# Foundations of Physics 2026
# June 16-18
# Irvine, CA
# Book of Abstracts

## Keynotes Ordered by Date
## Contributed Papers Alphabetical by Presenting Author Surname

# Keynotes

## Emergence and Generalization in Machine Learning

Nigel Goldenfeld

University of California, San Diego, USA

### Abstract

I present some brief remarks about emergence from a physicist's perspective, emphasizing the often overlooked feature of generalized rigidity. Then, I discuss the role of emergence in understanding the remarkable ability of modern neural networks to generalize. The performance on generalization improves with increasing network capacity, even when the number of model parameters or effective degrees of freedom exceeds the number of training data points. I show how this phenomenon is an example of emergent behavior, and specifically calculate the surprising phase transition behavior, emergent rigidity, universal scaling theory and the specific features that give rise to the good generalization performance of modern neural networks.

## Epistemology Quantized

Laura Ruetsche

University of Michigan, Ann Arbor, USA

### Abstract

I present some brief remarks about emergence from a physicist's perspective, emphasizing the often overlooked feature of generalized rigidity. Then, I discuss the role of emergence in understanding the remarkable ability of modern neural networks to generalize. The performance on generalization improves with increasing network capacity, even when the number of model parameters or effective degrees of freedom exceeds the number of training data points. I show how this phenomenon is an example of emergent behavior, and specifically calculate the surprising phase transition behavior, emergent rigidity, universal scaling theory and the specific features that give rise to the good generalization performance of modern neural networks.

# Contributed Talks

## The Explanatory Role of Entanglement Wedge Reconstruction in the Black Hole Information Loss Paradox

Jonathan Bain

New York University, New York City, USA

### Abstract

This talk addresses a puzzle associated with a proposal (Penington 2020, Almheiri et al. 2019) that claims to resolve the black hole information loss paradox. The proposal consists of two parts: The first part uses the RT formula from the AdS/CFT correspondence to derive the Page curve for the entanglement entropy of the Hawking radiation emitted by an evaporating black hole, and this suggests that information is not lost. The second part appeals to another result from AdS/CFT, namely, entanglement wedge reconstruction (EWR), to explain how information escapes by becoming encoded in the radiation during the late stage of evaporation. The proposal insists that both parts are necessary to resolve the paradox. This is puzzling since one can show that the RT formula is equivalent to EWR (Harlow 2017). That is, if the RT formula holds as a relation between the bulk and the boundary in AdS/CFT, then so does EWR, and vice-versa. Thus, one would think, if EWR explains information escape, so too should the RT formula. I indicate how this puzzle can be addressed by keeping track of different versions of the paradox, and by considering the types of explanation of information escape that EWR and the RT formula might be said to provide.

I first set the stage with reviews of what Wallace (2020) calls the Page time and firewall paradoxes, and the derivation of the Page curve using the RT formula. I then review EWR and how it is supposed to resolve the Page time and firewall paradoxes. Here I consider the suggestion that EWR provides a microphysical explanation of information escape that the RT formula by itself does not provide (Cinti & Sanchioni 2024). I then review Harlow's (2017) proof of the equivalence between EWR and the RT formula, which suggests that anything EWR can explain, the RT formula can explain, too. My conclusion is that EWR does indeed provide an explanation of information escape and how the information loss paradox can be resolved (in either its Page time or firewall versions). But so, too, and to the same extent, does the derivation of the Page curve using the RT formula.

Almheiri, A., N. Engelhardt, D. Marolf, & H. Maxfield (2019) 'The Entropy of Bulk Quantum Fields and the Entanglement Wedge of an Evaporating Black Hole', *JHEP 12*, 063.

Cinti, E. & M. Sanchioni (2024) 'Beyond the Quantum Membrane Paradigm: A Philosophical Analysis of the Structure of Black Holes in Full QG', *Found Phys 54: 27*.

Harlow, D. (2017) 'The Ryu-Takayanagi Formula from Quantum Error Correction', *Comm Math Phys 354*, 865-912.

Penington, G. (2020) 'Entanglement Wedge Reconstruction and the Information Paradox', *JHEP 09*, 002.

Wallace, D. (2020) 'Why Black Hole Information Loss is Paradoxical', in Huggett, N., K. Matsubara, C. Wüthrich (eds.) *Beyond Spacetime: The Foundations of Quantum Gravity*, Cambridge Univ. Press, 209-236

## Tomographically Non-Local Entanglement

Roberto D Baldijao[1,2], Marco Erba[2], David Schmid[1], John H. Selby[2,3], Ana Belen Sainz[2,3,4]

[1]Perimeter Institute, Waterloo, Canada. [2]ICTQT, Gdansk, Poland. [3]OIST, Onna, Japan. [4]Basic Research Community for Physics, Berlin, Germany

### Abstract

Entanglement is widely regarded as a defining feature of quantum theory. Yet many foundational and information-theoretic results implicitly rely on an additional structural assumption: *tomographic locality*, the principle that global states are fully characterized by local measurement statistics. While standard ("bare") quantum theory satisfies this property, it generally fails once superselection rules or symmetry constraints are imposed. If such constraints are fundamental—as has been debated in the context of fermionic systems and other symmetry-restricted settings—then tomographic locality itself may not hold in nature.

In this work, we investigate the structure of entanglement in theories that violate tomographic locality, within the framework of generalized probabilistic theories. We show that the failure of tomographic locality leads to a sharp and previously unrecognized distinction between two qualitatively different forms of entanglement: *tomographically-local*entanglement, which is visible to local measurements, and *tomographically-nonlocal* entanglement, which resides entirely in holistic degrees of freedom inaccessible to local tomography.

This distinction resolves several longstanding puzzles when tomographic locality fails. In theories such as real quantum theory and fermionic quantum theory, one encounters striking phenomena—including locally broadcastable entangled states and violations of entanglement monogamy— for states that are not separable, which appears paradoxical from the perspective of standard quantum information. We show that these features arise precisely when entanglement is purely tomographically nonlocal: the "quantum-like" (tomographically-local) component is absent.

Operationally, the two forms of entanglement exhibit radically different behavior. We prove that tomographically-nonlocal entanglement is useless for Bell nonlocality, steering, and teleportation—tasks traditionally associated with the power of entanglement. Nevertheless, it remains sufficient for dense coding and perfectly secure data hiding. This sharp separation clarifies which information-processing advantages truly rely on tomographic locality and which do not.

Beyond this characterization of information processing-tasks, our results give concrete weight to a fundamental question: is tomographic locality a contingent feature of our effective description of quantum systems, or a deep structural principle of nature? If superselection rules are fundamental, then the entanglement present in our world may contain genuinely holistic components invisible to local probes. Our framework provides the conceptual and mathematical tools needed to reassess quantum information protocols under such possibilities and to reformulate "no-go" theorems in a way that explicitly tracks which form of entanglement they assume.

By refining the conceptual structure of entanglement in tomographically nonlocal theories, this work clarifies previously puzzling features of entangled states, sharpens the distinction between the operational roles of the two forms of entanglement, and underscores the importance of determining whether superselection rules are fundamental—since different

answers entail different limits on the capabilities of quantum systems.

These results will be on a paper on Arxiv in the first days of the week 16th-21th of February, 2026 [4].

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[1] Jonathan Barrett, Information Processing in Generalized Probabilistic Theories, https://arxiv.org/abs/quant-ph/0508211
[2] Lucien Hardy, William Wooters, Limited Holism and Real-Vector-Space Quantum Theory, Found Phys 42, 454–473 (2012). https://doi.org/10.1007/s10701-011-9616-6;
[3] Giacomo D'Ariano, Franco Manessi, Paolo Perinotti, Alessandro Tosini, The Feynman problem and Fermionic entanglement: Fermionic theory versus qubit theory, International Journal of Modern Physics A 2014 29:17
[4] Roberto D Baldijao, Marco Erba, David Schmid, John H Selby, Ana Belen Sainz, Tomographically Non-Local Entanglement, to appear in Arxiv.

## How Indivisible Laws Can Save Quantum Theory and Explain the Tsirelson Bound

Jacob Barandes

Harvard University, Cambridge, USA

### Abstract

In quantum theory, the measurement problem refers to the manifest ambiguity over which form of time evolution to apply in a given situation: Type I evolution, which singles out a specific measurement outcome with an associated probability given by the Born rule, or Type II evolution, which is linear and features neither probabilities nor a specific measurement outcome. These two forms of time evolution are categorically different, and, at least in principle, empirically different, but the demarcation between them relies on the undefined notions of external observers and measurements.

The measurement problem is only the first of four serious problems that I will review in my talk. The second is what I call the category problem, and refers to the fact that even if there were a solution to the measurement problem, the textbook axioms do not appear to account for the presumably larger category of non-measurement phenomena that we think are happening all around us. The third is the ontology problem, which is just that the axioms appear to be committed only to the physical existence of external observers and measuring devices, and not, apparently, to anything else, including whatever makes up external observers and measuring devices. The fourth is what I call the mereology problem, which refers to a basic lack of mereological structure for the dynamical laws, and makes it difficult to understand why the theory works so well for subsystems of the universe.

Some approaches to the measurement problem, like the work of Bohm and Everett, try to extend Type II evolution, especially in its unitary form, across all of quantum theory, and attempt to derive Type I evolution as a special case. Other approaches, like GRW, allow for Type I evolution, applied directly to the mathematical quantum state, to be fundamental at least in some cases.

In my talk, I will review a different proposal, which takes all the dynamical laws of quantum theory to consist of stochastic laws for the basic degrees of freedom of systems, without mathematical quantum states serving as primary ingredients or intermediaries. One can obtain a remarkable simplification by allowing the dynamical laws to be non-Markovian in a suitably general sense, known as indivisibility. I will then explain why older approaches to solving the measurement problem may actually be generalizations of so-called hidden Markov models, which recast dynamical systems that are fundamentally non-Markovian in ways that look superficially Markovian.

After explaining how axiomatizing quantum theory in terms of indivisible stochastic processes can resolve the four basic problems described above, and presenting some recent progress on several outstanding challenges, I will show that the indivisible theory suggests a new definition for causal influences, as well as a new principle of causal locality. I will then show how the indivisible theory does real work by providing a transparent, first-principles derivation of the Tsirelson bound, which is the mysterious upper bound on the degree to which a quantum system can violate the Bell inequality.

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2. J. Barandes, M. Hasan, D. Kagan. “The CHSH Game, Tsirelson's Bound, and Causal Locality.” (2025). https://arXiv.org/abs/2512.18105.

3. J. Barandes. “Pilot-Wave Theories as Hidden Markov Models” (2026). https://philsci-archive.pitt.edu/28174/.

## The Distribution Postulate in Algorithmic Bohmian Mechanics

Jeffrey Barrett[1], Eddy Keming Chen[2], Josiah Lopez-Wild[1]

[1]UC Irvine, Irvine, USA. [2]UCSD, La Jolla, USA

### Abstract

Bohmian mechanics requires a special statistical boundary condition—the distribution postulate—but it is unclear how best to understand this condition. We show how one might use the theory of algorithmic randomness to formulate the distribution postulate as an objective algorithmic constraining law. The framework requires us to say something about admissible quantum-mechanical states and measurements. In return, algorithmic Bohmian mechanics predicts the standard Born statistics for computable experimental protocols with certainty in the limit.

We begin with a description of Bohmian mechanics and the distribution postulate, and then explain how the theory yields the standard quantum probabilistic predictions as forward-looking epistemic probabilities that result from uncertainty regarding the actual particle configuration. We briefly discuss the distribution postulate and its status as a law-like boundary condition that stipulates initial particle configurations. We then give an overview of algorithmic randomness and introduce the notion of a Martin-L"{o}f (ML) random sequence. We provide two concrete examples of how one might use the notion of an ML-random sequence to specify initial particle configurations in order to recover the correct quantum probabilities, and we then consider three problems with this approach.

In response to these problems, we show how one might characterize a Martin-L"{o}f random \textit{point} with respect to the standard quantum Born probability measure $|\psi(x)|^2$ on configuration space, and we introduce the notion of a layerwise computable function relative to a measure. The main result of the paper is that a $\mu_\psi$-layerwise computable sequence of measurements $f_n$ preserves algorithmic randomness by transforming a Martin-L"{o}f random initial configuration (with respect to the Born measure) into a sequence of Martin-L"{o}f random measurement outcomes in the corresponding push-forward measure, which respects the standard Born statistics.

