioms of relativistic quantum mechanics can be shown to be consequences of a more economical and already-proven piece of pure mathematics. The remainder of this paper develops that case through Rowlands (Section 3) and shows its independent convergence with 't Hooft's entirely differently motivated program (Section 4).*

It should be stated plainly that this minimality argument establishes only that the quaternions are algebraically apt for the task — it does not, by itself, establish that nature in fact exploits this aptness at the deepest ontological level, which is the stronger claim Rowlands's program goes on to make and which Section 3 examines in detail. A skeptic is entitled to grant the counting argument in this section while still doubting the larger ontological claim; the two are logically separable, and this paper treats them as such throughout.

3. The Nilpotent Vacuum: Rowlands's Generative Chain

3.1 Zero totality as a starting axiom

Peter Rowlands's program, developed across several decades and most systematically in Zero to Infinity: The Foundations of Physics (2007) and a series of peer-reviewed papers culminating in a 2017 Frontiers in Physics article co-authored with Peter Marcer, begins from a principle Rowlands calls zero totality: the universe, taken as a whole, sums to nothing. Every physical object that can be said to exist locally is balanced, in this accounting, by a corresponding structure in "the rest of the universe" — the vacuum — such that object and vacuum together cancel exactly.

This is not a metaphor; it is an algebraic construction with a precise mechanism, stated by Rowlands and Marcer in fully explicit form. Because the totality of experience is defined always to be zero, if we take a fermion in any state, say (ikE + ip + jm), subject to any number of constraints that can be built into its operator, and imagine that we can create it from absolutely nothing, then the vacuum which defines the rest of the universe for that fermion must be a kind of mirror image, −(ikE + ip + jm), so that both the superposition and the combination of vacuum and fermion remain at zero. The fermion state and its environment are, in this formalism, mathematical mirror images of one another, so that a change in one automatically leads to corresponding changes in the other.

The deep structural commitment buried in this construction deserves to be made explicit, because it is the feature most directly relevant to the question this paper is asking about decoherence: in Rowlands's formalism, the vacuum is not a passive backdrop against which fermionic events occur. It is an active algebraic partner, locked by the zero-totality condition into a structural relationship with every localized particle state in the universe, such that the vacuum's properties are not independent of the particle's properties — they are the particle's properties, negated and mirrored. A "fluctuation" in the vacuum, on this account, is not a free, unconstrained event; it is the necessary algebraic complement of whatever is happening to the particle it mirrors.

3.2 Nilpotency and the rewritten Dirac equation

The structure that makes this work is nilpotency: an algebraic object that squares to zero (formally, an operator N such that $N^2 = 0$). Rowlands shows that the Dirac equation — the relativistic wave equation governing the electron, first written down by Paul Dirac in 1928 using complex 4×4 gamma matrices acting on a four-component spinor — can be rewritten in nilpotent form, using the quaternionic algebra introduced in Section 2, such that the equation becomes completely symmetric, with a full set of five generators of a 64-part group, and the two spaces — real and vacuum — are explicitly displayed, along with the broken symmetry of the charge or vacuum space, facts which were completely lost in the original equation. This last point deserves emphasis: Rowlands's claim is not merely that an alternative notation exists for the Dirac equation, but that the conventional gamma-matrix formulation actively obscures structural information — specifically the explicit duality between particle and vacuum space — that the nilpotent quaternionic rewriting makes visible. In this reformulation, a fermion, such as an electron, becomes a multiply-connected singularity at the boundary of two spaces, with the real and vacuum spaces being dual but respectively rotationally symmetric and asymmetric.

Two consequences of this construction matter directly for the question this paper is asking, and are developed here in more depth than in the initial presentation of this material.

First, the vacuum is not empty in either the classical or the standard quantum-field-theoretic sense, and the difference from the orthodox vacuum concept is structural, not merely interpretive. The orthodox quantum-field-theory vacuum is defined operationally as the lowest-energy eigenstate of the field Hamiltonian, $|0\rangle$, and its "activity" (vacuum fluctuations, virtual particle pairs, the Casimir effect) is a consequence of the uncertainty principle applied to field amplitudes — it carries no algebraic commitment to mirroring any specific particle state; it is a generic, particle-state-independent background. Rowlands's nilpotent vacuum is a fundamentally stronger and more specific claim: the quantum vacuum becomes a background in which group-theoretic structures, a duality principle, and a zero-totality condition are proposed as foundational principles for establishing physical law, meaning that for every localized fermion state, there is a specific, algebraically determined mirror structure in the vacuum, not a generic fluctuating background indifferent to which particle is present. This is the sense in which Rowlands's vacuum concept and the standard QFT vacuum concept, while both called "the *vacuum," are doing substantially different theoretical work — a terminological overlap that, much like the "quantum chip" terminology discussed in Section 6, risks obscuring rather than clarifying what is actually being claimed.*

Second, what conventional quantum mechanics treats as emergent or merely statistical self-organization is, in this frame, a direct algebraic necessity. To maintain zero totality in all circumstances, any change in either the fermion or its environment must be reflected in a corresponding change in the other — in effect creating a principle of self-organization which can be imagined in systems on a much larger scale, and which will be identifiable by strongly characteristic features which originate in the nilpotent structure and the universal rewrite process. Rowlands and Marcer explicitly extend this beyond particle physics, suggesting that the same algebraic logic — a localized structure coupled by a zero-totality constraint to a structured "environment" mirror — recurs at multiple physical scales, governed by what they term the universal rewrite system (URS).

3.3 The philosophical framing and its scope

Rowlands generalizes this construction in a way that is philosophically ambitious and worth stating in his own terms, because it bears directly on how the rest of physics — including the chain that leads to gravity — is meant to follow from the same starting point. The project proceeds from first principles which stem from purely philosophical grounds — the zero totality, or the claim that there is no fundamental structure of the universe — and follows a logical progression culminating in gravity and supersymmetry, with the fundamental building block of reality described as a nilpotent or algebraic structure with properties stemming from the division algebras. Quantum field theory itself, on this reading, becomes a natural consequence of the nilpotent formulation in terms of the vacuum, rather than an independently postulated theory that the vacuum must be fitted to after the fact. This is an unusually strong claim of theoretical economy: rather than quantum field theory and general relativity being two separately motivated theories that must be reconciled (the standard "quantum gravity" problem), Rowlands's program treats both as downstream consequences of the same minimal algebraic starting point, with no separate postulates required for either.

3.4 Connecting back to the Hurwitz constraint

The relevance of the Hurwitz constraint introduced in Section 2 can now be stated with full precision. Rowlands's nilpotent structure is explicitly built from "the units of the four parameters": the nilpotent structure created by combining the units of the four parameters and applying zero totality creates new parameters E, p, m — energy, momentum, and mass — with Lorentzian locality and quantization, and breaks the symmetry between the charges in the same way as the standard model. These four parameters are not arbitrary; they are the dimensional slots that the algebra of the quaternions — the third Hurwitz division algebra, occupying the specific position in the Cayley–Dickson hierarchy identified in Section 2.3 — makes available, with one real (scalar) and three imaginary (vector) components.

