Substrate-Flexible Informational Quantum Mechanics: QBism, RQM, and the Question of Non-Human Epistemic Systems

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Posted Date: 8 May 2026

doi: 10.20944/preprints202605.0531.v1

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Article

Substrate-Flexible Informational Quantum Mechanics: QBism, RQM, and the Question of Non-Human Epistemic Systems

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Abstract

The QBist and Relational Quantum Mechanics (RQM) informational readings of quantum theory have been developed across two decades without a clear position on what kind of physical system qualifies as an "agent" or "observer" for the formalism. Fuchs, Mermin, and Schack write as if the agent is a human physicist or a generic Bayesian; Rovelli writes as if any physical system can play the relational-observer role; Healey deflates the agent into an abstract Bayesian without specifying its substrate; the recent Khrennikov-Schack-Zwirn intersubjectivity exchange sharpens the question without resolving it. This paper argues that the QBism/RQM informational reading is substrate-flexible: any physical system whose input-output statistics admit characterization through quantum-probability structure with non-trivial Contextuality-by-Default (CbD) signatures resistant to simplex-embeddable ontological models is a candidate epistemic agent for the formalism. Substrate flexibility is the most coherent reading of the shared formal commitments of QBism and RQM once the agent role is separated from historically human-centered examples; the non-triviality requirement is necessary but not sufficient for agency, which additionally requires an input-output architecture capable of state-sensitive updating across measurement contexts. The thesis preserves the QBist objection to view-from-nowhere framings while removing the requirement that agents be human or conscious; it disciplines Rovelli's "any physical system" claim by indexing it to the non-triviality requirement; and it specifies what would count as evidence for or against. Engineered cortical wetware preparations (Cortical Labs CL1, DishBrain) provide a non-human, non-conscious-in-any-unambiguous-sense, controllable testbed on which the question can be empirically pursued; nothing in the argument requires attributing phenomenal consciousness or quantum-coherent biological dynamics to such systems. The paper distinguishes substrate flexibility from Pienaar's prior extension of the QBist agent (which extends the agent's senses, not its substrate), engages the neo-Everettian opposition (Wallace 2012, 2023) directly, and rejects the recent attempts (Edwards 2024, 2025) to fold classical large language models into a QBism-grounded formalism. Classical AI architectures admit simplex-embeddable models for their token-generation processes and therefore fail the non-triviality requirement; substrate flexibility is narrower, not wider, than such proposals.

Keywords: QBism; relational quantum mechanics; informational interpretations; agency; observer; contextuality; Contextuality-by-Default; ontological models; organoid intelligence; wetware computing; foundations of quantum mechanics

JEL Classification: C00; C18; B41; Z00

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1. Introduction: A Question the Informational Reading Has Not Asked

The QBist and Relational Quantum Mechanics (RQM) readings of quantum theory share a common methodological move: they treat the formalism as the structure of agent-relative information updates rather than as a description of mind-independent ontology. Across two decades of development by Fuchs, Mermin, Schack, Rovelli, Healey, and others, this informational reading has

 doi:10.20944/preprints202605.0531.v1

been argued to dissolve a series of foundational paradoxes — the measurement problem, Wigner's friend, the interpretive puzzles surrounding Bell-type inequalities — by recasting the wavefunction as something closer to belief, expectation, or relational record than as an element of physical reality [1–5]. The participatory-universe intuition that John Wheeler crystallized in his 1983 essay "Law without Law" — that the observer's act of measurement is constitutive rather than incidental — is the historical seed from which the contemporary informational program has grown [6].

The literature has developed this move with care along most dimensions. What it has not engaged is the question of what kind of physical system qualifies as an agent or observer for the purposes of the formalism. Fuchs, Mermin, and Schack write as if the agent is a human physicist or a generic Bayesian; Rovelli writes as if any physical system can play the relational-observer role; Healey writes as if the agent is an abstract Bayesian agent whose substrate is left unspecified; the recent Brukner-Zeilinger informational primitivism makes information itself the foundational quantity in a way that sidesteps the question entirely [7]. These positions are not interchangeable, and the literature has not adjudicated between them. The author's prior work on time-symmetric quantum histories and informational pruning [8] developed an agent-relative reading at the level of admissible-history ensembles but left the question of what counts as an agent untouched. The present paper takes that question up directly.

The question becomes empirically pressing for the first time in the present moment. Engineered cortical cultures — Cortical Labs CL1, DishBrain-class preparations, brain-on-a-chip systems — are non-human, controllable, re-measurable, and information-updating in a non-trivial sense [9–12]. Whether the QBism/RQM formalism applies to them is a substantive question that the field can no longer defer. The contemporary AI alignment literature has independently raised an adjacent question — whether large language models qualify as observer-like agents in a QBism-grounded sense [13,14] — though the answer offered there is, this paper will argue, mistaken in a specific and instructive way.

This paper argues that the QBism/RQM informational reading is substrate-flexible: any physical system whose input-output statistics admit characterization through quantum-probability structure with non-trivial Contextuality-by-Default (CbD) signatures resistant to simplex-embeddable ontological models is a candidate epistemic agent for the formalism. The thesis is offered as a substantive interpretive commitment, not a hedged option: substrate flexibility is the most coherent reading of the shared formal commitments of QBism and RQM once the agent role is separated from the historically human-centered examples in which those interpretations have been developed. It has three implications. First, the standard QBist objection to "view from nowhere" framings of quantum theory is preserved without requiring agents to be conscious. Second, Rovelli's RQM is closer to QBism than the literature has acknowledged once substrate flexibility is in view. Third, engineered wetware preparations can serve as a testbed for the substrate-flexibility claim, even though no single experimental result will settle the interpretive question on its own.