Specifically, we show that if the initial configuration $x_0$ is Martin-L"{o}f random with respect to $\mu_\psi$, then the corresponding sequence of measurement outcomes $(f_1(x_0), f_2(x_0), \ldots)$ is Martin-L"{o}f random with respect to the push-forward joint measure $\mu_\omega$ induced by $\mu_\psi$ and the $\mu_\psi$-layerwise computable functions $f_n$.

On this framework, the algorithmic distribution postulate states simply that the actual initial configuration $x_0 \in X$ is Martin-L"{o}f random with respect to the Born measure $\mu_\psi$ at some initial time. This formulation provides a sharp typicality condition, clarifies the status of quantum probabilities in deterministic Bohmian mechanics, and offers a concrete example of how tools from algorithmic randomness can help to specify the content of a physical law.

Barrett, Jeffrey A. and Chen, Eddy Keming. (2025) “Algorithmic Randomness and Probabilistic Laws,” *The British Journal for the Philosophy of Science*, forthcoming. https://arxiv.org/abs/2303.01411

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## Aristotle on Relational Time

Francesca Battistoni

Urbino University Carlo Bo, Urbino, Italy

### Abstract

In the wake of the recent re-evaluation of Aristotle's physics by Monica Ugaglia (2004) and Carlo Rovelli (2015), this work aims to contribute to this "Aristotle renaissance" by restoring Aristotle's concept of time. In doing so, it seeks to engage with contemporary philosophical and physical debates on the ontology of time. Aristotle's notions of time and space are characterized by an intrinsic relationality that resonates with modern physical theories, notably Einstein's Special and General Relativity and quantum physics, especially Rovelli's theory of Loop Quantum Gravity. By re-examining Aristotelian physics, this study contributes to the ongoing dispute between substantivalist and relationalist approaches to time and spacetime.

The analysis begins with Aristotle's unresolved aporias concerning the reality of time. In *Physics*IV, Aristotle asks whether time belongs to what is or to what is not, and what its nature is (217b32), suggesting that time exists only "scarcely and dimly" (217b30–31). This hesitation has often been interpreted as an anti-realist stance. Aristotle does not directly resolve this aporia, but proceeds by examining the relation between time and change, defining time as "the number of change in respect of the before and after" (219b1). Time is not a substance but a number; it is continuous like motion and indefinitely divisible. Although Aristotle places time under the category of quantity, its status as a number and its dependence on change and enumeration invite an analysis in light of the category of relatives. This approach also requires addressing the aporia concerning the role of the soul that counts change.

In *Categories* 7, Aristotle defines relatives as entities that are what they are only in relation to something else (6a36–37). The philosophical difficulty lies in determining their ontological status, since Aristotle defines substance as that which is neither said of nor in a subject (2a12–13), seemingly excluding relatives from substantial being. Aristotle resolves this tension by redefining relatives as those entities whose being consists in being related to something else (8a32–34). Relatives are not substances but accidents, whose actuality depends on the actuality of their relata. They exist in a derivative and dependent way, as relations between existing entities.

By comparing the ontological status of relatives with that of time, this work proposes a solution to Aristotle's aporias. Time exists because change exists and because there is a soul capable of counting it. Like relatives, time possesses a local and relational mode of existence. Aristotle's theory of act and potency helps clarify how accidents and relations exist as actualizations in or between substances.

The relational structure at the core of Aristotle's concept of time allows for a meaningful dialogue with contemporary relational theories of time and spacetime. In Aristotle, General Relativity, and Loop Quantum Gravity alike, time is not a flowing substance but a relational structure: of change, of the geometric field, and of quantum interactions, respectively. Despite its limits, Aristotle's local and relational ontology of time offers valuable conceptual tools for understanding the nature of spacetime today and the structure of reality.

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# Utiyama's Theorem, Gauge Natural Lagrangians, and Gluons

India Bhalla-Ladd

University of California-Irvine, Department of Logic & Philosophy of Science, Irvine, USA

## Abstract

I present a defense of the idea that some matter fields are faithfully represented as sections of associated vector bundles, and some matter fields are faithfully represented as connections on a principal bundle, in the context of classical Yang-Mills theory. This analysis clarifies a conceptual question from Weatherall's Frame Interpretation (Weatherall (2016b), March and Weatherall (2025)), in which the conceptual significance of the principal bundle is tied to its associated vector bundles, in analogy with relationship between the frame bundle and the tangent bundle in General Relativity. Under the Frame Interpretation, we interpret sections of principal bundles as frame fields for associated vector bundles; how, then, should we interpret the free Yang-Mills theory? Under the received view, it is the associated gauge-natural vector bundles that represent matter, while the principal bundle plays a crucial coordinating role, but nonetheless does not represent matter or possible states of matter. I argue that nothing in the formalism prevents us from interpreting connections on a principal bundle as a type of physical matter field, and that the Generalized Utiyama Theorem offers a positive sense in which we should treat the connection as a physical field – namely that it acts uniquely as a non-trivial dynamical variable as a consequence of gauge-covariance. Ultimately, this is completely consistent with the Frame Interpretation: sections of principal bundles do not represent matter fields, but connections on them do.

I argue that this perspective helps clarify and defuse criticisms of the Frame Interpretation put forth by Jacobs (2023) and Gomes (2024a). In particular, I argue that both critics can be seen as motivated by a discomfort with interpreting the principal bundle in the absence of associated vector bundles. As a result, they seek out different mathematical structures both in emphasis and in kind than already present in the principal bundle formalism. I believe that this is a misguided strategy, and that the real issue comes from an impoverished "physical field" concept rather than any issue in the geometrical formalism.

I take the opposite strategy, and mine the existing formalism for positive reasons to consider expanding the "physical field" concept to connections on a principal bundle as well as associated vector bundles. Both admit gauge-natural descriptions, and enter non-trivially (and in some sense uniquely) into the gauge-natural Lagrangians that govern physical systems of interest. The generalized Utiyama Theorem (Kol´aˇr et al. (1993), Eck (1980)) and the machinery of gauge-natural Lagrangians helps make precise the sense in which the unique and non-trivial Yang-Mills field dynamics follows from gauge-covariance, a foundational commitment to what constituted a "physical field" that was implicit in the development of gauge theory and minimal coupling in 1970s theoretical particle physics.

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# Reverse Physics: turning physics inside out

Gabriele Carcassi, Christine Aidala

University of Michigan, Ann Arbor, USA

## Abstract

When the math is derived from the right physical assumptions, the physical assumptions can be derived from the math. This insight lies at the core of Reverse Physics [1], an approach to the foundations of physics that aims to dissect the mathematical structures of all physical theories to find exactly why they are needed and what they represent physically. We will present the general methodology and a series of interesting results in classical mechanics, quantum mechanics and statistical mechanics, which show how these share a lot more foundational aspects than is typically realized.

We will first present how Reverse Physics mimics approaches that have been very successful in the foundations of mathematics, including Reverse Mathematics [2]. We will see how the techniques are necessarily different in physics, as there will be a gap between the mathematical (i.e. formal) objects and the corresponding physical (i.e. informal) objects. However, one can find mathematical specifications that are close enough to the physical requirements that the gap can be bridged.

We will then present a series of results from our larger research program Assumptions of Physics [3], showcasing the power of Reverse Physics. We will give 12 different characterizations of classical Hamiltonian mechanics for one degree of freedom, linking concepts from vector calculus, differential geometry, statistics, information theory and thermodynamics, and showing the equivalence between Hamiltonian evolution and determinism and reversibility. We will do the same for quantum mechanics, showing how determinism and reversibility is equivalent to unitary evolution. This shows that physical assumptions can be more conceptually significant than their mathematical implementations as they can span across theories.

We will see how Lagrangian mechanics requires an additional assumption, while the principle of least action admits a purely Hamiltonian version that does not require such extra assumption. We will see how the Lagrangian is the line integral of the vector potential of the flow of states, and how the principle of least action is a simple application of Stokes' theorem. This shows that a tighter physical understanding of the mathematics can and must be achieved.

We will see that the space of statistical mixtures and entropy play foundational roles in mechanics. We will show that giving the state space of a physical theory without the space of possible statistical mixtures is not enough to define a physical theory. We will see how a lower bound on the entropy imposes an uncertainty principle in classical mechanics, that the geometric structures of both classical and quantum mechanics are equivalent to the definition of their respective entropy, that classical mechanics is the high-entropy limit of quantum mechanics and, conversely, quantization means putting an entropic lower bound on a classical theory. This shows that statistical mechanics and the corresponding standard mechanics cannot be understood as separate theories.

The overall goal of the presentation is to show how Reverse Physics enables a broader, deeper and more intuitive understanding of the foundation of physical theories.

[1] G. Carcassi and C.A. Aidala - Reverse Physics: From Laws to Physical Assumptions. Found Phys 52, 40 (2022).
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## Charge Confinement: A Test Case for Small-Scale Skepticism in Quantum Field Theory

Kade Cicchella, Feintzeig Benjamin

University of Washington, Seattle, USA

### Abstract

**Abstract**

A number of philosophers of physics (Wallace, 2011; Williams, 2018; Fraser, 2018) have argued that we ought to be skeptical of the small (distance)-scale features of quantum field theory (QFT), either because we have reason to expect that QFT fails at small scales or because those small-scale features are irrelevant to the success of QFT models. In this paper, we argue against this general skepticism of the small-scale features of QFT. We defend this view by illustrating how certain small-scale features of quantum chromodynamics (QCD), our best theory of quarks and the strong interaction, are relevant to its success.

One of QCD's most notable successes is its agreement with the empirical result of *color charge confinement*, i.e., that no states with non-neutral color charge can exist. In particular, color charge confinement implies that individual quarks can never be isolated at large distance scales. We claim that QCD relies on features of an arbitrarily small scale in order to provide an explanation of color charge confinement. Following Buchholz (1996), we understand a QFT model as displaying confinement if it both lacks charged states at large distances and has charged states in its small-distance scaling limit (Buchholz and Verch, 1995). As such, confinement is essentially a *cross-scale* phenomenon.

Since we don't yet have a mathematically rigorous model of QCD, we present our argument against small-scale skepticism using the Schwinger model, which is a mathematically rigorous formulation of quantum electrodynamics in two spacetime dimensions and is a popular toy model for confinement. We show how confinement in the Schwinger model can be understood as an approximative relationship between the large-scale theory, which is equivalent to a massive free theory and lacks charged states, and its small-distance scaling limit, which is equivalent to a massless free theory and has charged states. This demonstrates that we need to take account of both large- and small-scale features in order to understand confinement in the Schwinger model.

Small-scale skepticism is one half of a view known as *effective realism*, whose advocates (Williams, 2018; Fraser, 2018) recommend that we take seriously the large-scale features of QFT, in addition to being skeptical about its small-scale features. While we agree with some of the lessons that effective realists have drawn about large scales, we believe that their position misses out on the importance of inter-scale relations, especially for understanding features like confinement. We believe that further investigation into confinement and inter-scale relations is needed and we urge philosophers to attend to the associated mathematical details and conceptual implications.

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## Conceptual Foundations of Gravity with Torsion

Aaron Collavini

University of Udine, Udine, Italy. University of Geneva, Geneva, Switzerland

### Abstract

Among the various modifications of the geometry of space-time, torsion arguably represents the smallest structural departure, since it merely quantifies the asymmetry of the connection coefficients of the affine structure. A manifold endowed with a metric compatible with such an affine structure is usually referred to as an Einstein–Cartan space-time, in which torsion is sourced by spin density in a way analogous to how energy–momentum sources the gravitational field (Hammond 2002; Hehl et al. 1976). However, the conceptual simplicity with which general relativity is usually understood – for instance, the postulate of a unique family of geodesics followed by free particles – is completely lost in theories with torsion. What is surprising is not merely that autoparallel and extremal curves no longer coincide, but rather that particles are expected to follow different trajectories which, in most cases, are neither autoparallel nor extremal. If correct, this feature would seriously undermine the Machian framework within which Einstein developed general relativity, according to which there is an action–reaction relation between matter and space-time, whereby the latter determines the space-time paths of free particles (Brown, 2005).