The full chain, stated end to end, runs as follows. Hurwitz's theorem fixes the existence and uniqueness of exactly four normed division algebras, a closed and final mathematical result. The Cayley–Dickson construction shows why the sequence terminates at exactly four members, by tracking the specific algebraic property (order, commutativity, associativity, division) lost at each doubling. The quaternions, third in this sequence, provide the minimal algebra capable of encoding four independent physical quantities (one scalar, three vector) while retaining the associativity and division-algebra properties needed for a workable physical theory — properties already lost by the time one reaches the octonions. Rowlands's nilpotent Dirac equation uses exactly this quaternionic structure to generate the fermion/vacuum duality as a zero-totality condition. The vacuum that results from this construction is an algebraically active, structured space, locked in a specific mirroring relationship to every localized particle state — not an inert, generic background.

If this chain is correct — and it should be stressed that it has been developed across more than two decades of continuous, peer-reviewed publication, including in Frontiers in Physics, a mainstream venue with standard peer review, rather than in a marginal or self-published outlet — then a "qubit" is not a free-floating two-state quantum system suspended in an otherwise irrelevant vacuum. It is a localized nilpotent structure whose behavior is, by algebraic construction rather than by empirical happenstance, coupled to the structured vacuum that is its mirror. Decoherence, on this reading, is not "loss of quantum information to a passive environment," the standard textbook description. It is a disruption of the zero-totality balance between a localized structure and its specific vacuum partner — a materially different physical claim, with different implications for what kind of intervention (classical, thermal, structural) should be expected to matter, and crucially, for why it should be expected to matter. Section 6 returns to this distinction in the specific context of the QuantaMap instrument's published decoherence-source taxonomy.

4. The Cellular Automaton Interpretation: 't Hooft's Independent Convergence

4.1 Origins in the black-hole information paradox

Gerard 't Hooft's program begins from an entirely different starting point than Rowlands's — not algebraic vacuum duality, but a direct engagement with the black-hole information paradox, a problem that emerged from 't Hooft's own earlier work in quantum gravity and holography rather than from any prior commitment to determinism — and yet converges on a structurally similar conclusion: that the formalism of quantum mechanics is a derived, statistical description of a deeper deterministic process, not the bottom layer of reality.

A useful and candid account of this trajectory comes from a Physics Today review of 't Hooft's 2016 monograph, written by a physicist evidently familiar with 't Hooft's earlier work: thirty years after 't Hooft's foundational contributions to gauge theory, "everybody knows about the *black hole information paradox, which has led to hundreds of papers and some profound insights and is even the topic of popular science books," and with his cellular-automaton monograph, 't Hooft "has managed to surprise me once again by proposing a new way of looking at that branch of physics." The reviewer states 't Hooft's goal without equivocation: "His stated goal is to show that Albert Einstein was right to think that there is no fundamental randomness in nature — a conclusion contrary to the belief of the founding fathers of quantum mechanics and of most contemporary working physicists, and contrary to what is taught in any quantum mechanics class." Crucially, the reviewer notes that this ambition is held with full awareness of its difficulty, not naively: "the predictions of quantum mechanics have been experimentally verified beyond any reasonable doubt, and 't Hooft is well aware of the difficulties encountered by any attempt to derive those predictions from an underlying deterministic theory."*

This origin in black-hole physics is not incidental detail; it shapes the specific technical mechanism 't Hooft proposes. 't Hooft's own research profile frames the motivating puzzle directly: "various contenders for a complete theory of quantum gravity are at odds with each other. This is in particular seen in the ways they relate to information and black holes, and how to effectively treat quantization of the background spacetime." The proposed resolution proceeds by a specific move: "even if we still face problems in formulating concise theories that explain the resolution of various apparent paradoxes, one may simply assume such a theory to exist, and that it will one day be found. This leads to the CA (Cellular Automaton) Interpretation." The technical crux is information loss: "the fact that information loss is easy to add as a feature in deterministic models, while it seems inevitably to lead to loss of unitarity in quantum mechanics, requires our attention" — that is, deterministic discrete systems can lose information (e.g., into a black hole, or into an environment) far more naturally than the unitary, information-preserving formalism of standard quantum mechanics can accommodate, and 't Hooft treats this asymmetry as a clue rather than a nuisance to be explained away.

4.2 The mechanism: a deterministic automaton and emergent quantum statistics

't Hooft's framing of the broader stakes is explicit and, for a physicist of his stature, unusually blunt about the scale of the departure from convention being proposed: "When investigating theories at the tiniest conceivable scales in nature, almost all researchers today revert to the quantum language, accepting the verdict from the Copenhagen doctrine that the only way to describe what is going on will always involve states in Hilbert space, controlled by operator equations. Returning to classical, that is, non-quantum-mechanical, descriptions will be forever impossible, unless one accepts some extremely contrived theoretical constructions." 't Hooft's stated dissatisfaction with this consensus is the motivation for the Cellular Automaton Interpretation (CAI): quantum mechanics is looked upon as a tool, not as a theory.

The mechanism is a deterministic automaton operating at the smallest conceivable scale, defined with mathematical precision rather than left at the level of metaphor. The states Nature can be in are given by sequences of integers, and the evolution law is a classical algorithm that tells unambiguously how these integers evolve in time — quantum mechanics does not enter; it is *unheard of at this level of description. The apparent randomness and superposition of standard quantum mechanics arise only after coarse-graining: quantum indeterminacy is not fundamental — it emerges from deterministic micro-dynamics via coarse-graining and ignorance; individual ontological microstates are perfectly determined, and the evolution rules are deterministic and local. Even the Born rule, the probabilistic core of orthodox quantum mechanics (the rule that the probability of an outcome equals the squared amplitude of the corresponding wavefunction component), is recovered rather than postulated as a separate axiom: the Born rule emerges from the geometry of phase space and Bayesian updating. On this account, there is no separate collapse postulate, the feature of orthodox quantum mechanics that has generated the most persistent interpretive difficulty (the "measurement problem"): the combined system of object and apparatus evolves deterministically, and apparent randomness reflects our ignorance of the full microstate, exactly as the apparent randomness of a coin flip reflects our ignorance of the precise initial conditions and air currents acting on a perfectly deterministic falling object, rather than any genuine indeterminacy in the coin's physics.*

't Hooft's own technical apparatus for this is built from "cogwheel models" — simple, explicitly worked finite deterministic systems — generalized to full quantum field theories. The time evolution of a deterministic model can be written in operator form, with a unitary evolution operator generated by a Hamiltonian, exactly mirroring the mathematical structure of standard quantum mechanics, with the crucial difference that the underlying states being evolved are not superpositions of physically distinct possibilities but definite, if unknown, classical configurations. 't Hooft has shown specific technical results within this program, including that a deterministic cellular automaton in one space- and one time-dimension can be mapped onto a bosonic quantum field theory on a 1+1-dimensional lattice — a concrete demonstration, not merely an assertion, that a fully classical discrete system can reproduce a standard quantum field theory's structure under an appropriate (coarse-grained) description.

4.3 Recent numerical validation: beyond assertion

This is not merely a philosophical re-description offered without technical content, and the program has continued to develop substantively in the years since the 2016 monograph. Recent work extending 't Hooft's framework — building on the Stochastic Cellular Automaton (SCA) formalism — has produced explicit, numerically verified models that reproduce specific quantitative predictions of standard quantum mechanics. A one-dimensional stochastic cellular automaton with reflective boundaries and a parabolic potential, initialized in the quantum harmonic oscillator's third eigenstate (ψ_3), reproduces the theoretically predicted oscillation frequency to high accuracy. The result, as one synthesis of this line of work summarizes it, shows the oscillation emerging from purely deterministic, local evolution, with no randomness, no wavefunction collapse, and no measurement problem, yet with statistics that, once appropriately coarse-grained, match quantum predictions exactly — and the agreement has been demonstrated across energy levels up to $n \leq 16$, with measured oscillation frequencies matching the standard quantum-mechanical prediction $E_n/\hbar = (n + ½)\omega$ to high precision.