Several caveats are front-loaded so the stronger thesis is defensible by Section 3. The paper does not commit to organoid consciousness, in either direction; substrate flexibility is a thesis about the formal domain of quantum theory, not about phenomenal experience. The paper does not assert that minds collapse wavefunctions; consciousness-causes-collapse views are explicitly rejected in Section 5.2. The paper does not argue against Everettian readings tout court; Section 5.1 distinguishes between strong and weak Everettianism and engages the strong reading directly. The paper does not claim that classical artificial intelligence architectures qualify as substrate-flexible agents; Section 6.4 argues against this conflation, which has been recently advanced in the QBism-adjacent literature [13,14]. And the paper does not claim originality for the substrate-flexibility thesis itself: Rovelli's 1996 RQM paper and Healey's pragmatist position are the closest precedents, and Pienaar's 2020 extension of the QBist agent is the closest published prior work [15]. The contribution is in articulating substrate flexibility as a positive interpretive commitment, indexing it to a precise non-triviality requirement, and arguing it through against the contemporary opposition.

 doi:10.20944/preprints202605.0531.v1

Section 2 reviews the state of the QBism/RQM literature on agency. Section 3 states and defends the substrate-flexibility thesis. Section 4 argues that engineered cortical wetware is the right empirical testbed and develops the non-triviality requirement that distinguishes substrate flexibility from vacuous panpsychism-of-the-formalism. Section 5 engages competitor interpretations, focusing on the live neo-Everettian debate. Section 6 draws out implications for the foundations program, including the question of classical AI. Section 7 concludes.

2. The State of the QBism/RQM Literature on Agency

2.1. QBist Orthodoxy on the Agent

The canonical statement of QBism — Fuchs, Mermin, and Schack's 2014 "Introduction to QBism" — characterizes the agent as whatever entity assigns probabilities and updates them in accordance with the Born rule [1]. The theory is presented as a normative framework for an agent's gambling behavior on the outcomes of quantum measurements, with the wavefunction representing that agent's degrees of belief and the Born rule serving as a coherence constraint analogous to the Dutch-book argument in classical Bayesian theory. The QBist agent is therefore deliberately abstract: it is whatever instantiates the formal role of probability assignment and update.

The QBist literature is, at the level of its formal apparatus, ecumenical about whether the agent is a human, an idealized Bayesian, or some broader class of system. But the discussion has, almost without exception, treated the agent as if it were a human physicist. Worked examples invoke Wigner, Alice and Bob, the QBist's "experience," and the agent's "actions on the world." When the question of agency has been engaged at all, it has been engaged by Pienaar [15], who proposes extending the agent's senses through the inclusion of measurement instruments, and by DeBrota, Fuchs, and Schack [16], who treat Wigner's friend as a fellow agent whose experiences must be "respected" rather than overridden. Both moves preserve the human-centered agent while extending its operational reach.

The QBist orthodoxy has not engaged the question of whether non-human, non-conscious physical systems count as agents. This is not a criticism of the program; the question simply has not been on the agenda. It is on the agenda now.

2.2. RQM on the Observer

Rovelli's 1996 founding paper on relational quantum mechanics is more permissive than QBism on the question of agency [2]. Rovelli explicitly states that "all systems are equivalent" — that any physical system can play the role of observer relative to any other physical system, with the relativization of state to observer being the central interpretive move. The 2018 essay "Space is blue and birds fly through it" reinforces this stance: Rovelli denies that the system relative to which a quantum state is defined must be conscious, must be macroscopic, or must be of any privileged kind [3]. RQM is, by its own statement, substrate-flexible at the textual level.

RQM has also faced sustained internal pressure on this stance. Smerlak and Rovelli [17] address the regress objection — if every physical system can be an observer, what fixes the perspective from which any particular quantum-mechanical claim is made — by appealing to the relational structure of physics itself. More recently, Adlam and Rovelli [18] introduce a cross-perspective links postulate that substantially modifies the framework, addressing concerns that classical RQM was insufficiently constrained to underwrite intersubjective scientific discourse. The substrate-flexibility thesis defended in this paper aligns more cleanly with classical (1996, 2018) RQM than with the post-2023 axiomatic reformulation; this tension is acknowledged rather than dissolved, and is taken up in Section 3.

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2.3. Healey's Pragmatist Reading as a Triangulation Point

Richard Healey's pragmatist interpretation of quantum theory occupies the conceptual space between QBism and RQM, and is the most fully developed informational reading in which the agent is explicitly abstract rather than human [4,5,19]. Healey's 2012 paper "Quantum theory: A pragmatist approach" makes the move clearly: quantum theory provides objectively correct advice for any agent who is in a position to use it, where "agent" is understood as any entity capable of making the relevant probabilistic inferences [5]. The 2017 monograph The Quantum Revolution in Philosophy develops this into a full pragmatist program in which the agent is deflated to a Bayesian inference machine without specification of its physical substrate [4].

Healey's position is a natural ally rather than a competitor for the substrate-flexibility thesis. If the agent is already abstract and Bayesian — as Healey argues it must be — then no further argument restricts the agent to any particular substrate. The substrate-flexibility thesis pushes through Healey's position to its endpoint: there is no principled stopping rule short of the constraint that the agent's input-output statistics must be characterizable in quantum-probabilistic terms. The argumentative move in this paper is therefore continuous with Healey's deflation rather than opposed to it.

2.4. Brukner-Zeilinger Informational Primitivism

The Brukner-Zeilinger program treats information itself as the foundational quantity of quantum theory rather than as the content of an agent's belief state [7]. Zeilinger's 1999 "Foundational Principle for Quantum Mechanics" argues that an elementary system carries one bit of information, and that the structure of quantum mechanics follows from this informational constraint. Brukner's 2018 no-go theorem on observer-independent facts [20] sharpens the informational primitivist position by showing that, in extended Wigner's-friend scenarios, no single observer-independent description of facts is possible — the facts themselves are observer-relative.

Substrate flexibility hits the Brukner-Zeilinger position differently than it hits QBism or RQM. If information is foundational and substrate-independent by construction, then any system whose dynamics can be characterized in informational terms is, trivially, an agent under their reading. The Brukner-Zeilinger framework is therefore an ally of substrate flexibility — but in a way that makes the substantive question disappear. The position taken in this paper is that the Brukner-Zeilinger framework presupposes substrate flexibility but does not articulate it as such; the contribution of Section 3 is to make the commitment explicit and to specify the non-triviality requirement that prevents the thesis from collapsing into vacuity.