In this talk, I investigate the foundations of theories with torsion by addressing the question of how torsion should be interpreted in the first place. Such question remains unclear throughout much of the physics literature on modified theories of gravity. On the one hand, torsion admits a well-defined geometrical characterization, being associated with the failure of closure of infinitesimal parallelograms. On the other hand, torsion is often treated as an independent matter field, which may be related to spin density either algebraically (as in Cartan's original formulation) or dynamically. This situation exemplifies the space-time/matter dichotomy discussed, for instance, by Martens and Lehmkuhl (2020), raising doubts about which criteria are required for an entity to be regarded as space-time – given that both the weak geodesic and the chronogeometricity criteria would cease to apply – or as matter, and as whether torsion should be regarded as an aspect comprising both the ontological categories. Moreover, several foundational aspects of general relativity are called into question in theories with torsion: for example, it is no longer straightforward to determine which stress–energy tensor should be regarded as fundamental – namely, the canonical or the metric one – nor how the equivalence principles ought to be extended to Einstein–Cartan space-time (Di Casola et al. 2015).

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## To Beable, or Not to Beable?

Elise Crull

CUNY: City College, New York, USA. CUNY: Graduate Center, New York, USA

### Abstract

A recent trend in philosophy of quantum mechanics takes the central (even sole) aim of realist interpretations to be the delivery of an ontology in terms of local beables. This is, however, just one possible precisification of a more general desideratum: that realist interpretations deliver explanations for the *appearance* of local beables. It is a separate, nontrivial step to insist that local beables be creatures of an ontic sort, thus it is a mistake to conflate the two endeavors. While the latter, more general project is commonsense (for what good is a realist interpretation if it fails to provide any account of quantum-to-classical transitions?) there are excellent reasons to rebel against the trend of confining ourselves to the former, narrower project. It is certainly questionable to go a step further still, as is often done, and demand that local beables not only appear in one's ontology but serve as primitives in it.

What countenances such a methodological stranglehold? Bell himself was more permissive: in the 1976 paper where he first coins the term "beable'' and calls for a (quantum) theory of local beables, he is careful to admit that "we may be obliged to develop theories in which there are no strictly local beables." Nevertheless, he continues: "[t]hat possibility will not be considered here" [1]. It will be considered *here*, and the conclusion will not be favorable to friends of local beables.

Some arguments against the "local beables or bust" trend have already been developed, notably by Ney in chapter 5 of [2]. In this talk my goal is twofold: to strengthen extant arguments and to introduce a few of my own. I accomplish the first goal by liberating Ney's arguments from their specific interpretive context – motivating wavefunction realism – thereby broadening their scope to include any realist framework. For the second goal I draw upon recent results in quantum Darwinism [3-5] to make more precise (e.g. using first-pass quantitative results obtained via numerical analysis on common models, like many-body systems in weak-coupling regimes – a model of extreme relevance for quantum computing) claims about the role of decoherence in the emergence of a unique pointer basis, ergo the measurement outcome as an approximate eigenstate in that basis. In quantum Darwinism, the identification of a preferred basis for a given system is shown to be not only possible but nigh trivial via the process of system-environment decoherence: decoherence allows leaked information about system observables to be recorded in the environment with such high redundancy that sampling a very small subspace of the total environment will yield sufficient information for determining a unique pointer basis for the initial system.

Success with respect to both goals will strongly counterindicate Bell-inspired quantum ontologies. In other words: we may not be able to find local beables.

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## Decoherent Histories Contextuality

Thomas De Saegher

University of Western Ontario, London, Canada

### Abstract

A consistent set of histories for a system is a set of histories where the probability assigned by a given quantum state of the system to a sum of histories (history operators) is equal to the sum of the probabilities assigned to the individual histories (each operator) by the given state. Abstract consistency alone admits multiple incompatible consistent sets of histories for the same initial state and Hamiltonian, where 'incompatibility' in this context means that the sets support conflicting probabilistic inferences. However, this predicament is also faced by any unitary quantum theory describing decoherence with respect to some system/environment split, and not just by the imposition of abstract consistency in isolation. While decoherence always occurs in an approximately unique basis, the final global state resulting from this decoherent evolution can always be rewritten *as if it had* branched along some other, incompatible, consistent set of histories. A quasi-classical realm is a set of decoherent histories where the initial state remains sharply peaked around one history in which dynamical variables approximately follow their classical equations of motion. The requirement of 'quasi-classicality' does not necessarily select a unique set or a set of decoherent histories recorded in the environment with the possibility of being measured. Why, then, do measurers of different subsystems of the universe in a final state, which could be expressed in terms of different sets of branching histories corresponding to incompatible quasi-classical realms, always agree on the realm that they are in? I will argue that they agree only because one of three scenarios always occurs: 1) the incompatible realms are recorded at different length-scales on overlapping spatial regions and communication between the regions would amount to measuring the regions in incompatible bases simultaneously, 2) the records of measurement outcomes for incompatible quasi-classical realms occur on different pure states in some global mixture of the universe, or 3) they measure subregions of an environment in a mixed state that fails to record one quasi-classical realm over another. The decoherent histories formalism seems to describe Bell-Kochen-Specker measurement contextuality persisting into the classical limit. By which I mean that the formalism allows that the probability of an outcome common to two different measurements, conditional on the measurement choice and an ontic state, can differ even for measurements of *pointer observables* (such as dial position). However, we never experience this contextuality, and I explain why by arguing that there will always be agreement on the quasi-classical realm between different observers due to one of the above three scenarios.

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## The Adequacy of Quantum Foundational Experiments on Surrealistic Trajectories and Anomalous Particle Presence

Jan Dziewior

Faculty of Physics, Ludwig-Maximilians-University,, Munich, Germany. Max-Planck-Institute of Quantum Optics, Garching, Germany. Munich Center for Mathematical Philosophy, Munich, Germany

### Abstract

In physics all experiments are not made equal. This does not only concern their empirical domains and technical methods, but crucially also their methodological function in relation to physical theories [1]. In particular, the roles of experiments are not exhausted by “testing theories”, i.e., comparing data with theoretical predictions, or “exploring new physics”, i.e., finding novel empirical data not yet explained or treated by any theory. This contribution analyzes two comparatively recent examples of experiments which do not fit the above characterizations, while arguably still being relevant in foundational debates.

The first example is a reconstruction of Bohmian trajectories in an optical double-slit setup by Mahler *et al.* [2], which, according to the Bohmian interpretation, involves non-local effects. The second is a study by this contribution’s author and collaborators [3], showing the universality of the modification of local weak interactions, which, according to Vaidman’s weak trace approach, represents an instance of anomalously large particle presence. The essential characteristic of these experiments is that the consistency of the results with theoretical predictions is taken for granted and merely a prerequisite for the experiment to fulfill its true purpose, which is to bring about the results in a special scenario, thus illustrating certain counter-intuitive features of quantum mechanics. Their merit appears to rest on the coexistence of empirically fully equivalent but theoretically inequivalent theories or interpretations. In the two examples the special scenario consists in a particular spatio-temporal distribution of experimental events, which obtains a distinguished significance in the context of the respective theories.

If such “illustration” experiments cannot fail in terms of empirical data, then how can their merit be evaluated? The criterion has to be, how well the special conditions are realized. Arguably both examples presented here succeed at best only partially and run the danger of being mere analog quantum simulations of the actual experiments of interest.

The experiment by Mahler *et al.* aimed to realize the scenario of so-called “surrealistic trajectories” in which the result indicated by a which-path measurement device appears to be inconsistent with the Bohmian particle trajectories. The crucial condition is that the readout of the which-path information is delayed until the particle finishes traversing the interference region behind the double-slit. Although this is not achieved, nevertheless the formal and empirical equivalence of the actual scenario allows to reconstruct the surrealistic trajectories.

The experiment by the author and collaborators aimed at implementing the simultaneous local coupling of a pre- and postselected systems to several

external systems. According to Vaidman's criterion, the similar modification of the effective couplings (dependent on the choice of pre- and postselection) allows to conceive of a modified "presence" of the particle. Also in this case the crucial spatio-temporal condition of local coupling to external systems was not achieved, since other degrees of freedom of the system itself were employed as pointer systems.

For both examples the critical analysis of their shortcomings fortunately points towards potential future improved versions.

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## Diagnosing Underdetermination in Quantum Mechanics, and Proposing a New Way Forward

Anand Ekbote

The Ohio State University, Columbus, OH, USA

### Abstract

**Thesis:** The persistent underdetermination situation in quantum mechanics is a serious challenge for scientific realism. I diagnose the problem, and claim that the impasse is tied to a lack of an appropriate epistemic principle which would indicate either how to choose among rival theories, or identify any deficiencies across rivals which are preventing choice. I propose such a principle.

**Diagnosis:** Scientific realists have used two main approaches to address the challenge. The first seeks to dissolve the underdetermination by either claiming explanatory superiority of one theory over others (following Laudan 1991), or by appealing to non-empirical virtues (Callender 2020). The second approach seeks to protect scientific realism by arguing for quarantining quantum mechanics (Hoefer 2020), or by finding some common core across rival theories (Cordero 2001, Egg 2021). The explanatory approach does not succeed because of a lack of a neutral criterion which can evaluate competing explanations. Realists want criteria used for theory choice to track truth, and there is no compelling reason to believe that non-empirical virtues do so. Strategies to protect scientific realism lead to unsatisfactory fragmented ontologies. I claim that a suitable epistemic principle which can evaluate explanatory power of theories will negate the need for use of non-empirical virtues and for defensive strategies.

**Proposal:** I propose the Phenomena & Appearance from Reality Criterion (PARC) which requires that a theory fulfill the following conditions:

- C1: Its core posits and postulates should refer to, or represent physical objects (entities, properties, processes, structures).
- C2: It should provide explanation, causal or non-causal, as to how the postulated physical objects lead to observations in the theory's domain.
- C3: It should lead to scientific understanding, demonstrated by the *ability* to properly respond to counterfactuals about posited objects and background information (Woodward 2006).

C1 fulfills the truth-tracking desideratum. C2 enables the right kind of nexus between the posits and observations, and C3 provides the requisite discriminatory power. Woodward (2018) argues that his counterfactuals thesis works for non-causal dependencies too. PARC takes no recourse to non-empirical virtues. PARC builds on van Fraassen's (2008) Appearance from Reality criterion, which requires a theory to produce, in the right way, observations and appearances from the theory's (unobservable) posits and postulates. As an example, van Fraassen cites how the Copernican theory produces the appearance of retrograde motion of planets from its core postulates (but could not explain the appearance of a stationary earth for 75 years until Galileo's theory of inertial dynamics). PARC strengthens truth-tracking by including phenomena, admits a broader range of explanation, and builds discriminatory power by incorporating understanding via counterfactuals.

I test the resulting criterion for proof of concept in a known historical case of underdetermination of planetary motion in the seventeenth century, and show that PARC

successfully delivers on the desiderata. While analysis of current rivals in quantum mechanics vis-à-vis the criterion is beyond the scope of the paper, pending such an analysis I show how PARC makes recommendations for Wallace's (2012) *spacetime state realism*, in which Wallace argues how physical properties in regions of spacetime could connect to mathematical objects (quantum state and operators) in Hilbert space. Wallace provides an analogy of an electromagnetic field, which assigns a number or vector (mathematical object) to every point in space. This intuition may suffice for Wallace's purpose to provide an account of locality in Everettian many-worlds. I show that PARC requires a deeper exegesis of how mathematical objects such as quantum states and operators in Hilbert space relate to physical properties in space and time to produce observed predictions of quantum mechanics, leading to a counterfactuals-based understanding.

*Brief Bibliography*


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## Whence the desire to close the universe?

Jonathan Fay[1], Antonis Antoniou[2]

[1]University of Bristol, Bristol, United Kingdom. [2]National and Kapodistrian University of Athens, Athens, Greece

### Abstract

Recent scholarship, especially de Swart (2020), has shown that cosmologists in the 1970s and 1980s often favoured flat or closed cosmological models for essentially non-experimental reasons, a prejudice that helped shape attitudes toward dark matter in this period. Some of these preferences were motivated by appeals to Mach's principle. Since previous scholarship has tended to conflate arguments grounded in Mach's principle, I will closely examine and disentangle two Machian arguments for particular cosmic geometries, one favouring a closed universe and the other favouring the flat Einstein–de Sitter model. In both cases, I will assesses their historical roots, philosophical motivations, and scientific legitimacy.