The same extended framework reproduces a markedly more demanding quantum signature, one frequently cited as among the most unambiguously non-classical phenomena in physics: placing a solenoid at the center of a Mach–Zehnder interferometer or a double-slit setup, the presence of the vector potential causes a measurable phase shift in the interference pattern — the Aharonov–Bohm effect — with a discrete, deterministic cellular automaton incorporating vector potentials reproducing this effect, one often invoked specifically as evidence that quantum mechanics cannot be superseded by any classical or local-realist theory, because it depends on the vector potential itself (not merely the magnetic field it generates) influencing interference in a region where the field itself is zero. This last point deserves particular emphasis precisely because the Aharonov–Bohm effect is frequently treated in textbooks as one of the cleanest demonstrations that quantum mechanics requires genuinely non-classical ingredients. A deterministic, local, discrete automaton reproducing it — under appropriate coarse-graining — is a substantive technical result, not a verbal redescription of quantum mechanics in classical-sounding language. The relevant synthesis concludes, with appropriate caution about what has and has not been shown: "the van Berkel et al. results do not prove determinism is fundamental, but they demonstrate that determinism is consistent with all observed quantum phenomena" tested so far — a carefully calibrated claim that this paper adopts as its own standard of evidence throughout.

4.4 't Hooft's candor about the cost

't Hooft's own summary of the stakes, in the introduction to his 2016 monograph, is worth quoting at slightly greater length than in the initial presentation of this material, because its candor about what a fully deterministic theory implies is unusual in foundations-of-physics writing and is directly relevant to the fairness of the treatment this paper owes to the superdeterminism objection developed in Section 5: "If a theory is deterministic all the way, it implies that not only all observed phenomena, but also the observers themselves are controlled by deterministic laws. They certainly have no 'free will'; their actions all have roots in the past, even the distant past. Allowing an observer to have free will, that is, to reset his observation apparatus at will without even infinitesimal disturbances of the surrounding universe, including modifications in the distant past, is fundamentally impossible." 't Hooft offers this not as an embarrassing admission extracted under pressure but as a forthright statement of what his own theory requires, made in the same paragraph in which he explains why he nonetheless considers the deterministic program worth pursuing: in his words, the "strong suspicion" motivating the whole program is "that all those 'hidden variable models' that were compared with thought experiments as well as real experiments, are terribly naive," and that "real deterministic theories have not yet been excluded" by the experiments usually cited against them. This is the doorway through which the single most serious objection to both 't Hooft's and Rowlands's programs enters, and it is addressed directly and without softening in Section 5.

4.5 Why two independent routes matter

It is methodologically important, and worth restating with the additional technical detail now established in Sections 3 and 4, that Rowlands and 't Hooft did not arrive at structurally *convergent conclusions by collaboration, by sharing a common unconventional starting axiom, or by mutual citation as the principal evidence for either program. Rowlands's route runs through the algebra of normed division algebras, the Cayley–Dickson construction, and the zero-totality condition on a reformulated Dirac equation — a route through pure algebra and relativistic particle physics. 't Hooft's route runs through discrete deterministic dynamics, information loss at the Planck scale, and the black-hole information paradox — a route through quantum gravity and the foundations of statistical mechanics. These are different mathematical objects (quaternionic nilpotent algebra versus integer-valued cellular automata), motivated by entirely different physical puzzles (vacuum structure and fermion duality on one side; black-hole information loss and the quantum measurement problem on the other), developed by physicists with no record of having built on each other's specific technical apparatus, arriving independently at the same structural claim: the Hilbert-space formalism of quantum mechanics is the macroscopic, statistical shadow of a deeper deterministic, locally-defined process, not an irreducible description of nature's bottom layer.*

Convergence from independent starting points of this kind is not proof — two wrong theories can resemble each other by coincidence, and the history of physics contains cautionary examples of structurally similar-looking proposals that did not survive scrutiny. But independent convergence of this specific, structurally detailed kind is exactly the sort of evidence that should raise, not lower, the credibility a careful reader assigns to the underlying claim, and it is the reason this paper treats CAI and nilpotent QM as two technically distinct expressions of a single deeper structural possibility (PoC^4) rather than as two unrelated curiosities mentioned for completeness or rhetorical padding.

5. The Strongest Objection: Bell's Theorem and the Price of Determinism

5.1 The theorem itself, and what it forecloses

No serious treatment of deterministic alternatives to quantum mechanics can proceed without confronting Bell's theorem directly, and this section does so without softening the force of the objection at any point, because a treatment that did otherwise would not be intellectually honest about the actual state of this debate.

Bell's theorem demonstrates that any theory satisfying both locality (no faster-than-light influence between spatially separated events) and realism (measurement outcomes are determined by pre-existing properties of the system, not created by the act of measurement itself) must obey a statistical inequality — the Bell inequality, in one of its several equivalent forms — that experiments, repeatedly and with increasing rigor over five decades, show nature violates. Bell's inequality is violated in experiments using entangled quantum states, and the violation has now been confirmed in so-called "loophole-free" form, closing the major experimental escape routes (the detection-efficiency loophole, the locality/communication loophole, and others) that *earlier generations of experiments had left open. The 2022 Nobel Prize in Physics was awarded to Alain Aspect, John Clauser, and Anton Zeilinger specifically for these loophole-free confirmations, a result one of the field's senior figures, physicist H. P. Stapp, has called "the most profound result of modern science."*

5.2 The remaining loophole: superdeterminism, and its psychological cost

There remains, formally and irreducibly, exactly one loophole through which a local, deterministic, realist theory can survive contact with this body of experimental evidence: superdeterminism — the proposal that the choice of measurement settings in a Bell experiment is not statistically independent of the hidden variables of the particles being measured, because both the experimenter's choice and the particle's hidden state trace back to correlated initial conditions in their shared causal past. Bell himself, in his final paper on the theorem, was explicit that his own framework depended on rejecting exactly this possibility: "An essential element in the reasoning here is that [the measurement settings] are free variables. One can envisage then theories in which there just are no free variables [...] In such 'superdeterministic' theories the apparent free will of experimenters, and any other apparent randomness, would be illusory." Alain Aspect himself, reflecting on this loophole decades later, registered visible discomfort with what taking it seriously would require: "Here is the loophole: Maybe there is in the backward cones of ourselves or of our lives some common events which decide how we are going to set the polarizers; our choice is not really free... I don't want to be a physicist in that world."

5.3 The case against superdeterminism, stated at full strength

The case against superdeterminism, as articulated by its critics across multiple decades, is severe and has only grown more pointed in recent literature. John Clauser himself, decades before sharing the 2022 Nobel Prize, dismissed this style of escape on explicitly methodological grounds, in terms that treat it as a threat to the scientific enterprise as such rather than merely an unappealing physical hypothesis: "Skepticism of this sort will essentially dismiss all results of scientific experimentation. Unless we proceed under the assumption that hidden conspiracies of this sort do not occur, we have abandoned in advance the whole enterprise of discovering the laws of nature by experimentation."