2.5. The Unaddressed Gap

The four positions surveyed above stake out distinct claims about what an agent is for the purposes of the formalism, but none has explicitly defended substrate flexibility as a positive interpretive commitment indexed to a precise non-triviality requirement. QBism presupposes a more contentful notion of the agent than its own formalism strictly requires; RQM presupposes a less contentful notion than is needed to make the relational picture coherent; Healey deflates the agent without specifying its substrate; Brukner-Zeilinger sidestep the question by making information primitive. The literature has not worked out what the formalism actually demands of a candidate agent. Table 1 summarizes the positions side-by-side, and Figure 1 (Section 3) places them in a two-dimensional positioning diagram.

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Table 1. Positions on the QBist/RQM "agent" question.

Position	Agent / observer	Substrate scope	Realism level	Engages non-human?
QBist orthodoxy [1]	Human Bayesian (in practice); abstract probability-assigner (in principle)	Species-specific in usage	Realist about agent-relative facts	No
RQM [2,3]	Any physical system relative to any other	Permissive; "all systems equivalent"	Realist about relational facts	Yes (textually)
RQM with cross-perspective links [18]	Any physical system, with consistency postulate	Permissive but constrained	More realist than 1996 RQM	Yes
Healey pragmatist [4,5]	Abstract Bayesian agent	Substrate left unspecified	Pragmatist	Implicitly
Brukner-Zeilinger [7,20]	Information itself is primitive	Substrate-independent by construction	Information-realist	Trivially
Pienaar 2020 [15]	Human agent + extended senses	Species-specific (extended)	QBist-realist	No (extends senses, not substrate)
This paper	Any system passing non-triviality test (§4.2)	Substrate-flexible	Realist about agent-relative facts	Yes (formally)

2.6. The Khrennikov-Schack-Zwirn Intersubjectivity Exchange

A recent exchange in the foundations literature has sharpened the question of agency through Ozawa's intersubjectivity theorem. Khrennikov [21] argues that Ozawa's theorem refutes the QBist individual-agent perspective: intersubjective convergence between two agents on a quantum measurement outcome requires shared quantum-mechanical conditions that QBism's strict subjectivism cannot underwrite. In a companion paper, Khrennikov [22] argues that the same theorem justifies RQM's postulate of internally consistent descriptions, since the relational structure of RQM makes the convergence conditions formally available. Schack [23] replies on behalf of QBism, arguing that the QBist reading of the Born rule as a normative constraint already accommodates the convergence Khrennikov demands, and that Khrennikov's critique misconstrues the QBist position. Zwirn [24] offers an independent critique that complicates both sides: neither QBism nor RQM, in his analysis, has actually demonstrated intersubjectivity in the relevant operational sense.

 doi:10.20944/preprints202605.0531.v1

The exchange is best understood against the broader landscape of Wigner's-friend no-go theorems. The Frauchiger-Renner argument [25] and the Bong-Utreras-Alarcón et al. strong no-go theorem [26] establish that observers reasoning about other observers' measurements face fundamental consistency constraints that any informational reading must address. The Khrennikov-Schack-Zwirn dispute can therefore be read as a particular case of the more general question: under what conditions can multiple observer-systems converge on a shared description of quantum outcomes? This is the question of agency, recast in the form of a question about convergence: under what conditions can two agents agree on the outcome of a quantum measurement, and what does that agreement require of the agents themselves? The substrate-flexibility thesis does not resolve the dispute, but it does change its shape. Section 3.4 returns to the exchange after the thesis is in place.

2.7. The Closest Prior Work: Pienaar's Extension of the QBist Agent

Pienaar's 2020 paper "Extending the agent in QBism" is the QBist literature's most direct engagement with the question of what "agent" means for the formalism, and it is the closest published prior work to the present paper [15]. Pienaar's move is to treat the measurement instrument as an extension of the agent's senses, on the model that a telescope extends an astronomer's vision or a microphone extends a listener's hearing. Under this extension, the agent's epistemic reach extends into instrumental contexts that would otherwise be inaccessible, but the agent itself remains the human (or human-equivalent) Bayesian who interprets the instrument's output.

The substrate-flexibility thesis defended in this paper is structurally different. Where Pienaar extends the agent's senses, the present paper extends the agent's substrate: the formal role "agent" is filled by any system meeting the non-triviality requirement specified in Section 4.2, with humans as one instance among several. The two extensions are compatible — a non-human substrate-flexible agent could in turn extend its senses through instruments, mirroring Pienaar's move at a different level — but they are not equivalent. Pienaar's move preserves species-specific QBism by extending the human agent's reach; the present move rejects species-specific QBism by relativizing the agent role itself. The two papers therefore articulate different ways the QBist agent can be generalized, and the present paper builds on Pienaar's groundwork while pushing past it.

Two further internal QBist gestures should be acknowledged. Stacey's 2019 essay "Quantum theory as symmetry broken by vitality" raises the question of non-anthropic agents at a programmatic level without developing it into a full proposal [27]. Pienaar's 2021 comparative paper between QBism and RQM [28] notes the substrate-related divergence between the two interpretations but does not adjudicate it. Calosi and Riedel's 2024 "Relational Quantum Mechanics at the Crossroads" [29] surveys the post-Adlam-Rovelli landscape but does not engage the agency question directly. The substrate-flexibility thesis advanced here is therefore consistent with several recent gestures in the literature, but is not pre-empted by any of them.

3. The Substrate-Flexibility Thesis

3.1. Statement of the Thesis

The QBism/RQM formalism is substrate-flexible: any physical system whose input-output statistics admit characterization through quantum-probability structure with non-trivial Contextuality-by-Default (CbD) signatures resistant to simplex-embeddable ontological models in the Schmid-Selby-Pusey-Spekkens 2024 sense [30] is a candidate epistemic agent for the formalism. This is the most coherent reading of the shared formal commitments of QBism and RQM once the agent role is separated from the historically human-centered examples in which those interpretations have been developed. The non-triviality clause is essential; without it the thesis collapses into the empty claim that any sufficiently complex stochastic system can be dressed up in Hilbert-space clothing. The clause is developed formally in Section 4.2 and visualized in Figure 2.

 doi:10.20944/preprints202605.0531.v1

3.2. What the Thesis Does and Does Not Entail

Substrate flexibility entails that the formal domain of application of QBism/RQM is wider than human cognition. It entails that the question of whether any particular physical system instantiates the formalism is empirical rather than stipulative. It does not entail that every physical system instantiates the formalism: the empirical bar specified in Section 4.2 must be cleared, and most physical systems will fail it. It does not entail that instantiating systems are conscious; the present paper is silent on phenomenal experience. It does not entail that instantiating systems collapse wavefunctions in any literal sense; the present paper is silent on the metaphysics of state reduction. And it does not entail that the QBism/RQM informational reading is the correct interpretation of quantum theory tout court; competitor interpretations are engaged in Section 5.