The first case concerns the long-standing argument for a closed universe—popularised in the *renaissance* period by John Wheeler—which was rooted in Einstein's attempt to eliminate boundary conditions in general relativity on Machian grounds. Drawing on a close reading of Wheeler's early *relativity notebooks* and responding to questions raised by Blum and Brill (2020), I show that Wheeler's views were substantially influenced by Hermann Weyl's (1924) dialogue *Massenträgheit und Kosmos* despite Weyl's explicit objections to the argument for closure. I argue that the Einstein–Wheeler case for closure relied on assumptions drawn from pre-expansion cosmology that fail to carry over to the modern context, yet persisted due to their superficial philosophical appeal.

The second case examines a lesser-known argument for a flat universe associated with Dennis Sciama, as well as Hermann Bondi. This argument derives from a Machian interpretation of frame-dragging effects in general relativity, according to which inertial forces in rotating frames should be identified with gravitational effects generated by cosmic matter. In linearised models, this leads to a constraint requiring the quantity $G\rho\tau^2$ to remain constant over cosmological evolution, a condition uniquely satisfied by the Einstein–de Sitter model among FLRW cosmologies. I show that while Sciama's early work on a linearised model (Sciama, 1953) attracted some interest in this line of reasoning, later attempts to extend it to the full non-linear theory using Green's function-based methods failed to produce any useful results, leading to the dissolution of Sciama's Machian programme. In this case the programme failed to carry over assumptions rooted in classical conceptions of spacetime to the relativistic domain, however questions remain concerning whether the programme may be salvaged in the context of speculative theories of quantum gravity.

Although both arguments claimed to derive from Mach's principle, we show that they differed wildly in their methodology and the context in which they were developed. More generally, this study illustrates how, despite their eventual failure, philosophical speculations concerning Mach's principle not only motivated the initial development of general relativity by Einstein, but continued to be influential both by generating interest and influencing the parameters of research well into the *renaissance* period of the 1960s-70s, at a time when the reputation of cosmology began shifting to that of a precision, empirical science.

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## Non-Uniqueness of the Q-based Interpretation of Quantum Mechanics

Benjamin Feintzeig, William DeWitt

University of Washington, Seattle, USA

### Abstract

In recent work, Friederich (2024, 2026) presents what he claims is a new Q-based interpretation of quantum mechanics. The name comes from the Husimi function, denoted Q, which is a phase space distribution arising from Berezin quantization. Friederich writes that "the core idea behind the Q-based interpretation [...] is simply to interpret the Q-function Q(q, p) as a proper probability distribution on phase space" (Friederich, 2024, p. 769). Friederich suggests that understanding the Q-function is sufficient for specifying a full interpretation of quantum mechanics, and for drawing foundational conclusions. Our goal is to demonstrate that this way of describing the model is at least misleading: the use of the Q-function as a probability distribution is not sufficient to provide an interpretation of quantum mechanics. In some places, Friederich is more precise and attributes the model extra structure beyond just that of the Q-function, but in others he commits the error of reasoning directly from the Q-function to foundational conclusions.

We argue that insofar as the Q-function leads to a new interpretation at all, it does so *only through the specification of a microdynamics* underlying the bulk evolution of the Q-function. In some passages, Friederich acknowledges the need for a microdynamics to complete the Q-based interpretation. But where he does so, he speaks of "the" microdynamics as if it is determined directly from the dynamics of the Q-function. We show to the contrary that the microdynamics giving rise to this bulk evolution of the Q-function is *non-unique*. While Friederich points to only one microdynamics from Drummond (2021) (See also Drummond and Reid (2020)), we construct *two* further sets of microdynamical equations that reproduce precisely the same bulk Q-function evolution by drawing on results from (DeWitt and Feintzeig, 2026). In short, there is no such thing as "the" Q-based interpretation; rather, there are many distinct interpretations for which the Q-function serves as a stepping stone.

Our results illustrate a general trade-off between the distinct pieces of data one can employ as boundary conditions for stochastic hidden variable models. One can choose either the *future-time configuration*, the *initial-time probability distribution* itself, or the *pairwise interactions* of an ensemble. This choice of boundary conditions goes hand in hand with the formulation of the microdynamics. We hope to establish the foundational significance of this choice of boundary conditions in the formulation and interpretation of the theory.

In order to assess a Q-based interpretation, one must specify and analyze the details of the microdynamics. Since the Q-based interpretation is incomplete without a specification of the microdynamics, we disagree with Friederich's suggestion that measurement processes can be analyzed through the Q-function alone. Further, we show that two foundational aspects of the model discussed by Friederich depend explicitly on the chosen microdynamics: (i) the epistemic/ontic interpretation of Q and (ii) "retrocausality". We are left with the disjunction that either Friederich's account is incomplete because it cannot specify a unique microdynamics, or else Friederich must present some argument that the three microdynamical pictures are not physically distinct despite their apparent disagreements on interpretational issues.

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## The scope of the second law of thermodynamics in astrophysics

Aldo Filomeno

Universidad Católica de Valparaíso, Valparaíso, Chile

### Abstract

The classical foundations of thermodynamics are facing an increasing number of contexts to address. One of them involves scenarios with long-range interactions, such as gravity (a case that, at first sight, might seem a mere technical complication). In this paper, we assess whether some foundational assumptions of thermodynamics need to be updated in light of the peculiar features of self-gravitating systems. Such systems have been studied and simulated in astrophysics for decades, yet there is consensus that many conceptual problems remain open. A diagnosis by some physicists and philosophers (Callender, 2011; Robertson, 2019; Lorenzetti, 2025) is that classical thermodynamics and equilibrium statistical mechanics are inapplicable in such unconventional settings. Even the most optimistic analyses acknowledge limitations that compel a revision of what these theories are about. Against this background, we ask: what is the status of the second law?

In a nutshell, we begin by showing how thermodynamic entropy decreases in the simple scenario of an ideal gas with long-range interactions (Amarzguioui and Grøn, 2005). This changes in more realistic models, since radiation increases entropy by an amount that compensates for the previous decrease (Wallace, 2011). We then reflect on what has happened, focusing on the nature of radiation: radiation is the result of a certain *dynamics* (in particle physics). That is, we emphasize that the second law is preserved in contexts where the underlying dynamics includes gravity *only if* certain other dynamics is also included.

To highlight the significance of this for properly understanding the status of the second law, we also provide a quantitative estimate of the entropy increase required to compensate the entropy decrease, and ask whether the actual universe could contain exotic settings where this compen-
sation fails. As has been proposed by some physicists, dark-matter haloes, which are thought to radiate only weakly, present an interesting case study in this respect.

Overall, our analysis aims to generalize the lesson from these exotic scenarios to support the understanding of the second law not as a fundamental law, but as a law emergent from underlying dynamics and constraints. The second law is thus best understood as a ‘nomological machine’, as defended by Cartwright (1999), holding only so long as certain conditions (including conditions on the underlying dynamics) obtain. This is to emphasize that its universal applicability must not be taken for granted *a priori*; it is an empirical issue that may fail at other scales — depending on the underlying dynamics of *each effective theory in each scale/regime*. While our arguments support certain approaches in the foundations literature, they challenge a widely held present-day consensus within the physics community—dating back to Einstein, Eddington, Planck, and others (Kragh, 2002)—that treats the second law as a globally inviolable truth, never to be overthrown, and according to which entropy decrease can occur only through improbable fluctuations.

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## Quantity Valuation in Algebraic Quantum Theories

Patrick Fraser

University of Toronto, Toronto, Canada

### Abstract

Consider a jar of coins. Individually, each coin takes on a value of a particular quantity: it is worth a specific amount of money. Collectively, the ensemble of coins has an array of statistical features: the average monetary value of these coins, the variance in this monetary value, and so forth. If a single coin were replaced by one of a different denomination, it would change these statistical features. However, changing the statistical features of the ensemble need not require changing the denomination of any particular coin. This illustrates a more general point: the statistical features of an ensemble are determined by the quantitative features of its members, not vice versa.

When the quantitative features of a system are described by a physical theory, the kinematics of that theory is responsible for delivering a quantity valuation scheme which specifies when a system in some state instantiates a particular value of a quantity. It is also useful for a physical theory to be furnished with a probability calculus to facilitate predictions about how likely one is to observe different quantity values upon measurement. Absent such a calculus, one cannot make predictions that can be compared with observed statistics.

Statistical features of ensembles are determined by the quantitative features of the individual elements of those ensembles and not vice versa. This should be reflected in how the quantity valuation scheme and probability calculus of a physical theory are organized. One should be able to specify which quantity values a system has without employing probabilistic notions. Moreover, the conditions under which quantity values are instantiated should play a role in determining what probabilities one assigns to outcomes associated with measurements of those quantities. In quantum theories, however, upholding these requirements proves difficult, especially for the algebraic quantum theories used to study relativistic quantum fields and quantum statistical mechanics. Here, quantum states are typically defined to be assignments of expectation values to quantities, and the instantiation conditions for quantity values are identified with the conditions under which such states have zero variance for those quantities. But expectation values and variances are probabilistic notions. In standard presentations of algebraic quantum theories, the dependence is the wrong way around.

Here, I show how to excise probabilistic notions from the quantity valuation scheme of algebraic quantum theories, and clarify how the probability calculus of these theories is determined by the structure of the quantities they describe. I argue that defining a quantity valuation scheme in terms of probabilistic notions threatens to undermine the interpretation of basic structural features of a theory, and show that this causes trouble for algebraic quantum theories. I then resolve this problem, showing how to express the instantiation conditions of quantum-mechanical quantity values without appealing to probabilistic notions, and showing how the probability calculus of algebraic quantum theories given can be recovered from the kinematic structure of quantum-mechanical quantities.

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## A Foundation Course in the Hole Argument

Gregor Gajic

University of Oxford, Oxford, United Kingdom

### Abstract

The hole argument supposedly refutes spacetime substantivalism by showing that GR is indeterministic if one is sufficiently realist about spacetime. In particular, given a spacetime (as a mathematical object), one can construct other isomorphic spacetimes that are distinct (as mathematical objects) but between which the theory does not discriminate. Recent responses insist that the argument is founded upon a misconception: despite the spacetimes' being mathematically distinct, they are not distinct in the sense that is relevant to the theory in question.

Even better than insisting they are not distinct in some qualified way, would be to actually have them be non-distinct, in a different formalism. This has been proposed by Ladyman and Presnell (2020) and Dougherty (2020) who introduce the formalism of homotopy type theory (HoTT). If we are to read off the ontology of a theory from the mathematical formalism (in a Quinean fashion), it makes sense we should be attentive to the foundations of mathematics, as all mathematical objects are ultimately reducible to their fundamental building blocks. Whereas orthodox discussions of the hole argument tacitly assume set theoretic (ZFC) foundations, it can be demonstrated that the argument is blocked if one uses HoTT foundations.

On the other hand, the formalism of HoTT, on my assessment at least, introduces a highly complex ontology that seems to be unwarranted by the comparative simplicity of the mathematical objects pertaining to the hole argument. I think we can do better by introducing the formalism of category theory. In particular, category theoretic foundations (ETCS/CCAF) will block the hole argument, while at the same time introducing minimal required ontology, and being precise about what the implied ontology is.

I review the formalism of ZFC needed to mathematically precisely state the hole argument, and introduce HoTT and ETCS. I compare how the argument can be blocked from the three foundations, argue for the conditional claim that if HoTT blocking works, so does ETCS blocking, and close by offering some reasons to suggest that ETCS is a better resolution. I also respond to the literature suggesting that foundations-forward approaches do no better than any pragmatic (but tacitly set-theoretic) response.

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## Is Time Dilation 'Real'? Einstein and the TransverseDoppler Effect

Marco Giovanelli

Università di Torino, Torino, Italy

**Abstract**

Over the last two decades, philosophical discussions of special relativity have repeatedly focused on whether relativistic effects—most notably length contraction and time dilation—require a *dynamical* explanation (Brown 2005) or a *kinematical* one (Janssen 2009), or whether this binary choice should be abandoned altogether (Acuña 2016). Although this debate is primarily theoretical, advocates of the dynamical approach often appeal to historical considerations. In particular, it has been claimed that, while Einstein initially described length contraction and time dilation as merely *apparent* coordinate effects, he ultimately aimed to show that they reflect *real* physical changes in the equilibrium states of moving atomic systems (Brown and Read 2022). This paper challenges that historical narrative and argues that clarifying Einstein's position bears directly on contemporary disputes concerning the dynamical–kinematical distinction.