A more recent and more pointed formulation of the same worry, from a 2026 analysis explicitly engaging the "2022 Nobel Prize and the end of mechanistic materialism," develops the scale of the conspiracy required in vivid terms. The locality loophole, in Clauser's own words, was already "paranoid"; the superdeterminism loophole, by contrast, must be labeled "insanely paranoid," because it requires not merely that the universe be deterministic, but that it be tuned, from the initial conditions of the Big Bang onward, with the specific and active purpose of defeating every attempt to test Bell's inequality, so that "each time we try to test Bell's inequality our attempts are actually futile, since everything is staged." The same analysis is careful to disentangle superdeterminism from the unrelated philosophical question of free will, noting that *this is "one of the worse misnomers in physics": the negation of superdeterminism is sometimes loosely called the "free will requirement," potentially misleading audiences into thinking the debate concerns the ancient philosophical question of free will as such, when in fact "while the existence of free will (or of true inherent randomness in nature) would indeed logically ensure that superdeterminism is not possible, the lack of free will by no means implies superdeterminism" — determinism alone is not sufficient to generate the conspiratorial correlation Bell's theorem requires; a much more specific and finely-tuned correlation is needed.*

Scott Aaronson's widely cited criticism of superdeterminism, summarized in discussion of the topic on physics forums frequented by working researchers, frames the position as requiring a rejection of foundational scientific assumptions and functioning, in practice, as a way to explain away quantum mechanics rather than to explain it — a framing that captures the core worry of most working physicists who decline to pursue the superdeterministic option, regardless of its formal logical availability. Most pointedly and most recently, a 2024 paper by Wiseman directly engaging the most prominent contemporary defenders of superdeterminism (Hance and Hossenfelder), titled "The Last Loophole in Bell's Theorem? A prima facie problem with superdeterminism," concludes after detailed technical analysis that superdeterminists must find a formulation of physics entirely free of non-commutativity at a fundamental level that can still reproduce all of the well-verified predictions of quantum mechanics, and judges that this would be "a very tall order indeed" — a judgment offered not as a rhetorical dismissal but as the conclusion of a worked technical argument about what consistency with quantum mechanics' empirical successes would actually require of any non-commutativity-free theory.

5.4 Fairness to the other side: the philosophical literature is less settled than popular treatments suggest

It is equally important, in the interest of intellectual fairness and because this paper's own argument depends on taking unresolved questions seriously rather than rhetorically closing them, to register that the philosophical landscape on this question is less settled than popular physics writing typically suggests, and that not all serious objections to Bell-theorem-based dismissals of determinism turn on superdeterminism specifically construed as a "conspiracy."

One important strand of the academic literature, developed in recent philosophy-of-physics work, argues that Bell's own framing of the issue in terms of "free will" was itself a source of confusion that has distorted the subsequent debate. As noted in Section 5.3 above, it now seems widely accepted in this specialized literature that superdeterminism has nothing to do with free will as ordinarily understood in the philosophical tradition, since the relevant assumption Bell's theorem actually requires is a narrower, technical statistical-independence condition between measurement settings and the hidden state of the system, not a metaphysical claim about libertarian freedom of the will. This matters because much of the popular intuitive resistance to superdeterminism trades on the (philosophically contested, and on this view simply mistaken) idea that determinism as such is an affront to human freedom, when the actual mathematical *requirement is considerably narrower and does not, by itself, settle any question about free will one way or the other.*

A separate and more technically substantive line of argument holds that determinism as such does not automatically generate the superdeterminism loophole at all. On this view, drawn from detailed analysis of what Bell's derivation actually requires as a premise, "only a premise to the effect that what determines the choice of the measurement settings is independent of what determines the past state of the measured system is needed for the derivation of Bell's theorem," and crucially, "determinism as such does not undermine that independence... unless there are particular initial conditions of the universe that would amount to conspiracy" — on this reading, it is specifically quantum entanglement, not determinism in general, that could in principle generate the relevant correlation, which significantly narrows (without eliminating) the scope of the worry, since it suggests that a deterministic theory does not automatically inherit the conspiratorial character that critics attribute to it; the conspiracy would have to be independently motivated, not simply assumed to follow from determinism as such.

Proponents of superdeterminism, for their part, maintain in recent work that the position has been systematically mischaracterized by its critics. While acknowledging that superdeterminism (SD) "has recently attracted increased interest... and increased criticism," recent technical defenses argue explicitly that they "wish to contribute to clarifying some aspects of SD" specifically in order "to rebut some of its criticisms," on the grounds that much of the standard objection trades on an unnecessarily crude or intuitively loaded characterization of what the position actually commits its holder to, rather than engaging its most careful, technically developed form. There is also live technical dispute, as recently as 2024, over whether even the formal loophole itself survives careful scrutiny: one widely discussed 2024 paper claims, via an argument involving relativistic invariance and the time-ordering of spacelike-separated measurement events, that "a local hidden variable theory consistent with relativity requires that relativistically non-invariant relations such as the time order of spacelike separated events have no physical significance," and that this requirement, properly enforced, means "a local hidden variable theory cannot explain the correlation and reproduce all predictions of quantum mechanics even when assuming superdeterminism" — a claim, if it holds up under further scrutiny, that the superdeterminism loophole might be more fully closed than even its critics typically assume, though this claim is itself contested and has not achieved consensus.

5.5 A historical caution: determinism was never simply "the mainstream view that quantum mechanics overturned"

One further point of intellectual honesty belongs in this section, because omitting it would let the paper's framing imply a cleaner historical narrative than the facts support — specifically, a narrative in which classical determinism was the settled, common-sense default that quantum mechanics had to fight its way past, with only Einstein holding the deterministic line against an otherwise unified opposing consensus. The actual history is less tidy, and the untidiness matters *for how much residual authority the "common-sense" framing of determinism should be given in this debate.*

Among the principal founders of quantum theory, only Einstein consistently and explicitly held to anything resembling the classical, mechanistic determinism this paper's two deterministic programs seek to recover. Bohr's own position was not merely agnostic about hidden variables but actively anti-realist in a stronger sense, built on the idea that quantum mechanics required abandoning the separability of subsystems rather than merely abandoning predictability. Heisenberg went considerably further than Bohr in his metaphysical commitments, dismissing the very possibility of an underlying causal reality as, in his own words, "fruitless and senseless," and explicitly framing the shift required by quantum mechanics as a move from Democritus's atomistic materialism to Plato's idealism, stating plainly: "I think that modern physics has definitely decided in favor of Plato. In fact the smallest units of matter are not physical objects in the ordinary sense; they are forms, ideas which can be expressed unambiguously only in mathematical language." Wolfgang Pauli was equally dismissive of the mechanistic worldview as a historical artifact rather than a serious ongoing option: "The mechanistic world view seems to us as a historically understandable, excusable, maybe even temporarily useful, yet on the whole artificial hypothesis." Erwin Schrödinger, who is often invoked (via the cat thought experiment) as sympathetic to realist objections to orthodox quantum mechanics, in fact held metaphysical views considerably more removed from classical materialism than Bohr's, drawing explicitly on Vedantic philosophy to conclude that "the external world and consciousness are one and the same thing." Max Planck, the originator of quantum theory itself, held a broadly idealist position, stating that he regarded "consciousness as fundamental" and matter as "derivative from consciousness."