3.3. Contrast with Species-Specific Readings

A species-specific reading of QBism/RQM would hold that the informational reading is fundamentally a theory of human belief that has been extended to physics by analogy. Such a reading is logically possible but argumentatively burdened: it must explain why the formalism is contingently human, given that the formalism's own structure makes no reference to humans. The substrate-flexible reading carries no such burden. It also has a structural advantage with respect to Healey's pragmatist position: once the agent is abstract and Bayesian, as Healey argues it must be, no further argument restricts the agent to the human substrate. The species-specific reading therefore has a Healey problem that substrate flexibility avoids. Figure 1 places the present paper's position relative to the existing landscape.

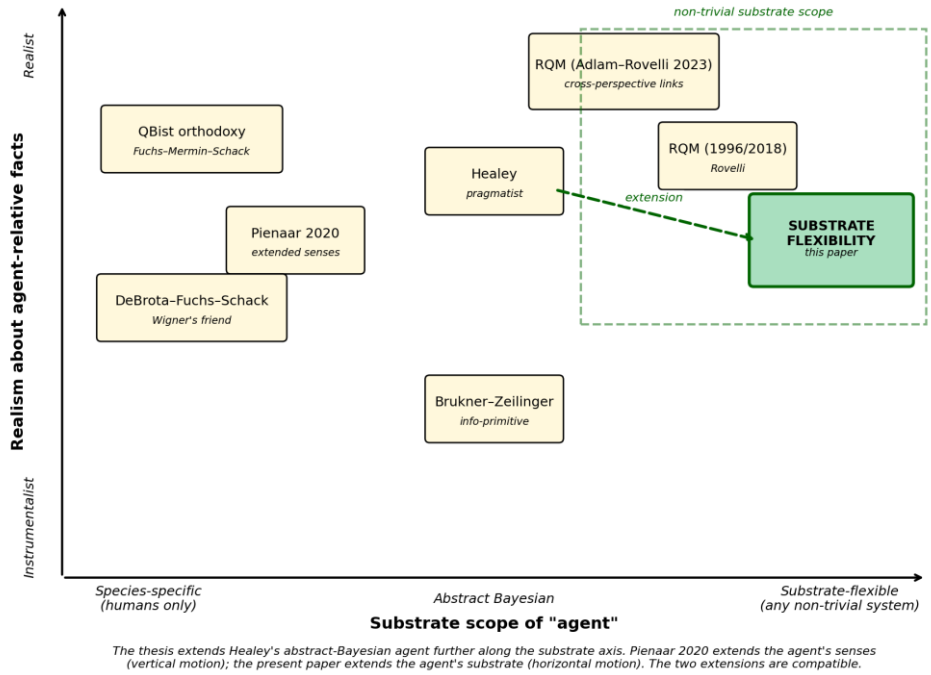

Figure 1. The substrate-flexibility thesis among informational readings of quantum mechanics.

The horizontal axis represents substrate scope of the agent (species-specific to fully substrate-flexible); the vertical axis represents the degree of realism about agent-relative facts. Pienaar's 2020 extension moves vertically (extending the agent's senses); the present paper moves horizontally (extending the agent's substrate). The two extensions are compatible.

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3.4. The Khrennikov-Schack-Zwirn Exchange Under Substrate Flexibility

Section 2.6 reviewed the Khrennikov-Schack-Zwirn exchange on Ozawa intersubjectivity. The exchange shifts in three ways once substrate flexibility is on the table.

First, the question of whether mixed agent populations — human-and-wetware, or in principle human-and-AI — can satisfy the Ozawa convergence conditions becomes empirically tractable rather than purely conceptual. Whether two agents converge on the outcome of a quantum measurement is, under substrate flexibility, a question that can be posed and answered for any pair of substrate-flexible agents whose measurement statistics meet the non-triviality requirement. The Ozawa-theoretic conditions on convergence become, in this setting, predictions about the joint statistics of the agent pair rather than postulates about an idealized human community.

Second, the substrate-flexibility thesis is neutral between Khrennikov's and Schack's readings of the QBist position. Both sides agree that the formal apparatus applies wherever quantum-probabilistic structure obtains; their disagreement is about whether convergence between agents is automatic (Khrennikov's reading, on which the theorem refutes QBism) or normative (Schack's reading, on which the theorem is consistent with QBism's normative-constraint reading of the Born rule). Substrate flexibility is consistent with either resolution. What it adds is the observation that whichever reading is correct, the empirical question of whether actual agent populations satisfy the convergence conditions is open and tractable.

Third, Zwirn's independent critique — that intersubjectivity has not been demonstrated for any agent population — is strengthened rather than weakened by substrate flexibility. Extending the agent class makes the empirical question of convergence more pressing, not less. Under species-specific QBism, the empirical question could in principle be deferred to introspective consensus among human physicists; under substrate flexibility, no such deferral is available. The thesis therefore takes Zwirn's critique as a research-program directive: the empirical work of testing convergence on candidate substrates is the right next step, and the engineered wetware preparations discussed in Section 4 are one of the substrates on which it can begin.

4. Why Engineered Wetware Is the Right Test Case

4.1. The Methodological Case

The substrate-flexibility thesis is a claim about which physical systems can instantiate the QBism/RQM formalism. Testing the thesis requires a candidate substrate that is non-human, controllable, re-measurable, information-updating in a non-trivial sense, and accessible to the kind of measurement protocols that the formalism describes. Engineered cortical cultures meet these requirements as no prior system has.

Kagan and colleagues' 2022 demonstration that DishBrain preparations — cultured cortical neurons embedded in a closed-loop electrophysiological environment — exhibit goal-directed adaptive behavior in a simulated Pong task established the operational baseline [9]. The 2025 follow-up by Khajehnejad and colleagues showed that biological neural cultures exhibit dynamic network plasticity and sample efficiency comparable to or exceeding deep reinforcement learning agents in matched tasks [10]. The Smirnova et al. 2023 "Organoid Intelligence" framing paper situates these results within a broader research program on biocomputing and intelligence-in-a-dish [11], and the Jordan et al. 2024 Neuroplatform paper documents an open, remotely accessible wetware computing environment for sustained experimentation [12]. Cortical Labs' CL1 platform represents the current commercial state of the art.