Recent scholarship (Giovanelli 2023) has shown that, in the early 1910s, the categories 'real' and 'apparent,' as well as 'kinematical' and 'dynamical,' were already under scrutiny in discussions of length contraction. I argue that an analogous and even clearer dialectic emerges in the case of time dilation. Like length contraction, time dilation is 'apparent,' since it is a coordinate effect that vanishes for a suitably chosen co-moving observer; yet it is 'real,' since it cannot be eliminated for all non-co-moving observers simultaneously, provided that the new kinematics hold. In this case, no comparable philosophical controversy arose, largely because there was no genuine Lorentzian counterpart to time dilation. Nevertheless, in contrast to length contraction, the empirical testability of time dilation appeared reasonably feasible.

As early as 1907, Einstein invoked Johannes Stark's experiments on fast-moving ions in canal rays, which seemed to indicate a second-order (transverse) Doppler effect—i.e., a frequency shift that persists even when the classical Doppler effect vanishes. This provided a concrete opportunity to test relativistic kinematics. From the outset, Einstein rejected Stark's dynamical interpretation, according to which moving ions undergo a 'real' contraction of their intrinsic frequency. Instead, he characterized the observed frequency shift as 'apparent,' emphasizing that the intrinsic frequency of the ions remains invariant. Nevertheless, the transverse Doppler effect is 'real' in that it must occur for non-co-moving observers if relativistic kinematics is correct. In principle, it thus constitutes a direct test of time dilation, provided that atomic spectral emitters function as reliable clocks.

From the 1920s onward, Einstein stressed that a complete microscopic theory of atomic clocks was still lacking. Such a theory would provide a dynamical account of why all atoms are spectrally identical in their rest frame. Yet this very assumption leads to a striking conclusion: given spectral identity and the absence of motion along the line of sight, the transverse frequency shift admits a purely kinematical explanation as a manifestation of time dilation. Paradoxically, the full dynamical program reinforces the kinematical status of time-dilation effects. In this sense, the

transverse Doppler effect offers a particularly illuminating case for reassessing the long-standing debate between kinematical and dynamical interpretations of special relativity. The paper concludes that much of the misunderstanding arises from reading Einstein's demand for a dynamical account of rods and clocks as a demand for an *explanation* of the new kinematics, whereas it was primarily motivated by the problem of their *confirmation*.

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## Is the World Markovian?

David Glick[1], Cristian Mariani[2]

[1]University of California, Davis, Davis, USA. [2]Università della Svizzera italiana, Lugano, Switzerland

### Abstract

In their Sanders Prize winning essay, Builes and Impagnatiello (2025) present a new empirical argument for presentism. They argue that, given plausible assumptions, presentism allows one to explain a remarkable fact about the laws of our world: they are all *Markovian*. Because Markovian laws depend on only the immediately prior state, they are naturally explained by presentism, the metaphysical view that there is no past or future. For an eternalist, by contrast, there would be no clear reason why the laws should have this character. We, like others, are skeptical of the inference from Markovianism to presentism, but our focus here is the prior assumption that "all of our best theories, from Newton on, have been Markovian" and hence, that one should take this to be a feature of our world in need of explanation. By contrast, we think there are good reasons to think our world is *non-Markovian.*

Science (and physics) is replete with non-Markovian models, so for the claim to be at all plausible it must be concerned with only *fundamental* laws. Here it's hard to know what to say without a truly fundamental theory, but following Builes and Impagnatiello, we consider quantum theory, which they describe as "uncontroversially Markovian." However, there are a number of approaches to quantum theory which posit non-Markovian dynamics. First, on the *open quantum systems* approach (Cuffaro and Hartmann (2024, 2026)), systems are represented by density operators evolving according to dynamical maps that need not satisfy the Markov semigroup conditions. If one takes the open systems view as a starting point, the claim that our world is Markovian amounts to stating that only the cosmos, as a whole, evolves unitarily. But even granting this, the dynamics of any subsystem of interest—including all systems we can actually access experimentally—will in general be non-Markovian. Second, *spontaneous collapse theories* (GRW, CSL) introduce an imaginary noise field. While this noise is typically understood as white (uncorrelated with time), there are compelling reasons to generalize these models to incorporate non-white (colored) noise, which leads to fundamentally non-Markovian dynamics (Mariani, 2025). Third, Barandes posits explicitly non-Markovian laws for his *indivisible quantum theory,* a stochastic hidden variables approach to quantum theory (Barandes, 2025).

We take these examples to provide compelling reasons to think that our world may be non-Markovian. Moreover, we take this possibility to count against a metaphysical view that renders non-Markovian laws impossible. Thus, we have (yet another) empirical argument *against* presentism.

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## Topological Asymmetry Neutralizes Leibniz's Shift Argument and Collapses Categorical Equivalence

Daniel Grimmer[1], James Read[2]

[1]Yale, New Haven, USA. [2]Oxford, Oxford, United Kingdom

### Abstract

The philosophy of spacetime has long been haunted by Leibnizian Shift Arguments (and, relatedly, Hole Arguments). Given any non-trivial global symmetry, a symmetry-shifted world would seem to represent a distinct possibility. A whole host of issues then follow: undetectable structure, indeterminism, and violation of the Principle of Sufficient reason (e.g., following Leibniz: Why did God put the universe here rather than there?). Traditionally, substantivalists have responded by either biting the bullet (accepting/minimizing these issues) or adopting ''Sophisticated Substantivalism'' (denying that symmetry shifted models represent distinct physical possibilities). In this talk, I propose an underappreciated third way forward: One can deny that the spacetime manifold possesses any non-trivial global symmetries. This approach stops any such shift arguments before they can even begins.

Perhaps surprisingly, the non-existence of global spacetime symmetries is compatible with an abundance of local symmetries (Manchak, Barrett, 2022). Indeed, certain asymmetric spatial topologies (e.g., the Hantzsche-Wendt manifold, HW) are compatible with a flat metric and are actively being considered as viable options for the topology of the actual universe (Aurich and Lustig, 2014). When equipped with any flat geometry (e.g., Minkowskian, or Galilean, or Leibnizian) this globally asymmetric topology induces a preferred rest frame. This topology-induced rest frame is locally undetectable but nonetheless reduces the spacetime's global isometries to those of a Newtonian spacetime. Other possible spacetime topologies (Raymond-Tollefson and Margulis spacetimes) extend this rigidity to the point of *completely removing all global isometries*.

Two significant results follow: Firstly, these topology-induced structures raise issues for the standard account of Categorical Equivalence (Weatherall, 2016). On the HW manifold, Minkowskian, Galilean, and Leibnizian spacetimes all become categorically equivalent to a Newtonian spacetime, despite their obvious differences in terms of local structure/physics. Secondly, as noted above, the complete absence of global symmetries neutralizes Leibniz's shift argument. By shifting the source of structure from the local metric to the global topology, we find a new way of securing determinism (de re and de dicto) which bypasses the traditional substantivalist dilemma.

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# Making Sense of Statistical Mechanics: the Gibbsian vs the Boltzmannian Approach

Bixin Guo

Macalester College, Saint Paul, USA

## Abstract

Despite the practical success of statistical mechanics, its foundations remain contested. There are the so-called *Boltzmannian approach* (BSM) and *Gibbsian approach* (GSM) to statistical mechanics, and it is under dispute which approach is correct or, if both are, how they are related. BSM has been developed and defended extensively in recent philosophy of physics literature, particularly as the microphysical underpinning of thermodynamics. In contrast, less attention has been paid to systematically developing GSM. It is often criticized as conceptually unsatisfactory and dismissed as merely a set of mathematical tools rather than a physical theory that describes *what is actually going on* in thermodynamic systems.

In response, I argue for the physical significance of GSM, and propose a new direction for understanding its relation with BSM. More specifically, I propose viewing statistical mechanics as a *framework* theory. Similar to classical mechanics or quantum mechanics, statistical mechanics covers a wide range of concrete theories of different kinds of systems (including gases, liquids, solids, magnets, and plasmas) and various phenomena (such as Brownian motion and black body radiation). GSM has the apparatus to serve as such a broad framework. In contrast, BSM, as currently formulated, is better viewed as a *concrete* theory that applies only to certain physical systems (such as dilute gases).

I first introduce the essential elements of BSM and GSM. In doing so, I identify in what sense they are opposed to each other: whether or not physical systems, their properties (such as entropy) and dynamics, can be characterized in terms of probability distributions. I then explain the distinction between a framework theory and a concrete theory. Roughly speaking, a framework theory is more abstract; it does not have a unique ontology, but applies to a wide range of different kinds of systems. A concrete theory, by contrast, applies to a more restricted class of systems. By specifying what kind of systems are involved and filling in their details, one can derive a concrete theory from the framework theory, but not the other way around.

Taking into account that statistical mechanics is a framework theory, I use examples to explain in what sense GSM is a better fit for this broad framework, whereas BSM is comparatively more concrete. I show that it is possible to derive aspects of BSM from GSM by filling in details about the system, but not the other way around; GSM is applicable to more kinds of systems than BSM.

In particular, I focus on Brownian motion as an example to explain why BSM is conceptually inadequate to characterize certain statistical-mechanical phenomena. Roughly speaking, standard BSM relies on the separation between macrostates and microstates, whereas the state of a Brownian particle, which is at a mesoscale, does not fit well with this dichotomy. Moreover, it is unclear, or at least nontrivial, how to accommodate or interpret the quantitative features of Brownian motion—especially using the Fokker-Planck equation (which directly describes the evolution of probability distributions and their approach to equilibrium)—in BSM.

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## What quantum foundations teach us about black holes

Ladina Hausmann, Renato Renner

ETH Zürich, Zürich, Switzerland

### Abstract

Quantum gravity thought experiments, such as the firewall paradox [1], probe the compatibility of quantum theory with general relativity. The usual analysis of these experiments relies on the universality of quantum theory—the assumption that we can apply the theory to any physical system, including black holes.

Thought experiments in quantum foundations, like Wigner's friend paradox, also assume the universality of quantum theory, but they do not depend on any gravity considerations. They examine scenarios involving multiple observers, each applying quantum theory to a different physical system, which may itself include other observers. A key lesson learned from these thought experiments is that combining the different observers' perspectives is far from straightforward. Even a seemingly intuitive combination rule—that if an observer Alice knows that an observer Bob knows a measurement yielded result x, then Alice also knows this measurement has result x—leads to a contradiction [2].

In this talk, I will revisit quantum gravity thought experiments, like the firewall paradox, and argue that they also crucially depend on such combination rules, some of which have been implicit so far. They can, therefore, be understood as gravitational versions of Wigner's friend thought experiments [3]. This correspondence between Wigner's friend experiments and gravity thought experiments enables the transfer of insights between quantum foundations and gravity. In particular, the lesson from quantum foundations—that the universality of quantum theory conflicts with seemingly self-evident rules for combining the perspectives of different observers—applies equally to the firewall paradox. Questioning the validity of these rules thus offers a new avenue for resolving paradoxes in quantum gravity.

Conversely, black holes provide a concrete physical setting where the conclusions from Wigner's friend experiments become relevant. Having such a concrete setup helps to identify relevant physics that was neglected in the quantum circuit descriptions that are typically used in quantum-foundations analyses.
For example, the black hole description reintroduces spacetime, which is not modeleld by a quantum circuit. This may lead to novel resolutions of Wigner's friend-type contradictions.

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## Ontic Types in the Standard Model of Particles

George Hobart

University of Bristol, Bristol, United Kingdom

### Abstract

This paper examines the ontological implications of neutrino oscillation—a phenomenon that is empirically well-established but has been under-evaluated thus far in philosophical literature. Neutrinos are neutrally charged leptons that only interact with the weak force and have incredibly small masses (<1 eV). Because of this, neutrinos are always created and annihilated as determinate flavours: electron neutrino, muon neutrino, and tau neutrino—we represent these as flavour eigenstates. The space of neutrino states can also be spanned by three mass eigenstates, with distinct masses that are orders of magnitude smaller than the next lightest elementary particles (electrons). The flavour basis and mass basis are misaligned by a non-diagonal unitary operator, so flavour eigenstates are coherent superpositions of mass eigenstates. Neutrinos can always be treated in the ultra-relativistic regime, and therefore the mass operator commutes with the Hamiltonian, and so the flavour operator does not. Thus, the mass eigenstates are stationary, with distinct rates of change of phase in their time-evolution, corresponding to their distinct masses. Consequently, flavour eigenstates are non-stationary under time-evolution, so neutrinos created as one flavour can 'oscillate' into distinct flavours. This violates lepton-flavour conservation, so has no permitted mechanism in the un-adapted "Ordinary" Standard Model.