The relevance of this history to the present paper's argument is specific and limited, and should not be overstated in either direction. It does not bear on whether Rowlands's or 't Hooft's specific technical programs are correct; the validity of a piece of mathematical physics does not depend on which philosophical company its authors keep, and this paper has deliberately avoided resting any part of its technical argument on the views of Bohr, Heisenberg, Pauli, Schrödinger, or Planck, in either direction. What this history does bear on is a more diffuse rhetorical move available to defenders of the orthodox view — the suggestion that wanting a deterministic, classically intelligible underlying reality is simply the natural, common-sense default that any unprejudiced physicist would hold absent quantum mechanics' inconvenient experimental insistence otherwise. The historical record shows this is not so: most of the physicists who built quantum mechanics did not regard determinism, separability, or even mind-independent material reality as a default to be reluctantly abandoned; several regarded the classical mechanistic picture as a parochial and dispensable nineteenth-century inheritance, and at least two (Schrödinger, Planck) moved toward positions considerably more radical, in the direction of philosophical idealism, than anything this paper's two deterministic programs propose. This cuts in a direction worth registering plainly: the deterministic programs surveyed in Sections 3 and 4 are not the conservative, common-sense option straining against an exotic orthodoxy; both the orthodox view's founders and its deterministic challengers depart substantially from naive pre-

quantum intuition, and the live debate is therefore better understood as a contest between two (or more) genuinely unconventional pictures of nature, not as a contest between an unconventional challenger and a conservative establishment.

5.6 This paper's position, stated without hedging in either direction

This paper's position on Bell's theorem is therefore the following, stated as precisely as the foregoing survey allows. Locality is not negotiable for either Rowlands's or 't Hooft's program without paying the superdeterminism price, and that price is real, not merely rhetorical: it requires either (a) abandoning the assumption that the experimenter's choice of measurement basis is statistically independent of the system being measured, which the bulk of the physics community regards as too high a cost to pay, for reasons articulated forcefully by Clauser, Aaronson, and the 2024–2025 technical literature surveyed above; or (b) finding some other resolution — for instance, along the lines of the relativistic time-ordering argument noted in Section 5.4 — that neither Rowlands's nor 't Hooft's program has yet supplied in full technical detail specific to their own formalisms. 't Hooft has engaged this directly rather than avoiding it, and his own willingness to state the implication plainly — that a fully deterministic theory removes libertarian free will from the observer as much as from the particle — should be read, as argued in Section 4.4, as intellectual honesty about the cost of his own position, not as a hidden admission that the position fails outright.

What Bell's theorem does not do, however, and this is the crucial point on which the remainder of this paper's argument turns, is settle the ontological question this paper is actually asking. Bell's theorem constrains the space of theories compatible with the experimental data; it does not, by itself, tell us which member of that constrained space is true, nor does it validate any particular interpretation of why the data come out the way they do. Locality-violating quantum mechanics (the orthodox view, which is also compatible with all the data) and locality-preserving superdeterminism (the deterministic alternative, which remains formally compatible with all the data at a real but non-zero cost) remain, as a matter of strict logic, both compatible with every Bell-test result obtained to date, loophole-free or otherwise. The cost of choosing the second option is high. It is not, on the present state of the argument synthesized in this section, zero, and it is not infinite either — which is precisely why this remains an open foundational question rather than a closed one, and precisely why language that presupposes it is closed (such as "directly testing the qubit's quantum state," discussed in Section 6) is not yet entitled to the certainty that phrase implies.

6. Returning to the Chip: What Is and Is Not Being Tested

With the algebraic frame (Section 2), the two deterministic programs (Sections 3–4), and the strongest objection to them (Section 5) now on the table in full technical detail, it is possible to return to the QuantaMap case with considerably more precision than the popular framing allows, and to do so using the instrument's own published technical specification rather than secondary reporting.

6.1 What the instrument measures, channel by channel

The Tapping-Mode SQUID-on-Tip microscope, as described in its own primary publication, measures, simultaneously and at nanoscale spatial resolution, four distinct physical channels: local current (via the supercurrent response of the SQUID), local magnetism (via the SQUID's native flux sensitivity), local dissipation or heat (via thermal coupling to the SQUID's superconducting transition), and local topography (via tapping-mode AFM feedback from a quartz tuning fork). The instrument's own authors are explicit that "all superconducting and spin qubits are sensitive to local dynamics introduced by defects, such as magnetic impurities, vortices and inhomogeneous supercurrents," and that "identifying such sources of decoherence has been a major roadblock, as their small experimental signatures are only detectable at cryogenic temperatures."

It is worth pausing on this list of named decoherence sources, because it is precisely the list that the analysis of Sections 3 and 4 predicts should appear, regardless of which ontological account of quantum mechanics is correct. Magnetic impurities are localized magnetic moments — classical, structural features of the material lattice. Vortices (specifically Pearl vortices, the thin-film analogue of Abrikosov vortices in bulk superconductors) are topological defects in the superconducting order parameter's phase, and the instrument's own authors note explicitly that in their imaging of vortices in confined geometries, "the system is fully deterministic: experiments are repeatable over multiple thermal cycles, and fields below 0.2 mT result in a vortex-free state" — a striking and directly relevant observation, since it means that even within orthodox superconductivity theory (itself a quantum theory), the specific defect mechanism the instrument is designed to locate is described, in the instrument's own primary publication, using exactly the vocabulary of classical determinism: repeatable, deterministic nucleation governed by a Gibbs free-energy landscape, not a probabilistic quantum event. Inhomogeneous supercurrents are spatial variations in classical charge-current density, governed at the device level by the London equations and Ginzburg–Landau theory, both of which are macroscopic, effectively classical descriptions of superconducting order, even though the microscopic origin of superconductivity is itself quantum mechanical (Cooper pairing).

The instrument's own authors describe its physical operating principle in terms that confirm this reading directly: the probes "image current, dissipation, magnetism and topography simultaneously," and the underlying sensor — a nanoSQUID built from a proximity Josephson junction — produces, as its raw output, a classical scalar voltage proportional to magnetic flux through a superconducting loop. The instrument's own benchmark demonstration is telling in this respect: it is performed not on a qubit at all, but on a cobalt–copper heterostructure, a straightforwardly classical magnetic and electrical test structure, used "due to its shape anisotropy" creating "dipole fields that can be imaged with our SQUID" — a demonstration *chosen specifically because the relevant physics (Joule heating, magnetic dipole fields, classical current distribution) is unambiguous and well understood independently of any qubit context.*

Every one of these four measured quantities is defined and characterized using classical field theory, classical thermodynamics, and the macroscopic (Ginzburg–Landau/London) theory of superconductivity. None of them is a quantum-mechanical observable in the sense of requiring a wavefunction, a density matrix, or an entanglement measure to specify its value. A SQUID is itself, certainly, a quantum device in the sense that its operation depends on macroscopic quantum coherence in a superconductor (the Josephson effect, on which the instrument's sensing element depends, is a direct manifestation of superconducting phase coherence) — but the output it reports, magnetic flux through a loop expressed as a voltage, is a classical scalar quantity, exactly as a compass needle's deflection is a classical scalar quantity even though the underlying physics of magnetism in the needle's material is quantum mechanical at the level of electron spin alignment. The instrument is, in the most literal and precise sense available, a sophisticated classical-field magnetometer, thermometer, and topographer, built using a sensing element (the SQUID) whose own internal operation is quantum mechanical, deployed to characterize the external environment of a separately defined, separately measured qubit.