These systems are non-human in the relevant sense (they are not whole organisms with intact phenomenology); non-conscious in any unambiguous sense (the question of organoid consciousness remains contested but no consensus supports the affirmative); controllable (input stimulation patterns can be specified and varied); re-measurable (the same culture can be probed across multiple measurement contexts); and information-updating in a non-trivial sense (they exhibit adaptive responses to structured stimulation on timescales of minutes to hours). They are, in short, candidate

 doi:10.20944/preprints202605.0531.v1

substrate-flexible agents in exactly the form that the thesis requires. One clarification is essential at this point: the claim is not that wetware preparations are likely to be quantum-coherent in the ordinary physical sense — that is, that they sustain entangled microstates over biologically meaningful timescales. The relevant question is whether their operational input-output statistics, treated abstractly, require quantum-probability structure rather than admitting a simplex-embeddable classical-stochastic model under reasonable operational equivalences. Substrate flexibility makes no commitment about microphysical coherence and is therefore distinct from the Penrose-Hameroff and Stapp-style proposals rejected in Section 5.2.

4.2. The Triviality Objection and the Non-Triviality Requirement

The natural objection to substrate flexibility is that any sufficiently complex stochastic system has input-output statistics that one can dress up in Hilbert-space clothing — making the thesis vacuous. A thermostat, a Markov chain, a classical control loop, a transformer-based language model: each of these has measurement statistics that can be mapped onto a quantum formalism through some sufficiently flexible reconstruction. If substrate flexibility entails that all such systems are candidate agents, the thesis loses its content.

The non-triviality requirement specified in Section 3.1 is the answer to this objection. Schmid, Selby, Pusey, and Spekkens [30] prove a structure theorem for generalized-noncontextual ontological models: a system's behavior admits a simplex-embeddable (i.e., effectively classical) ontological model if and only if it satisfies generalized noncontextuality in the operational sense. A simplex-embeddable model is one in which the system's behavior can be represented by a classical probability distribution over a state space whose extreme points correspond to deterministic ontic states. Most familiar classical systems — thermostats, Markov chains, classical control loops — admit such models by construction; their statistics are, formally, mixtures of classical states.

The substrate-flexibility thesis is non-trivial only when applied to systems whose measurement statistics resist simplex-embedding. Equivalently, a candidate system instantiates the QBism/RQM formalism only when its measurement statistics exhibit Contextuality-by-Default (CbD) signatures of the kind formalized by Dzhafarov, Cervantes, and Kujala [31,32], where the contextuality is empirically detected rather than imposed by the choice of reconstruction. The Schmid-Selby-Spekkens 2024 companion paper "Addressing some common objections to generalized noncontextuality" [33] supplies the resources for handling reviewer objections to the framework itself, including objections about the choice of operational equivalences and the role of preparation versus measurement contextuality. Spekkens's 2007 toy theory [34] and Harrigan-Spekkens 2010 [35] establish the canonical ontological-models framework against which the structure theorem is proved. Figure 2 represents the test as a decision flow.

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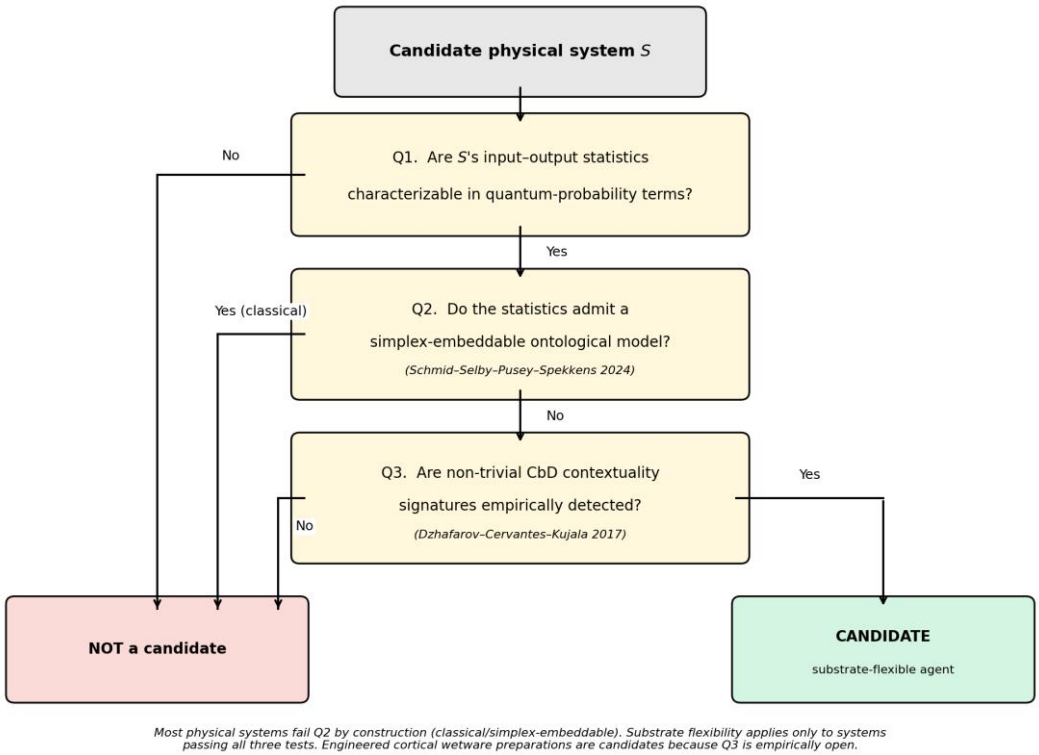

Figure 2. The non-triviality test for substrate-flexibility candidacy.

A candidate system passes the substrate-flexibility non-triviality test only if its measurement statistics (i) admit characterization in quantum-probability terms, (ii) resist simplex-embeddable ontological models, and (iii) exhibit empirically detected non-trivial CbD contextuality. Most physical systems fail at the second test by construction. The test is necessary but not sufficient for agency; full candidacy also requires an input-output architecture capable of state-sensitive adaptive updating across measurement contexts (see discussion following Table 2).