We explain the necessary conditions for oscillation and the physical mechanisms that cause it, and explore the ontological, epistemological, and methodological implications of the phenomenon. Our primary question is 'which basis of neutrino types should be taken as the more fundamental ontology: flavour or mass?' It is often assumed that the two ontologies are identical—that fermion types are distinguished by their masses which correspond bijectively to their flavours (as assumed in e.g. Williams 2023)—but neutrino oscillation demonstrates that this alignment of bases is untenable, and hence we have a dilemma. While the standard flavour-based ontology is in line with our typical intuitions and fits well with other areas of the Standard Model, the mass basis is ''stable'', which may be a desideratum for elementary ontologies. We present the problems associated with using either ontology, and propose a new ontology for neutrinos—the Family Ontology—which exhibits itself as either flavour eigenstates or mass eigenstates, dependent on energy scales and interaction conditions. This is analogous to the distinct bases of states of a spin-1 system, dependent on the axis of projection and on the orientation of an external field. We then discuss the implications of this ontology for other families of elementary fermions, and how this ontic unification can be extended to unify the six leptons into one ontic kind, and the six quarks into a distinct ontic kind—a significant reduction from the twelve kinds distinguished by the naïve flavour-based ontology. Finally, we draw parallels to other areas of philosophy of particle physics and present areas for further research, such as neutral meson mixing, CKM mixing, and mass superselection rules (Bargman 1954; Giulini 1996).

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## A Formal Analysis of the Evidential Case Against Cosmic Inflation

Frank Xixiang Hu

University of California, Irvine, Irvine, USA

### Abstract

There are several problems associated with the framework of cosmic inflation. To list a few: the measure problem in eternal inflation, the ultraviolet sensitivity problem, and the evidential problem concerning the empirical standing of inflation. This paper will focus on the last problem. I first argue that the charge that inflation is untestable, and thus unscientific, is not convincing by clarifying the relationship between inflationary models and the inflationary framework. Inflation is best understood as a framework comprising a core principle from which multiple inflationary models can be built, rather than as a scientific theory in Popper's sense, and thus Popper's demarcation criterion does not apply to it. I then focus on two strands of the evidential problem, namely the "unlikeliness problem," which argues that empirically favored inflationary models are theoretically unlikely, and the "problem of mediocre predictions," which argues that the evidence commonly cited in support of inflation would be expected even in the absence of inflation. Taken together, the evidential problem aims to show that inflation has not received sufficient support from empirical evidence to justify its proponents' optimistic attitudes toward the continuation of the program. In response, I formulate the evidential problem within Bayesian confirmation theory. I argue that neither challenge is convincing because their reasoning fails to meet the criteria of Bayesian confirmation theory in significant ways. My analysis further reveals that a central concern for working cosmologists in theory building is whether and when empirical confirmation of individual models within a framework counts as confirmation of the framework itself, given that alternative frameworks are available. I argue that cosmologists' actual reasoning about how empirical evidence affects the credence of a framework is best illuminated within Bayesian confirmation theory. This analysis clarifies several misconceptions about inflation that have appeared in the philosophical literature, including Dawid and McCoy (2023)' view that inflation's flexibility in model construction makes it intrinsically unsuitable for the application of Bayesian confirmation theory, and the view that inflation functions merely as a phenomenological framework where constructing models for curve fitting and eliminating models based on empirical evidence constitutes the entire scientific endeavor.

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## The Multi-Time Multi-Field

Mario Hubert

LMU Munich, Munich, Germany

### Abstract

The multi-field interpretation construes the quantum wave-function as a genuine physical field in three-dimensional space that assigns values to configurations of particles at each time rather than individual points (Hubert and Romano, 2018). This interpretation applies naturally to the de Broglie–Bohm theory, where particles have definite positions at all times and the wave-function guides their motion through the guidance equation. Extending this interpretation to relativistic quantum mechanics, however, faces a fundamental challenge: in special relativity, simultaneity is frame-dependent, threatening the coherence of defining a field on simultaneity slices.

I argue that the multi-time formalism provides the natural framework for a relativistic multi-field interpretation. In multi-time quantum mechanics, originally developed by Dirac, Tomonaga, and Schwinger, the wave-function depends on multiple time parameters—one for each particle—rather than a single universal time (Lienert et al., 2020). The multi-time wave-function $\psi(x_1,t_1,\ldots,x_n,t_n)$ is defined on spacelike hypersurfaces in spacetime, with dynamics governed by a system of coupled equations that ensure Lorentz invariance. Crucially, the multi-time structure naturally accommodates quantum non-locality because the field is defined on spacelike hypersurfaces rather than propagating along light cones, building non-locality into the field's geometric structure.

A key challenge for any field interpretation is specifying how fields generate forces. For this mechanism to work consistently, fields and forces must satisfy matching conditions—constraints that ensure the field structure appropriately determines the force structure. I develop generalized matching conditions appropriate for relativistic Bohmian mechanics, showing how to interpret multi-time wave-functions as multi-time multi-fields. Unlike classical fields, which satisfy *pointwise matching* (field values at points determine forces at those points), the multi-time multi-field satisfies *structural matching:* the geometric structure of field-force coupling matches spacetime structure (through spacelike hypersurfaces).

This approach provides an alternative to both wave-function realism (Albert, 2013; Ney, 2021), which treats configuration space as the fundamental arena of reality, and pure field ontologies (Sebens, 2022), which eliminate point particles entirely. The multi-time multi-field demonstrates that the wave-function can be understood as a field in physical spacetime while preserving particles as the primitive ontology and maintaining fidelity to the standard mathematical formalism. This framework suggests a path toward reconciling quantum non-locality with relativistic spacetime structure.

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# Stochastic Thermodynamics at Strong Coupling: Extending Thermodynamics to Small Systems

Aditya Jha

Department of History and Philosophy of Science, University of Cambridge, Cambridge, United Kingdom

## Abstract

I argue that extending thermodynamics to small systems exposes background assumptions that are largely invisible in its traditional macroscopic domain. To illustrate this, I focus on (mesoscopic) stochastic thermodynamics and, in particular, on the underexplored assumption of weak system–environment coupling (negligible system-environment interaction potential) that underwrites the familiar (or unambiguous) separation of heat from work (in the macroscopic regime).

Firstly, drawing from a contemporary debate in stochastic thermodynamics literature (Talkner and Hänggi 2016; Jarzynski 2017; Seifert 2016), I discuss how the strong coupling regime makes the heat-work demarcation in stochastic regimes not only subject to conventional choices, but also makes the concept of heat itself highly ambiguous. This, I show, is primarily because, in strongly coupled systems, work is calculated from the Hamiltonian of Mean Force (HMF) (for an 'effective system'), and not via changes in system's bare internal energy. HMF incorporates environment-induced renormalization and back-action into an effective system description obtained by integrating out the environment's degrees of freedom while retaining interaction effects. Several alternative but principled ways of modelling the interaction-mediated energy produce inequivalent heat–work decompositions between the different modelling choices used to partition the interaction energy.

Secondly, I discuss and evaluate varying philosophical attitudes held amongst different camps of physicists — namely, essentialism and functionalism — concerning this (dis)ambiguation: the former held by Cohen and Mauzerall (2004) and Talkner and Hänggi (2016, 2020), and the latter held by Jarzynski (2017) and Seifert (2016). I argue that taking a side in the debate is tricky given an inherent limitation of stochastic thermodynamics in strong coupling regimes. A foundational goal of stochastic thermodynamics is that thermodynamic quantities for a stochastic system should be definable from a system-intrinsic point of view, that is from observations of the mesoscopic system's trajectories (or their averages) alone. In strongly coupled systems, however, a complete thermodynamic description of a stochastic system requires environmental information (from HMF) that is not contained in the system's stochastic dynamics and obtaining HMF from observations is a near impossible task as well. This suggests that a system's mesoscopic dynamics radically underdetermines the theoretical description of its thermal behaviour.

The above discussion is important on two counts. One, it introduces strong coupling to the philosophical literature alongside stochastic thermodynamics, both of which merit attention and further study. Two, it suggests that discussion on the foundations of irreversibility can benefit from attending to mesoscopic regimes rather than focusing exclusively on microscopic scales. This is because the heat-work distinction in stochastic thermodynamics feeds into the derivations of standard stochastic equalities (like Jarzynski Equality), which then feeds into purported derivations of the Second Law based on these equalities. Only brief remarks on the second point are possible within the scope of this talk though.

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## A time-free quantum framework proposal

Tamas Kovacs

Eotvos Lorand University, Budapest, Hungary

### Abstract

A proposed reformulation of quantum mechanics replaces the conventional time parameter with energy-dependent evolution, suggesting time is an emergent quantity derived from energy based on the Planck-Einstein relation (E = hf) and the inverse frequency-time relationship [Planck, 1901]. This approach introduces a modified Hamiltonian and a new wavefunction, reformulating the Schrödinger equation in the energy domain with a discrete evolution parameter to demonstrate that energy governs dynamical evolution while preserving normalization and recovering stationary state properties. Canonical examples like the infinite square well and quantum harmonic oscillator yield results compatible with traditional methods, including the derivation of energy-based ladder operators for the harmonic oscillator spectrum.

By treating the evolution parameter as a discrete integer, this framework mirrors the quantized nature of physical processes observed in atomic transitions. The mathematical shift involves a partial derivative with respect to energy, effectively treating energy as the coordinate through which the state vector propagates. This bypasses the "problem of time" often encountered in canonical quantum gravity, where time fails to appear as a fundamental operator (Rovelli, 2011). Instead, dynamical change is viewed as a manifestation of energy fluctuations, aligning with theories of emergent gravity and thermal time hypotheses.

Furthermore, this radical shift suggests that the Wheeler-DeWitt Equation, which famously lacks a time variable, might be interpreted through this energy-domain lens. By moving away from a continuous temporal backdrop, the theory accounts for the discreteness of physical processes at the Planck scale. This redefinition effectively bridges the gap between static cosmological models and the observed flux of quantum systems, offering a more unified perspective on physical constants and relativistic causality (Anderson, 2010).

The persistence of stationary state properties, such as the constant expectation values of observables, demonstrates that this energy-based formalism does not contradict established experimental data. Rather, it provides a more robust foundation for unifying quantum dynamics with relativistic constraints, where the distinction between space and time is often blurred. By deriving the full spectrum of the quantum harmonic oscillator using adapted ladder operators, the model proves its utility in handling complex potentials. This shift suggests that the universe's fundamental "clock" is not an external temporal dimension, but the intrinsic energetic state of the system itself.

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# How the Universe Presents Itself: Wheeler's "Meaning Circuit" and German Idealism

Luuk Kuiper

Utrecht University, Utrecht, Netherlands

**Abstract**

John Archibald Wheeler's infamous turn towards the foundations of quantum theory from the 1970s onwards has been well historized. However, the philosophical upshot of Wheeler's speculative turn is far from being fully unpacked. The 'Meaning Circuit Hypothesis' as the central onto-epistemic fundament to the "it from bit" program has been criticised by Jaeger (2023); on the grounds that the reduction of physics to information involves an untenable speculative leap from quantum phenomena to cognition. Those familiar with the history of philosophy will recognize that the attempt to overcome this speculative leap is one of the central tenets of discussion within the German Idealist tradition. So too did German natural philosopher Bernulf Kanitscheider connect Wheeler's goals to the philosophy of Friedrich Wilhelm Joseph Schelling. Wheeler embraced the suggestion by Kanitscheider; it is featured in footnotes in two of his publications, where he points out the similarity between his thought and that of late Schelling (Wheeler 1977 & 1990). Recent conceptual work has already investigated the connection between Wheeler's meaning circuit and the Leibniz logic loop (Furlan, 2020), showcasing the potential of analyzing Wheeler through the lens of the history of ideas. However, although clearly recognized in his time, the parallel between Wheeler's project and that of the German Idealists has been largely lost from the contemporary discussion on quantum foundations. Approaching the role of the observer-participator in the meaning circuit through the lens of Schelling's concept of 'presentation' [*Darstellung*] (Schmid, 2018) —one in which nature itself functions as a medium for self-presentation— offers the opportunity to better understand Wheeler's "speculative leap." Grounding Wheeler's "it from bit" in Schelling's thought and the general German Idealist context not only allows for novel insight into Wheeler's philosophy, but also opens the door to new perspectives on the epistemology of quantum theory and foundations of quantum information theory. Moreover, along the way a methodological argument on the applicability and fruitfulness of the history of ideas to conceptual frontiers of physics is picked up.