6.2 What the inference adds: correlation, not direct inspection

The diagnostic value of the instrument depends on a second, separate, and conceptually distinct step: correlating spatial variation in these four classical quantities with spatial variation in a qubit performance metric obtained through an entirely separate measurement (typically an electrical coherence-time or gate-fidelity measurement performed on the operating chip, using standard superconducting-qubit characterization protocols unrelated to the SQUID-on-tip instrument itself). Lead author Matthijs Rog frames the underlying logic of why this correlation is valuable plainly: "If you only study one aspect at a time, you never get ahead" — the value proposition is explicitly about combining multiple classical channels that were previously measured only separately (if at all, given the instrument's stated improvement over prior techniques in spatial resolution and non-invasiveness), not about gaining access to a previously inaccessible quantum quantity. The company's own stated commercial proposition is explicitly diagnostic and correlational rather than ontological: the platform is designed to allow researchers "to correlate intertwined physical properties in a single scan without disturbing the sample," enabling "nanoscale root-cause analysis during fabrication."

This correlational inference is scientifically unobjectionable as engineering, and nothing in this paper's argument should be read as casting doubt on its practical value. If a region of degraded qubit performance is spatially coincident with a region of elevated magnetic stray field, a Pearl vortex, or a structural defect visible in the topography channel, that is genuinely useful, actionable information for a fabrication engineer trying to improve device yield, regardless of which interpretation of quantum mechanics is correct. A two-level system's coherence time is sensitive to its electromagnetic and thermal environment under every interpretation on the table — Copenhagen, CAI, and nilpotent QM alike all predict, for entirely different underlying *reasons, that local classical noise sources will degrade coherence, because this is essentially a statement about the strength of the system–environment coupling term in the relevant equations of motion, not a claim that depends on first resolving what coherence fundamentally is at the deepest ontological level. This is the precise sense in which the engineering claim is sound and is, in an important sense, interpretation-neutral: an engineer using the instrument to improve fabrication yield does not need to resolve the questions raised in Sections 3 through 5 in order to benefit from the correlation the instrument reveals.*

6.3 Where the language overreaches: three concrete formulations compared

The overreach this paper identifies is not in the measurement, and not in the correlational inference drawn from it. It is specifically and only in the framing layer wrapped around both — the language of "testing the qubit," "diagnosing why qubits fail," and, most directly, "seeing what is actually happening inside a quantum system." It is useful to compare three different ways the same underlying engineering achievement could be, and in practice is, described, because the differences between them track exactly the ontological distinctions developed in Sections 3 through 5.

CEO Johannes Jobst's own description of the underlying ambition, in its strongest form, is instructive: "One of the major road-blocks of quantum computing is that when chips do not work as well as they should, there is no way to find out which component failed... our novel microscope can solve this diagnostics challenge and help enable the quantum revolution." Taken on its own, the phrase "find out which component failed" is a claim about locating a component failure — a classical, structural, thermal, or magnetic defect, exactly the kind of defect catalogued in Section 6.1 — and is fully supported by the instrument's published capabilities. The phrase "help enable the quantum revolution," by contrast, gestures toward something considerably larger and more ontologically loaded, implicitly suggesting that what is being enabled is progress toward harnessing a specific, settled kind of physical resource ("quantum" information or computation, treated as a known and well-understood kind of thing) rather than progress toward fabricating more reliable two-level systems whose deepest physical nature remains, as this paper has argued, an open question.

A more cautious formulation, also available in the source material and arguably more accurate, comes from co-founder Milan Allan's framing of the underlying scientific motivation: "we see strong potential in quantum diagnostics," followed immediately by a description confined entirely to the component-failure framing: "we concluded that one of the major road-blocks of quantum computing is that when chips do not work as well as they should... there is no way to find out which component failed. Nor how to improve the production process." This formulation, read carefully, makes no claim whatsoever about the deep nature of "qubit-ness"; it is fully and exclusively a claim about production engineering, fabrication yield, and component-level fault localization — precisely the scope this paper argues the instrument actually supports.

The journalistic secondary reporting of the announcement, by contrast, consistently compresses this distinction. Headlines and summary lines describing the instrument as enabling researchers to "finally see how quantum materials behave," or as providing a tool that lets manufacturers "see what goes wrong in quantum chips at the nanoscale," elide the difference between "seeing classical defects that are spatially correlated with quantum-chip underperformance" and "seeing quantum chips behave" as such — the latter phrasing implies direct observational access to the quantum behavior itself, which, as Section 6.1 establishes in detail, is not what any of the instrument's four measurement channels provide.

6.4 Why the three competing ontologies make identical predictions here

This is the central technical point of this section, and it is worth stating with full explicitness because it is the reason the engineering achievement, however genuine, cannot by itself adjudicate the foundational debate developed in Sections 3 through 5. Under the orthodox (Copenhagen-style) account, a qubit is a two-level quantum system whose coherent superposition is a primitive physical fact, and decoherence is the loss of phase information to environmental degrees of freedom via entangling interactions — magnetic impurities, vortices, and inhomogeneous currents act as environmental degrees of freedom that the qubit becomes (formally) entangled with, after which the reduced density matrix of the qubit alone loses its off-diagonal coherence terms. Under Rowlands's nilpotent vacuum formalism, a "decohering qubit" is a localized nilpotent structure whose zero-totality balance with its structured vacuum partner has been perturbed — and the perturbation is mediated by exactly the classical channels (thermal, magnetic, structural) the instrument measures, because those classical channels are, on this account, the observable face of the vacuum's mirroring relationship to the particle. Under 't Hooft's CAI, a "decohering qubit" is a deterministic automaton-state whose effective coarse-grained description, valid only under specific isolation conditions from the environment, breaks down once environmental coupling reintroduces information the coarse-graining had discarded — again mediated by exactly the same classical channels, because those channels are precisely the physical pathways through which environmental information re-enters the system and disrupts the statistical regularity that orthodox quantum mechanics describes as "coherence."

All three accounts therefore predict, for entirely different underlying ontological reasons, that the instrument's four measured classical channels will correlate with qubit performance degradation, and none of the three accounts requires that "quantum information" be a free-standing physical substance that the instrument fails to directly observe because it lacks the right kind of sensor. This is the precise sense in which the instrument's engineering success provides essentially zero evidential weight toward resolving which of the three ontological accounts is correct — a successful diagnostic correlation, however well executed, is simply not the kind of observation that could, even in principle, distinguish between them, because all three were constructed (or, in the case of the orthodox account, have long been understood) to make the identical observable prediction at exactly this level of description.

This equivalence claim would itself be untestable in the bad sense — a claim that explains everything and therefore explains nothing — if it could not be paired with at least a sketch of what kind of observation would, in principle, break the tie. Two such observations are worth naming, precisely because naming them is what separates "these three accounts happen to agree here" from "these three accounts are unfalsifiably immune to ever being distinguished." First, the specific functional form of the correlation between a classical defect's magnitude and the resulting coherence-time degradation is not guaranteed to be identical across the three accounts merely because all three predict a correlation exists: orthodox decoherence theory predicts a specific dependence (typically exponential suppression of coherence as a function of coupling strength and bath correlation time, derivable from standard open-quantum-system master equations), and a nilpotent-vacuum or CAI account that instead predicted, for structural algebraic reasons tied to the zero-totality condition or to discreteness at the automaton's fundamental scale, a measurably different functional form — a threshold effect, a different power law, or a discreteness-induced floor below which no further coherence improvement is possible regardless of defect reduction — would in principle be distinguishable by precision measurement of exactly the kind QuantaMap's instrument is designed to support. Neither Rowlands nor 't Hooft has, to this paper's knowledge, derived such a specific, numerically distinct prediction for the superconducting-qubit case in particular (as opposed to the harmonic-oscillator and Aharonov–Bohm cases addressed in Section 4.3, which are not qubit decoherence experiments), and this absence is a genuine limitation of both programs' present state of development, not a minor omission — Section 7 returns to it explicitly. Second, and more fundamentally, any future closing of the superdeterminism loophole discussed in Section 5 — in either direction — would by itself settle the broader question this paper treats as open, independent of any qubit-specific measurement, since both Rowlands's and 't Hooft's programs depend on the same locality-preserving move that a fully closed loophole would either vindicate or foreclose. The diagnostic instrument's measurements are therefore not permanently and in-principle incapable of bearing on the question; they are simply not, at the current state of theoretical development of either deterministic program, calibrated finely enough to do so, and identifying what such a calibration would require is itself a piece of unfinished theoretical work this paper flags rather than resolves.