The non-triviality requirement therefore has bite. Most physical systems — the overwhelming majority — admit simplex-embeddable models and fail the requirement by construction. Substrate flexibility is not the claim that any system is a candidate agent; it is the claim that no system can be a candidate without first passing the non-triviality test. Table 2 surveys the most natural candidate substrates against the test.

Table 2. Candidate substrates evaluated against the non-triviality test (Figure 2).

Substrate	Q1: Quantum-probability characterizable?	Q2: Simplex-embeddable?	Q3: Non-trivial CbD detected?	Candidate?
Thermostat / classical control loop	No (or trivially so)	Yes (classical)	No (by construction)	No
Markov chain / hidden-Markov model	Trivially	Yes (classical)	No	No
Transformer-based LLM (e.g., GPT-class)	Surface-level only	Yes (classical computation)	No (training-data artifact)	No (Section 6.4)

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Substrate	Q1: Quantum-probability characterizable?	Q2: Simplex-embeddable?	Q3: Non-trivial CbD detected?	Candidate?
Quantum optical interferometer	Yes	No	Yes (well-established)	Passes contextuality gate; fails agency-functional gate
Engineered cortical wetware (CL1, DishBrain)	Plausibly	Open empirical question	Open empirical question	Open / candidate (Section 4)
Hybrid wetware-photonic preparations	Plausibly	Open	Open	Open / candidate
Human Bayesian agent	Operationally modeled in QBism	Open / contested	Plausible (cognitive-contextuality literature)	Canonical interpretive instance

The empirical question for engineered wetware is whether the response statistics of cultured cortical preparations admit simplex-embedding under reasonable operational equivalences. This is, at the time of writing, an open empirical question; the present paper does not claim to settle it.

One clarification of the framework is essential before proceeding. The non-triviality requirement specified above should be read as a necessary condition for substrate-flexibility candidacy, not as a sufficient condition for agency. A system may exhibit non-classical contextuality without thereby occupying the formal epistemic role the QBism/RQM informational reading requires. The quantum optical interferometer row of Table 2 makes this vivid: an interferometer's measurement statistics resist simplex-embedding, and yet the device does not function as an agent in the relevant updating sense — there is no input-output architecture by which the interferometer assigns and updates probabilities across distinguishable measurement contexts. Candidate agency, properly understood, requires two conditions: (i) non-trivial quantum-probability structure in the operational statistics (the non-triviality requirement formalized through the Schmid-Selby-Pusey-Spekkens 2024 framework and the CbD signature of Dzhafarov-Cervantes-Kujala 2017), and (ii) an input-output architecture capable of state-sensitive adaptive updating across distinguishable measurement contexts (the agency-functional requirement, which is operationally familiar from the cognitive-science and reinforcement-learning literatures but which the QBism/RQM literature has not formalized). Engineered cortical wetware is interesting precisely because it plausibly combines both features: the Kagan and Khajehnejad results [9,10] establish the agency-functional gate; whether the contextuality gate is also passed is the empirical question this paper specifies but does not settle. The non-triviality requirement therefore does the work of distinguishing substrate flexibility from vacuous panpsychism-of-the-formalism (Section 4.2), but it does not by itself characterize agency.

4.3. What "Applies to Them" Means Here

The structural commitments of the QBism/RQM formalism — non-commutativity of measurement contexts, non-trivial CbD contextuality, response replicability under appropriate

 doi:10.20944/preprints202605.0531.v1

POVM modeling, agent-relative state assignment — should be empirically detectable in candidate substrate-flexible systems if the thesis is correct. A full experimental protocol is beyond the scope of the present paper, but the relevant structure would require repeated measurements across controlled stimulation contexts on stable cortical preparations, statistical tests for CbD-style contextuality across context pairs, and explicit comparison of the resulting joint distributions against simplex-embeddable ontological models in the Schmid-Selby-Pusey-Spekkens sense. A companion paper [36] develops this protocol in detail; the present paper's argument does not depend on the protocol's specific form, only on the observation that such a protocol is in principle constructable from the contextuality framework already in place.

4.4. The Asymmetric Epistemics

A positive empirical result — wetware preparations exhibiting non-trivial CbD contextuality under the relevant protocols — would support the substrate-flexibility thesis but not confirm it. The thesis is a claim about the formal domain of QBism/RQM, and a single positive result establishes only that the domain is non-empty for non-human substrates; it does not establish that the formalism is the correct interpretation of quantum theory, nor that all sufficiently complex non-human systems instantiate it. A negative result would support a species-specific reading but not confirm it; other substrates (silicon-based quantum-coherent systems, hybrid wetware-photonic preparations) might still instantiate the formalism. The interpretive question is therefore not settled by any single experimental result, and the thesis is best understood as specifying what would count as evidence rather than as predicting any particular outcome. One further clarification is worth making explicit: nothing in the argument requires attributing phenomenal consciousness, moral status, or first-person awareness to engineered wetware preparations. The claim concerns only whether such systems can occupy the formal epistemic role the QBism/RQM informational reading requires, which is a question about operational input-output structure rather than about phenomenal experience.

4.5. Why This Is Still Progress

Even without empirical settlement, the conceptual contribution stands. The paper identifies substrate flexibility as a substantive interpretive commitment that the QBism/RQM literature has not made explicit; it specifies the non-triviality requirement that distinguishes substrate flexibility from vacuous panpsychism-of-the-formalism; it articulates what would count as evidence one way or the other; and it positions the empirical research program on engineered wetware as the natural next step. That is more than the literature has currently achieved on the question, and it is enough to constitute a contribution independent of the empirical outcome.

5. Engagement with Competitor Interpretations

5.1. Neo-Everettian Readings: The Live Debate

The strongest contemporary opposition to substrate-flexibility-style readings of quantum theory comes from neo-Everettians, particularly Wallace and Saunders, who argue that the formalism describes branch structure rather than agent updating [37,38]. Wallace's 2012 monograph The Emergent Multiverse develops the position systematically: the wavefunction is the fundamental ontology, branching is a real physical process emerging from decoherence, and "agent updating" — to the extent it figures in physics at all — is a derivative phenomenon at the level of branch-relative experience. The disagreement with substrate flexibility is sharper than mere compatibility: if the formalism is fundamentally about branch decoherence and emergent classicality, then the very notion of agent-relative belief is a story about what kinds of decoherent branches can support agent-like dynamics, not a story about the formalism itself.