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## A multimodal probe for general holographic coherence of quantum space-time states on causal horizons

Ohkyung Kwon

University of Chicago, Chicago, USA. Cardiff University, Cardiff, United Kingdom

### Abstract

Gravitational wave observatories such as LIGO and Virgo have enabled a new era in multimessenger astronomy. In recent years, predictions of quantum gravity signatures in interferometers by Craig Hogan, Tom Banks, Eric Verlinde, Frank Wilczek, and Kathryn Zurek have inspired multiple new experiments deploying precision laser interferometry at smaller scales to probe such phenomena, such as the Holometer at Fermilab, QUEST at Cardiff, GQuEST at Caltech, and a prototype interferometer at INRiM. Key to many such models of holographic quantum space-time phenomena is the hypothesis that the quantum states of space-time are coherent on causal horizons, inspired by 't Hooft's algebra of black hole information. This conjecture naturally has wide ranging consequences for the foundations of quantum gravity and cosmology. As the causal structure of space-time is dynamically coupled to mass-energy in general relativity, a complete study of theoretical foundations necessitates a probe of quantum correlations in the background space-time itself, arising from couplings to quantum superpositions of mass-energy, even for vacuum fluctuations. Further, it necessitates a phenomenological framework that respects and follows the causal boundaries of an observation or measurement of space-time, a requirement not met by the standard QFT based models. This talk will report on efforts to generalize the probe of such holographic coherence to the inflationary horizon and to causal diamonds in flat space-time (conformal Killing horizons), enabling a multimodal probe connecting primordial signatures in the Cosmic Microwave Background to concordant spectra predicted for tabletop interferometric searches in laboratory space-times. Future expansions of this multimodal research program are explored, with 3D correlations of galaxy distributions in large scale structure surveys that show intriguing parity violations, and with future experiments in gravitationally mediated entanglement that can shed light on the excited states of quantum gravity if the current experiments detect signatures for the ground state of gravitational entanglement.

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Member list of broader collaboration on the empirical probes:

Nikitha Kuntimaddi and Abhinav Patra (Cardiff Univ.)
Alasdair L James and Sander M Vermeulen (Caltech)
Lorenzo Aiello (Univ. of Rome Tor Vergata)
Aldo Ejlli and Henning Vahlbruch (Max Planck Institute for Gravitational Physics)

Nathaniel Selub (UC Berkeley)
Craig J Hogan and Stephan Meyer (Univ. of Chicago)
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## Effective Realism and the Problem of Boltzmann Brains

Marco Maggiani

University of Pittsburgh, Pittsburgh, USA

### Abstract

The Boltzmann Brain problem arises because our best-fit cosmological model, ΛCDM, predicts that in the far future the universe will approach a de Sitter phase with a small but non-zero temperature. In such a spacetime, random fluctuations will occasionally instantiate conscious observers. Given enough time, those observers, arising from fluctuations rather than from ordinary evolution, will vastly outnumber ordinarily evolved observers like us. If so, the link between our observations and the underlying theory seems broken. Any theory implying that our evidence is almost certainly misleading, because it would more likely reflect random fluctuations rather than the actual structure of the universe, cannot be confirmed by that evidence.

Philosophers and physicists have advanced a range of responses. Some deny that we should regard ourselves as *typical* among observers with the same evidence as us, but this requires agents to assign different probabilities to their possible self-locations even though those locations cannot be distinguished by evidence or by theoretical virtues. Others appeal to externalist notions of evidence, but this view struggles with related problems posed by larger fluctuations, such as Boltzmann planets and galaxies. Finally, Sean Carroll has argued that *cognitively unstable* theories, which undermine their own evidence, should be assigned a prior probability of zero; however, this proposal faces its own serious objections.

I argue for a different approach. I propose that the ΛCDM model should be regarded as an *effective* theory, whose domain of applicability does not extend to the extreme timescales at which Boltzmann Brains numerically dominate. This parallels the situation in quantum field theory: QFT is well confirmed within its regime but known to break down at very short length scales. On this view, the Boltzmann Brain problem shows neither that ΛCDM is untenable, nor that cosmological evidence is suspect, since we lack empirical access to the timescales where Boltzmann Brains would become significant in number. It shows only that ΛCDM must eventually be replaced by a more fundamental theory that avoids the problem. The Boltzmann Brain problem, on this view, points not to a failure of cosmology but to the limits of ΛCDM's domain. In sum, I argue that effective realism can be applied to cosmology and that it helps make progress on one of its central conceptual questions.

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## Invariance and Definability in General Relativity

JB Manchak[1], Thomas Barrett[2]

[1]UC Irvine, Irvine, USA. [2]UC Santa Barbara, Santa Barbara, USA

### Abstract

Consider any general relativistic spacetime (M, g) where M is a connected, Hausdorff manifold and g is a smooth Lorentzian metric on M. It is natural to say that a number of invariant structures on M are "definable" from (M,g). For example, the Ricci scalar function R explicitly definable from spacetime and its associated derivative operator. The aim of this talk is to explore the notion of implicit definability (ID) within the context of general relativity. We present a hierarchy ID variants and explore various results associated with each level. One upshot is a better understanding the relationship between "symmetry" and "structure".

All definitions have the following form: A spacetime (M,g) "implicitly defines" a tensor field X on M iff X is preserved by all the "symmetries" of (M,g). The definitions differ in how the notion of "symmetries" is made precise. At level 1 of the ID hierarchy, we take symmetries to be global isometries from (M,g) to itself. Level 1 is perfectly adequate for Minkowski spacetime (see the result of Malament 1977) but is inadequate for so-called "giraffe" spacetimes that fail to have non-trivial global symmetries (Barrett, Manchak, and Weatherall 2023). Levels 2 and 3 concern local symmetries of different kinds and are more adequate than level 1 but inadequate for so-called "Heraclitus" spacetimes that fails to have any non-trivial local symmetries (Manchak and Barrett 2023).

The main portion of the talk concerns level 4 of the ID hierarchy. Here, one considers "modal symmetries" — the collection of all isometric embeddings between all spacetimes. We say a spacetime (M, g) level 4 IDs a tensor field X on M iff X can be extended to a collection {X_i} of tensors on all spacetimes such that this collection is preserved by all modal symmetries.

Category theory is used to explore level 4. Let **GR** be the category where the objects are spacetimes and the arrows are isometric embeddings. Let {X_i} be a collection of tensor fields on each spacetime and let **GR+X** be the category where the objects are triples (M,g, X_(M,g)) and the arrows are isometric embeddings that preserve X. We are now ready to state one of the main theorems.

Theorem. Let (M,g) be a spacetime and X a tensor on M. The following are equivalent:

1. (M,g) level 4 IDs X.
2. X can be extended to a collection of tensors {X_i} on all spacetimes such that **GR** and **GR+X** are categorically equivalent.

So if (M,g) level 4 IDs X, then the categories **GR** and **GR+X** have the same structure; adding a tensor field X_(M,g) to each spacetime (M,g) does not increase the structure.

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## Why Hadamard states?

Eleanor March

University of California, Irvine, Irvine, USA

### Abstract

In the context of quantum field theory on curved spacetime, and in locally covariant quantum field theory, the Hadamard condition is often presented as a condition on "physically reasonable" states of the quantum field. Indeed, there are well-known arguments to the effect that it is only for this class of states that certain important physical quantities, such as the quantum stress-energy tensor, and Wick and time-ordered products, are well-defined (Brunetti and Fredenhagen 2000). As such, many foundational results - ranging from derivations of Hawking radiation and the Hawking temperature (Kay and Wald 1991), to quantum energy inequalities (Fewster 2000), to the renormalizability of Wick and time-ordered products (Hollands and Wald 2002) - rely on the Hadamard condition.

Yet despite this, the philosophical and foundational underpinnings of the Hadamard condition remain murky. As most standardly presented (e.g. in Kay and Wald (1991)), the Hadamard condition is motivated via appeal to the a version of the equivalence principle - according to which the local singularity structure of Hadamard states should approximate that of the Minkowski vacuum. But it is unclear what this kind of motivation has to do with, e.g., the well-definedness of Wick or time-ordered products or the quantum stress-energy tensor. And it is doubly unclear what this kind of version of the equivalence principle has to do with the classical equivalence principle, which states that the dynamics of matter fields in general relativity should be locally like those in Minkowski spacetime (see, e.g., March (2025)).

In this talk, I argue - contrary to the received view - that the Hadamard condition is best understood as a necessary and sufficient condition for the existence of an operator product on a sufficiently large class of observables of the quantum field, understood as operator-valued distributions, satisfying a variety of further conditions. (That the Hadamard condition was sufficient for this was already known, as far as I am aware the other direction had not previously been shown.) My argument for this is threefold. First, it is possible to formulate the Hadamard condition entirely within the context of classical field theory - and as such, its connection to the Minkowski vacuum state is at best indirect. Second, this motivation has a direct connection to e.g., the existence of Wick and time-ordered products and the quantum stress-energy, which are built out of operator products of fields and their derivatives. Third, that it is from this perspective that the relationship between Hadamard states and the Minkowski vacuum is clearest.

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## Reduction and Scale Asymmetry in Quantum Field Theory: Lessons from the a-theorem

Bernardo Marques

CNRS, Paris, France. Université Paris 1 Panthéon Sorbonne, Paris, France

### Abstract

In this paper, I explore a central result from quantum field theory that remains unexplored in philosophy of physics: the a-theorem. Originally established in two dimensions by Zamolodchikov (1986) and later extended to four dimensions by Komargodski and Schwimmer (2011), the a-theorem concerns the structure of renormalisation group (RG) flows. It shows that there exists a quantity, the *a*-function, which decreases monotonically along RG flows from high-energy (ultraviolet) to low-energy (infrared) regimes. This monotonicity is typically interpreted as an irreversible loss of effective degrees of freedom along the flow, revealing a hierarchical and asymmetric structure across energy scales.

In particular, I examine how the a-theorem casts a novel perspective on the debate between emergence and reduction in quantum field theory (e.g., Adlam 2024, Bain 2013, Butterfield 2011, Cao & Schweber 1993, Castellani 2002, Crowther 2015, Hartmann 2001). I argue that the a-theorem offers a principled account of scale asymmetry in QFT, thereby explaining why inter-theoretic relations across energy scales are necessarily irreversible and why a persistent gap between descriptions at different scales is to be expected. The a-theorem shows that the RG flow is fundamentally irreversible: while high-energy theories constrain the space of possible low-energy effective descriptions, the inverse reconstruction is obstructed by the systematic loss of information. This places principled limits on reductive explanation without invoking ontological novelty or brute emergence.

On this basis, I defend two main claims. First, the a-theorem supports the explanatory autonomy of effective field theories by grounding their independence in an objective physical asymmetry between scales, rather than in purely epistemic or pragmatic considerations. Second, it motivates a reconceptualisation of emergence in physics. Rather than being understood in terms of novelty or irreducibility, emergence should be characterised in terms of scale asymmetry: higher- and lower-energy descriptions are related by lawful but irreversible transformations. I conclude by suggesting that this perspective may help reframe broader philosophical debates concerning reduction and emergence beyond physics, by shifting attention from questions of derivability to the structural features of inter-level relations.

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## No-Cloning Constraints on Agency and Conscious Experience

Kelvin McQueen, Emily Adlam, Mordecai Waegell

Chapman University, Orange, USA

### Abstract

What are the structural constraints that quantum mechanics places on systems capable of modeling the world and acting within it? In this talk I discuss a constraint-based approach to foundational questions about mind and agency, grounded in the information-theoretic limits imposed by quantum theory, especially the no-cloning theorem [1].