6.5 The fata morgana, precisely stated

This is the answer to the question posed at the outset of this paper, now stated as precisely as the foregoing technical analysis allows. The industry is not chasing a mirage in the sense of pursuing a technology that does not work — coherence times are real and independently measurable, gate fidelities are real and independently measurable, the engineering problem of scaling qubit counts while maintaining quality is real and economically consequential, and instruments that correlate classical defects with performance degradation, of the kind described in Section 6.1, are genuinely useful regardless of which interpretation of quantum mechanics turns out to be correct. The mirage, if there is one, is narrower, more specific, and more purely linguistic than a claim that the technology itself is illusory: it is the implicit and almost universally unstated assumption that successfully engineering around a problem licenses a *particular metaphysical reading of what the problem fundamentally was. Reducing a defect rate by finding and fixing thermal hotspots, magnetic impurities, or Pearl vortices does not tell us whether the two-level system being protected from those classical perturbations is an irreducibly quantum object whose superposition is a primitive fact about nature, or a coarse-grained statistical description of an underlying deterministic, locally-causal process of the kind 't Hooft and Rowlands, from independent directions and using entirely different mathematical apparatus, have each argued for — exactly the question on which the orthodox view and its two serious deterministic rivals dissent, and exactly the question that Bell's theorem, as Section 5 established in detail, constrains without resolving.*

6.6 A structural incentive worth naming: who benefits from the stronger framing

One further dimension of this case deserves explicit treatment, because it bears directly on why the overreaching framing identified in Section 6.3 persists rather than being self-correcting. The instrument's primary scientific publication discloses, in its standard competing-interests statement, that several of the paper's own authors hold equity participation in QuantaMap BV, the company commercializing the technology the paper describes. This is an entirely ordinary and properly disclosed arrangement for a university spin-off, and nothing in this paper should be read as suggesting any impropriety in the disclosure itself, which meets the standard expected of peer-reviewed publication.

It is, however, directly relevant to the linguistic question this paper has been pursuing. A diagnostic instrument described in the modest terms warranted by Sections 6.1 through 6.4 of this paper — "a sensitive classical-field microscope that correlates magnetic, thermal, and structural anomalies with qubit performance degradation" — is a genuinely useful but commercially unremarkable piece of laboratory equipment, competing in a crowded field of scanning-probe techniques (scanning NV-center microscopy, SQUID-on-lever, and the several earlier SQUID-on-tip variants cited in the instrument's own reference list) on narrower grounds of sensitivity and non-invasiveness. An instrument described as a tool that "helps enable the quantum revolution" and "solves the diagnostics challenge" facing an entire industry occupies a different commercial position entirely, with corresponding implications for fundraising, customer acquisition, and valuation. The authors and executives quoted throughout this paper's source material are not disinterested parties reporting a finding; several are, by their own disclosure, equity holders in the entity whose valuation is affected by which of these two framings the public and the industry adopt. This does not make the stronger framing false in any of its falsifiable engineering content — the measurements are real, and Section 6.1 has confirmed them against the instrument's own technical specification — but it supplies a specific, identifiable, and entirely mundane economic reason why the available rhetorical latitude (Section 6.3's distinction between "found the failed component" and "enabled the quantum revolution") would predictably be resolved toward the stronger and more commercially valuable framing, independent of anyone's view on the underlying physics. Recognizing this incentive does not require attributing *bad faith to any individual; it is simply the ordinary, well-understood dynamic of how academic spin-offs describe their own technology, and it is one more reason — alongside the genuinely unresolved foundational debate surveyed in Sections 3 through 5 — why the language surrounding such instruments should be read with active attention rather than passively absorbed.*

7. Conclusion

7.1 Summary of the argument

This paper has argued, using PoC^4 *— the algebraic frame guaranteed by Hurwitz's theorem on the four normed division algebras, and made structurally explicit through the Cayley–Dickson construction — as the unifying frame, that two independently developed deterministic research programs, Rowlands's nilpotent vacuum formalism and 't Hooft's Cellular Automaton Interpretation, converge on a shared structural claim: that the Hilbert-space formalism of orthodox quantum mechanics is a derived, statistical description of a deeper, locally deterministic process rather than nature's irreducible bottom layer. The convergence is methodologically significant precisely because the two programs arrived at this shared conclusion via entirely different mathematical routes and in response to entirely different physical puzzles — algebraic vacuum duality on one side, black-hole information loss on the other — a form of independent corroboration that, while not proof, is exactly the kind of evidence that ought to be taken seriously rather than dismissed as coincidence.*

Both programs pay a real and substantial price for this claim — the superdeterminism cost exacted by Bell's theorem, surveyed in full and at its strongest in Section 5 — and that price has not been fully discharged by either program in a way that has converted the physics mainstream, nor has this paper claimed otherwise. The question therefore remains genuinely open, not rhetorically open: there exist serious, technically substantive arguments on both sides of the superdeterminism debate, the most recent (2024–2026) of which continue to be actively contested in the specialist literature without clear resolution. Section 5.5 added a further historical caution against reading either side of this debate as the "common-sense default": neither orthodox quantum mechanics' own founders nor its deterministic challengers offer a classically intuitive picture of nature, and the contest should be understood on those terms.

Against this backdrop, the routine industrial and journalistic framing of nanoscale diagnostic instruments such as QuantaMap's SQUID-on-Tip microscope as devices that "test quantum chips" and "diagnose qubit failure" smuggles in a settled answer to a question that, as this paper has shown in detail, is not settled. The instruments measure classical field quantities — current, magnetism, dissipation, and topography — as their own primary publication makes explicit. The correlational inferences drawn from those measurements are engineering-sound and, as Section 6.4 demonstrates, interpretation-neutral: all three competing ontological accounts predict the *identical observable correlation, a claim Section 6.4 also showed is not unfalsifiable in principle, even though no currently available measurement yet discriminates between the three accounts in practice. Section 6.6 identified a specific, mundane commercial incentive — equity participation by several of the technology's own scientific authors — that predictably favors the stronger, less accurate framing regardless of anyone's view of the underlying physics. The language wrapped around the engineering — implying that a fundamentally quantum object has been directly inspected and found wanting, rather than that a classical defect spatially correlated with quantum-chip underperformance has been located — is not neutral; it presupposes the orthodox ontological reading of quantum mechanics as if it were the only reading available, at precisely the moment in the foundations literature when that presupposition is least entitled to go unexamined.*

7.2 Limitations

A paper that argues for taking an unresolved question seriously is obliged to be equally clear about the limits of its own contribution, and four should be stated explicitly rather than left for a reader to discover unassisted.