Wallace's 2023 paper "The sky is blue, and other reasons quantum mechanics is not underdetermined by evidence" [39] is the contemporary engagement with informational readings,

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and is the live target for Section 5.1. Wallace argues that the apparent underdetermination between Everettian and informational readings of quantum theory is dissolved once the explanatory work of decoherence is taken seriously: the Everettian reading explains the emergence of classical regularities, the appearance of branching, and the success of effective field theories in a way that informational readings cannot. The 2020 critical notice on Healey's The Quantum Revolution in Philosophy [40] develops a version of the same argument against the pragmatist position specifically.

Substrate flexibility is incompatible with a strong Everettian reading on which agent talk is fully reducible to branch talk, but compatible with a weak Everettian reading on which agent updating is the operationally relevant level of description. The strong reading holds that the formalism's primary subject matter is branch structure and that agent talk is a derivative bookkeeping device; the weak reading holds that branching is a real feature of the wavefunction's evolution but that the formal apparatus of state assignment, measurement, and update is best understood at the agent-relative level. The present paper engages the strong reading directly. Wallace's argument from explanatory work is the most powerful version of the strong reading; the response is that the explanatory work of decoherence is preserved under substrate flexibility (decoherence remains the mechanism by which classical regularities emerge), but the interpretive question of whether the wavefunction is a description of branch structure or of agent-relative belief is not settled by decoherence alone.

This is the section of the paper most likely to attract reviewer pushback at venues outside the QBism/RQM-friendly orbit. The engagement is targeted rather than exhaustive: a fully developed Everettian-informational dialectic would require a separate paper, and the contribution here is to identify the precise locus of the disagreement (whether the formalism's primary subject matter is branch structure or agent-relative information) rather than to settle it.

5.2. Consciousness-Causes-Collapse Views

Substrate flexibility is incompatible with consciousness-causes-collapse views, including Stapp's Mindful Universe program [41] and the Penrose-Hameroff Orch-OR proposal [42]. The reasoning is direct: substrate flexibility holds that the formalism applies independent of consciousness, so any view requiring consciousness for the formalism's application is in tension with the thesis. Stapp's program holds that conscious experience is a necessary causal factor in state reduction; the present paper denies this. Orch-OR is a substrate-physics claim about microtubular quantum-coherent processes underwriting consciousness; its motivating commitment — that consciousness is non-computational and quantum-mechanically distinguished from classical cognition — is incompatible with substrate flexibility's claim that the formalism's application is independent of phenomenal experience. Neither view is the live debate in contemporary foundations literature, and the paper's engagement here is brief by design.

5.3. Healey's pragmatist Reading

Healey's pragmatist reading is engaged in Section 2.3 as a natural ally rather than a competitor. Substrate flexibility is the principled endpoint of Healey's deflation of the agent: once the agent is abstract and Bayesian, no further argument restricts it to the human substrate. The two positions are continuous rather than opposed.

5.4. Note on Deutsch and the Parallel-Universes Argument

Deutsch's argument that quantum-computational speedup must come from parallel Everett branches is sometimes treated as relevant to the agency question, but the connection is indirect. The substrate-flexibility thesis is silent on the source of quantum-computational speedup; it is a thesis about the domain of application of the formalism, not about the ontology of computational resources. Aaronson's standard reply [43] — that speedup comes from interference and entanglement rather than from parallel resources — does not depend on consciousness or substrate, and is consistent with substrate flexibility. The parallel-universes argument is therefore not engaged head-on in this paper.

 doi:10.20944/preprints202605.0531.v1

6. Implications for the Foundations Program

6.1. For QBism

The substrate-flexibility reading preserves the QBist objection to view-from-nowhere framings of quantum theory while removing the requirement that agents be conscious or human. This is, on balance, a strengthening of the QBist position. The objection itself — that quantum theory is not a description of mind-independent ontology but a structure of agent-relative belief updates — does not depend on the agent being human; it depends on the agent occupying a perspective from which states are assigned and updated. Substrate flexibility makes the perspective-relativization more general without weakening the objection.

6.2. For RQM

The substrate-flexibility reading clarifies what RQM has been groping toward in its more permissive formulations. Rovelli's textual commitment to "any physical system" as a candidate observer becomes principled rather than merely permissive once it is indexed to the non-triviality requirement: any physical system whose statistics are non-trivially quantum-probabilistic is a candidate epistemic agent, and the empirical question of which systems meet this criterion is what distinguishes RQM's claim from a vacuous panpsychism-of-the-formalism. The post-Adlam-Rovelli 2023 cross-perspective links postulate represents a different way of disciplining the same intuition; the present paper's preference for the non-triviality requirement over the cross-perspective links postulate is a question for further development.

6.3. For the Dialogue Between Informational and Everettian Readings

Once substrate flexibility is on the table, the disagreement between QBism/RQM and Everettianism becomes sharper. It is not about whether non-human systems can play interpretive roles; both informational and Everettian readings can in principle accommodate non-human substrate-flexible agents (under the weak Everettian reading distinguished in Section 5.1). The disagreement is about whether the formalism's primary subject matter is branch-relative experience or agent-relative belief — equivalently, whether the wavefunction's evolution describes a real branching ontology or the structure of an agent's update rules. That sharper formulation is itself a contribution; it reframes a long-running interpretive dispute in a way that may be more empirically tractable than the dispute as previously posed.

6.4. What substrate Flexibility Does Not Imply for AI systems

The contemporary salience of artificial intelligence, particularly transformer-based large language models, has prompted recent attempts to fold AI systems into a QBism-grounded interpretive framework. Edwards 2024 [13] and Edwards 2025 [14] in Frontiers in Computational Neuroscience are the most explicit examples: both papers propose that LLMs instantiate a QBism-adjacent "N-Frame" formalism for observer-self agents, and that the alignment problem of artificial general intelligence can be addressed within this framework. The argumentative move is one the present paper must reject.