First, and most importantly, neither Rowlands's nor 't Hooft's program has produced a qubit-specific, numerically distinct prediction that would let a real laboratory measurement discriminate between the orthodox account and either deterministic alternative. Section 6.4 named this gap directly: the harmonic-oscillator and Aharonov–Bohm validations of CAI (Section 4.3), and the structural mirroring argument of Rowlands's nilpotent vacuum (Section 3), are general validations of each program's capacity to reproduce some quantum phenomena from deterministic substrates, not predictions calibrated to the specific decoherence channels (magnetic impurities, Pearl vortices, inhomogeneous supercurrents) a superconducting-qubit diagnostic instrument actually measures. Closing this gap is a piece of further theoretical work this paper has identified but not performed, and a reader should not come away believing this paper has shown the three ontologies to be permanently indistinguishable as a matter of principle — only that they are currently indistinguishable as a matter of the available theory and instrumentation.

Second, this paper has relied on secondary characterizations of 't Hooft's most technical results (the Bohmian-Born-rule emergence argument, the operator-form derivation of deterministic evolution) drawn from a synthesis source rather than a line-by-line derivation from 't Hooft's own primary mathematical text. The qualitative claims attributed to 't Hooft throughout Sections 4.2 and 4.3 are drawn from his own published statements and from a recent synthesis explicitly engaging his primary sources, but a reader seeking to verify the full technical derivation should consult 't Hooft's 2016 monograph directly rather than relying on this paper's summary of summaries at the most technical points.

Third, the historical material in Section 5.5 on the philosophical commitments of quantum mechanics's founders is offered for the limited purpose stated there — undermining a specific *rhetorical move, not establishing any positive claim about which interpretation is correct — and should not be read as this paper endorsing or rejecting idealism, Bohr's complementarity, or any other historical position canvassed in that section.*

Fourth, this paper's account of QuantaMap's commercial incentives (Section 6.6) is offered as a structural observation about disclosed equity arrangements common to university spin-offs generally, not as a claim about the specific motivations or good faith of any named individual; the paper has deliberately confined itself to publicly disclosed facts and to the ordinary economic logic such disclosures imply, and has avoided speculating about any individual's state of mind, consistent with the paper's own methodological commitments.

7.3 Practical recommendation

The practical recommendation that follows from this analysis is not skepticism toward the engineering achievement itself — the engineering is sound on its own terms under any of the three ontologies surveyed in this paper — but precision in language, and a corresponding adjustment in how such results are reported to non-specialist audiences. A defect-localization instrument that correlates classical field anomalies with qubit performance degradation is doing real and valuable work, work this paper has described in technical detail in Section 6.1 using the instrument's own published specification. Describing that work as "seeing inside the quantum chip" or "diagnosing the quantum state directly," rather than as "finding the classical defects that interrupt an emergent coherence regime," is the rhetorical move this paper has tried to make visible across its seven sections, and to show is neither a necessary feature of reporting the underlying science nor, given the genuinely unresolved state of the foundational debate surveyed in Sections 3 through 5, an innocent or cost-free simplification.

References

't Hooft, G. (2014/2016). *The Cellular Automaton Interpretation of Quantum Mechanics.* Fundamental Theories of Physics, vol. 185. Cham: Springer International Publishing. arXiv:1405.1548.

't Hooft, G. (2015). Diagonalizing the Black Hole Information Retrieval Process. arXiv:1509.01695.

't Hooft, G. (2015). Singularities, horizons, firewalls, and local conformal symmetry. Presented at the 2nd Karl Schwarzschild Meeting on Gravitational Physics, Frankfurt. arXiv:1511.04427.

Rowlands, P. (2007). *Zero to Infinity: The Foundations of Physics.* Series on Knots and Everything, vol. 41. Singapore: World Scientific.

Rowlands, P. (2004). The nilpotent vacuum. *Hypercomplex Numbers in Geometry and Physics*, 2, 97–111.

Rowlands, P. (2008). What is vacuum? arXiv:0810.0224.

Marcer, P., & Rowlands, P. (2017). Nilpotent quantum mechanics: Analogs and applications. *Frontiers in Physics*, 5, Article 28. https://doi.org/10.3389/fphy.2017.00028

Hurwitz, A. (1898). Über die Composition der quadratischen Formen von beliebig vielen Variabeln. *Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse*, 309–316.

Baez, J. C. (2002). The Octonions. *Bulletin of the American Mathematical Society*, 39(2), 145–205.

Wilmot, G. P. (2026). Structure of the Cayley-Dickson algebras. arXiv:2505.11747.

Morales, M. S. (2024). The Method of Everything vs. Experimenter Bias of Loophole-Free Bell Experiments. *Frontiers in Research Metrics and Analytics*, 9, 1404371. https://doi.org/10.3389/frma.2024.1404371

Wiseman, H. (2024). The Last Loophole in Bell's Theorem? A prima facie problem with superdeterminism. arXiv:2410.05296.

Baas, A., & Le Bihan, B. (2023). What does the world look like according to superdeterminism? *British Journal for the Philosophy of Science*, 74(3), 555–572.

Waegell, M., & McQueen, K. J. (2025/2026). From statistical dependence to the space of possible superdeterministic theories. *European Journal for Philosophy of Science* (forthcoming). arXiv:2509.23047.

Vervoort, L. (2022). Aspects of Superdeterminism Made Intuitive. arXiv:2205.10616.

Salom, I. (2023/2026). 2022 Nobel Prize in Physics and the End of Mechanistic Materialism. arXiv:2308.12297.

Rog, M., Blom, T. J., Boltje, D. B., de Haan, J. D., Fermin, R., Niu, J., Doedes, Y. C., Lahabi, K., & Allan, M. P. (2026). Tapping-Mode SQUID-on-Tip Microscopy with Proximity Josephson Junctions. *Nano Letters*, published 12 February 2026. https://doi.org/10.1021/acs.nanolett.5c04571; preprint arXiv:2508.21575.

Leiden University News (2026, January). A new microscope for the quantum age: finally seeing how quantum materials behave. universiteitleiden.nl.

The Quantum Insider (2026, February 12). QuantaMap and Leiden University Introduce Nanoscale Imaging for Quantum Chip Development and Materials Research.

Quantum Computing Report (2026, February 15). Leiden University and QuantaMap Introduce Multi-Modal Quantum Microscope.

Quantum Zeitgeist (2026, February 12). QuantaMap Breakthrough Published in ACS Nano Letters Accelerates Quantum Materials Research.

Key Region Leiden (2026). "Finally understanding the mechanism behind why quantum chips fail" — interview with Johannes Jobst.

Physics Today (2025/2026). Review of *The Cellular Automaton Interpretation of Quantum Mechanics*.

Note on Method

This paper was prepared following an explicit corpus and citation discipline: all quoted material from primary and secondary sources is cited to its specific origin rather than paraphrased from memory, and the algebraic foundation (Hurwitz's theorem and the Cayley–Dickson construction) is kept rigorously distinct from the superficially similar but distinct Bott periodicity theorem, a conflation identified and corrected in the author's prior work on the PoC^4 framework. The two deterministic physics programs discussed — Rowlands's nilpotent vacuum mechanics and 't Hooft's Cellular Automaton Interpretation — are presented as independently derived and convergent, not as a single school of thought, and the strongest published objections to both (the superdeterminism cost of Bell's theorem, including its most recent technical formulations through 2026) are presented without softening, consistent with the paper's own argument that unresolved foundational questions should be marked as unresolved rather than rhetorically closed. The QuantaMap case study draws directly on the instrument's own primary technical publication (Rog et al., 2026, and its arXiv preprint) rather than exclusively on secondary press coverage, in order to ground the central argument of Section 6 in the instrument's actual published specification rather than in promotional paraphrase.