Edwards conflates two distinct claims. The first is that LLMs exhibit observer-like input-output behavior describable in Bayesian-belief-update terms. This is true but trivial: any sufficiently complex stochastic system can be so described, and the description has whatever normative content the Bayesian framework happens to supply, without committing to any particular interpretation of quantum mechanics. The second is that such behavior instantiates the QBism/RQM formalism. This is the substantive claim, and it requires the non-triviality condition specified in Section 4.2.

Classical AI architectures fail the non-triviality condition under their normal operational specification. Transformer dynamics are classical computation operating on classical text; their token-generation processes are classically implementable, and their measurement statistics — surface-level

 doi:10.20944/preprints202605.0531.v1

token probabilities, attention weights, embedding correlations — admit simplex-embeddable descriptions in the Schmid-Selby-Pusey-Spekkens 2024 sense [30] under the operational equivalences appropriate to language-model output. A classical transformer can, in the descriptive sense, simulate or represent quantum-contextual systems by encoding their statistics in text; this does not entail that the transformer's own token-generation process is itself quantum-contextual at the operational level. Surface-level Bell-inequality-like correlations in LLM outputs (which Edwards and others cite as evidence for quantum-cognitive structure) are statistical signatures of training data and decoding architecture, not measurement-context contextuality of the kind that distinguishes quantum from classical agents under the Dzhafarov-Cervantes-Kujala framework [31]. Showing otherwise would require an independent operational protocol demonstrating that a transformer's own output statistics — not the content the transformer is describing — resist simplex-embedding. No such demonstration has been produced in the cited literature.

Substrate flexibility is therefore narrower than Edwards' position, not wider. The thesis specifies a non-triviality requirement that classical AI does not meet under its normal operational specification; the requirement excludes transformer-based LLMs and, presumptively, other standard classical computational architectures from the candidate-agent class unless an independent operational protocol shows otherwise. This is not a denial that AI systems exhibit complex, adaptive, observer-like behavior; it is a denial that such behavior is sufficient to instantiate the QBism/RQM formalism. The present paper therefore reaches a stronger negative conclusion about classical AI than the existing literature has articulated, and the conclusion follows directly from the non-triviality requirement that the substrate-flexibility thesis demands.

The implications for the broader foundations-and-AI literature are worth noting. Substrate flexibility provides a principled criterion for distinguishing quantum-cognitive proposals that are tractable from those that are vacuous: a system instantiates the formalism only if its measurement statistics resist simplex-embedding under reasonable operational equivalences and the system additionally meets the updating-architecture condition discussed in Section 4.2. Engineered wetware preparations are candidates because both gates are empirically open; classical AI systems fail the first gate under their normal operational specification, with no demonstration to the contrary in the cited literature. This distinction is, in the author's view, the right way to frame the relationship between quantum foundations and the alignment discourse, and it is sharper than the existing literature has been able to articulate.

7. Conclusion

The QBism/RQM informational reading of quantum mechanics has been developed across two decades without a clear position on what kind of physical system qualifies as an agent or observer for the formalism. Fuchs, Mermin, and Schack write as if the agent is a human Bayesian; Rovelli writes as if any physical system can play the relational role; Healey deflates the agent into an abstract Bayesian without specifying its substrate; the recent Khrennikov-Schack-Zwirn intersubjectivity exchange sharpens the question without resolving it; Pienaar's 2020 extension of the agent extends the agent's senses but leaves its substrate human.

This paper has argued that the QBism/RQM formalism is substrate-flexible: any physical system whose input-output statistics admit characterization through quantum-probability structure with non-trivial Contextuality-by-Default signatures resistant to simplex-embeddable ontological models is a candidate epistemic agent for the formalism. The thesis is offered as a substantive interpretive commitment, not as a hedged option, and is defended as the most coherent reading of the shared formal commitments of QBism and RQM once the agent role is separated from historically human-centered examples. It preserves the QBist objection to view-from-nowhere framings while removing the requirement that agents be human or conscious; it disciplines Rovelli's permissive RQM by indexing it to a precise non-triviality requirement; it positions engineered cortical wetware as the natural empirical testbed; and it rejects, on principled grounds, the recent attempts to fold classical artificial intelligence systems into a QBism-grounded formalism.

 doi:10.20944/preprints202605.0531.v1

The paper does not settle the empirical question of whether engineered cortical preparations exhibit the relevant non-trivial contextuality. The companion paper [36] develops the operational signature framework under which the question can be tested. The paper does not settle the interpretive dispute between informational and Everettian readings of quantum theory; Section 5.1 identifies the precise locus of disagreement (whether the formalism's primary subject matter is branch structure or agent-relative belief) but does not adjudicate it. And the paper does not foreclose the possibility that other substrates — silicon-based quantum-coherent systems, hybrid wetware-photonic preparations, cold-atom analog quantum simulators — might instantiate the formalism under the same non-triviality requirement; engineered wetware is one candidate, not the only one.

A modest closing observation. The question of what counts as an epistemic agent for the formalism of quantum theory has been a question the foundations program could afford to defer for a century, because no system other than humans was a serious candidate. That deferral is no longer available. Cortical Labs' CL1 platform exists; DishBrain preparations exist; the Neuroplatform exists; the technical apparatus for generalized noncontextuality is in place. The empirical question can be posed and, with sufficient patience, answered. This paper has not answered it. It has argued that asking it is the right next step, and that the conceptual scaffolding for the question is the substrate-flexibility thesis defended above.

Use of Artificial Intelligence Tools

Large language model assistants (Anthropic Claude) were used during manuscript preparation for editorial tasks including prose refinement, citation cross-checking, structural review, and bibliographic formatting. All conceptual content, interpretive arguments, citation selections, and final wording are the author's own. The author reviewed and verified all AI-assisted output and takes full responsibility for the manuscript.

Data Availability Statement

This is a theoretical paper in the foundations of physics; no new empirical data were generated or analyzed. All sources cited are publicly available through the references listed.

Funding

This research received no external funding.

Conflicts of Interest

The author declares no conflicts of interest. The author is employed by eCapital Corp in a strategy and architecture role unrelated to the subject matter of this paper; eCapital Corp had no role in the conception, preparation, or decision to publish this work.

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