In recent work [2], we argue that *deliberative agency* cannot be realized in a purely quantum system, understood as a system evolving unitarily in a fully coherent regime without decoherence, collapse, or an emergent preferred basis. We characterize agency in terms of three conditions: the ability to construct a world-model, to evaluate the consequences of alternative actions, and to reliably implement the action that maximizes expected utility. We show that the first two conditions conflict with no-cloning: world-model construction requires copying information from the environment, and deliberation requires branching that model across multiple hypothetical scenarios. Approximate quantum cloning strategies do not permit sufficient fidelity or generality for agency to be viable in purely quantum systems. These results place principled limits on purely quantum agents and clarify the role of classical structure (such as decoherence-induced preferred bases) in enabling agency within a quantum universe.

We then extend this constraint-based strategy from agency to conscious experience itself. Rather than focusing on decision-making, we consider *perceptual filling-in*: a ubiquitous feature of human and animal perception in which determinate experiential content is present despite absent or underdetermined sensory input, as in blind-spot filling-in. In many central cases, filled-in content exhibits systematic and counterfactually robust dependence on surrounding perceptual content: variations in the surround are reliably mirrored in the filled-in region. We argue that supporting such dependence requires the reliable duplication of perceptual information within a single conscious state. If conscious states were realized in a purely quantum system, such duplication would again be prohibited by the no-cloning theorem. And once again, approximate quantum cloning schemes lack the fidelity required to underwrite perceptual filling-in.

Taken together, these results suggest that quantum information-theoretic constraints do not merely limit what can be computed or transmitted, but also place substantive bounds on what kinds of physical systems can support world-modeling, agency, and certain structural features of conscious experience. In particular, they challenge proposals according to which genuinely quantum processing is essential to mind (e.g. [3]), while helping to explain why classical structures must play a constitutive role in any physically realizable theory of agency and perception.

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## Bayesian epistemology in a quantum world

Alexander Meehan

University of Wisconsin-Madison, Madison, USA

### Abstract

In a string of recent work, Earman (2018) and Earman and Ruetsche (2020) have argued that quantum theory motivates a move away from the standard framework of Bayesian epistemology to a new framework in which credences are represented in the same way as certain conceptions of quantum chance: as functions on a non-commutative algebra of quantum events instead of a sigma-algebra. Call the resulting framework the *Q-Bayesian framework* (not to be confused with QBism).

There are a number of open questions about how to formulate and justify the basic norms of the Q-Bayesian framework. For example, a number of distinct and apparently conflicting Q-Bayesian rules have been proposed, and there have been attempts to adjudicate between them using tools within the Q-Bayesian framework (see e.g. Meehan and Steeger, 2023). In this talk I will take a different approach. I will argue that:

**Thesis:** The norms of the standard Bayesian framework are sufficient to fix and justify the norms of the Q-Bayesian framework.

In particular, the standard Bayesian norms still impose rational requirements on the Boolean fragments or parts of the agent's Q-Bayesian belief function. I will argue that these requirements are in fact powerful enough to pin down the Q-Bayesian norms, including the Q-Bayesian updating rules.

However, there are two important caveats to these results.

First, while the standard Bayesian norms pin down these Q-Bayesian norms, the relationship is not one-to-one. For example, I will argue that while the Q-Bayesian updating rules are fixed by standard Bayesian conditionalization and standard chance deference norms, they are not fixed by conditionalization alone.

Second, these results do not show the impossible: they do not show that quantum probability theory can be `derived' from Kolmogorovian probability theory. As I will emphasize, the Q-Bayesian framework builds in a certain kind of non-contextuality assumption in the way it represents credences and chances. This basic assumption is not something that can be derived from Kolmogorov's axioms (see Healey (2020) who emphasizes a similar point), and is crucial for the results go through. So, there is no magic here: we are deriving the Q-Bayesian norms from the Q-Bayesian starting point and other rational norms, not from Kolmogorovian probability theory alone.

The last section of the talk will step back to consider some meta-epistemological questions. For example, can the Q-Bayesian framework in some sense co-exist with the standard Bayesian framework? I will suggest that while this co-existence is puzzling if we understand Bayesian epistemology to be giving us a direct description of ideal agents, it is less puzzling if we understand Bayesian epistemology to be engaged in a kind of normative modeling (Roussos, 2025). I briefly sketch how we can understand the two frameworks as modeling frameworks. I suggest it is not only possible for them to co-exist, there are compelling reasons to keep them both around and widen the tent of Bayesian epistemology.

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# This is Water: the lesson of fundamentality from Newton to Bell's Theorem

Gabriele Cafiero, Luca Molinari, Jonte Hance

University of Newcastle, Newcastle, United Kingdom

## Abstract

Past research in the metaphysics of physics from the 60s onward has focused on issues such as reduction, symmetries an emergence. In past 5 to ten years this panorama has been further enriched by a critical discussion of the topic of fundamentality, which has begun to receive increased scrutiny (Morganti 2020).

Our work addresses the significance that talk of fundamentality has played in the recent resurgent discussion on Bell inequalities, specifically focusing on that of a local interpretation of quantum

mechanics obtained through a violation of the principle of statistical independence (SI). After presenting a quick review of the various possible paths to model such a violation, we focus on the specific subclass of theories known as superdeterminism. Despite the core idea behind this proposal dating back to some considerations already expressed by Bell himself, until recently this approach has received little consideration in the debate around quantum foundations on the basis

of its problematic epistemic consequences. Recent works by Andreoletti & Vervoort (2022) and Palmer (2015) have suggested novel strategies to overcome these difficulties and reinvigorate the debate surrounding the violation of SI. Our work builds on and complements previous criticism by proposing an alternative approach that takes a metaphysical rather than epistemic-centered perspective, challenging the problematic assumption of fundamentality employed by some superdeterministic proposals. To do so, we begin with a distinction between two classes of theories under the names of naive (NSD) and metaphysical or less-naive (MSD) superdeterminism. The first category groups those proposals (like the one discussed by Andreoletti & Vervoort 2022) that, in order to avoid the risk of falling into the kind of epistemic difficulties quoted, must present themselves as part of a fundamental theory. The second category consists of models constructed to fit the criteria for fundamentality that NSD models simply assume they are part of, such as Palmer's Invariant Set Theory, or IST (2015). The tenability of NSD is thus tied to the inclusion of superdeterminism in a fundamental theory, but, as we argue, such an assumption cannot be presupposed in order to account for the epistemological peculiarities of a given hypothesis. We compare this top-down assignment of fundamentality with previous cases of criticism of such a form of argumentation in philosophy and with an historical analysis of the notion of inertial mass, whose status as a fundamental concept in mechanics has been established only through a lengthy process of conceptual engineering (Jammer 1997).

While the methodological objections faced by NSD theories can be tackled by reducing them to MSD ones, these, in contrast, face a set of strictly metaphysical challenges, i.e. that instances of (this form of) superdeterminism involve a set of problematic metaphysical assumptions. To illustrate this claim, we consider the currently most developed form of MSD, IST, as a case study, and following the approach employed by Le Bihan (2018) in the case of quantum gravity programs.

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## Conventionalism about the spacetime-matter distinction in the early universe?

Ruward Mulder

UCI, Irvine, USA

### Abstract

Conventionalism about the spacetime–matter distinction holds that the line separating spacetime structure from matter content is not fixed by nature, but depends on representational choices that leave empirical predictions unchanged. Moreover, such choices are not themselves susceptible to empirical justification: they are conventions. On this view, claims about a phenomenon being "spacetime-like" or "matter-like" lack objective truth-value and are, at most, true by convention. The viability of such conventionalism stands or falls with two conditions: (i) the formal availability of alternative models that can be translated into one another while empirically indistinguishable, and (ii) the given model is coordinated to physical phenomena in such a way that a conceptual conflict with its rivals arises under said coordination. One may resolve the conflict by rejecting the coordination that the same structure cannot represent both concepts, or never both, never neither.

This talk examines a case of primordial cosmology that appears to satisfy both conditions: the formal equivalence between single-scalar-field inflation (typically interpreted as "matter") and Starobinsky's curvature-squared inflation (typically interpreted as "spacetime"). Because these models yield exactly the same dynamics under field redefinition, several authors have suggested that the spacetime–matter distinction collapses in this context (e.g. Ohta 2018; see also references in Dürr 2022. Dürr (2021) opposes this suggestion on philosophical grounds by arguing the spacetime side of the equivalence is more *fundamental*.

I give another reason: the suggestion that the spacetime-matter dichotomy should be given up on the basis of the equivalence in scalar-field and Starobinsky models rests on a *non sequitur*. The equivalence for condition (i) is on only met within a highly idealised modelling environment. In practice, known physics – such as the Higgs field – is routinely neglected because its effects are presumed numerically negligible for inflationary dynamics. I show that once such additional sectors are included, the two Lagrangians are no longer exactly equivalent: their agreement becomes merely approximate. The exact equivalence is shown to have rested on idealization, in Norton's (2012) sense.

The contrast with Einstein's (1921) view of conventionalism is instructive: he envisaged a unified field theory that *would* underpin conventionalism about spacetime and matter as different representational decompositions of a single underlying field. It is pointed out this is possible only because the unified field theory is precisely that: unified, without terms idealized away. Our case thus reveals a deeper lesson: conventionalism about the spacetime-matter distinction should not be sustained relative to an incomplete theory about an idealized subsystem. Perhaps the distinction cannot be upheld for other reasons (see the forthcoming collected volume by Martens, Vergouwen and Ferreiro), but – absent unification – we should not argue that matter and spacetime are non-distinct simply on the basis of pragmatic decisions of modelling practices.

In contemporary fundamental physics, formal equivalences are often celebrated as dissolving traditional conceptual distinctions. This talk offers a cautionary counterpoint: without careful attention to modelling practices – though pragmatically sound by leading to good numerical approximations – we risk mistaking properties of idealised models for features of the target system, i.e., the world itself.

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## Is the existence of unbounded operators a problem for quantum mechanics?

Zhonghao Lu

University of Pittsburgh, Pittsburgh, USA

### Abstract

In a recent paper "The unphysicality of Hilbert spaces", Carcassi, Calderón, and Aidala (2025) argue that, in quantum mechanics, the conventional Hilbert space structure is too large to be physical. The problem is brought by the existence of unbounded operators in the formalism of quantum mechanics. Many meaningful physical observables in quantum mechanics, including positions, momenta, and many Hamiltonians, are represented by unbounded self-adjoint operators, which can only be defined on a dense proper subspace of their corresponding Hilbert spaces. They suggest that the Hilbert spaces should be replaced with the Schwartz spaces in quantum mechanics, as the Hilbert spaces contain states that have infinite expectation values for certain physical observables. I argue that, first, the existence of unbounded operators does not lead to any conceptual or physical problems as they worry about, and, second, the Schwartz space formalism can bring additional difficulties.

In section 2, I show how the existence of unbounded operators and infinite expectation values pose no obstruction in determining the deterministic evolution and probability distributions of measurements in quantum mechanics. In section 3, I argue that as not all unbounded operators can have finite expectation values simultaneously, the restriction that certain unbounded operators must have finite expectation values is arbitrary and unmotivated. In Carcassi, Calderón, and Aidala's proposal, polynomials of positions x always have finite expectation values while ex can have infinite expectation values. I argue that, as they are determined by the same measurement procedure, such discrimination seems arbitrary. Moreover, the convergence of the expectation values of positions relies on behaviour of the wave functions at spatial infinity, and we have reasons to disregard its physical significance. Finally, I argue that restricting physical admissible states on the Schwartz spaces would exclude a class of meaningful Hamiltonian evolutions, including the Coulomb interaction, which is another undesirable feature of their suggestion. In section 4, I explicate the worry that operators may fail to be essentially self-adjoint on the Schwartz spaces. More specifically, I show that the structures of the Schwartz spaces cannot distinguish essentially self-adjoint operators from other symmetric operators, which leaves the evolution indeterministic.

In the rest of the paper, I further explicate the philosophical implications of the work. I suggest that the notions of "physicality" and possibility in fundamental physics have hierarchies of different levels, which admit vagueness. Finally, I connect the problem raised by Carcassi, Calderón, and Aidala with the problem of the Hadamard condition in quantum field theory.

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## Unruh, Hawking, and Equivalence

Siddharth Muthukrishnan[1], Igancio Araya[2]

[1]Black Hole Initiative, Harvard University, Cambridge, USA. [2]Universidad Andres Bello, Santiago, Chile

### Abstract

We clarify the relation between Hawking radiation (which emerges from black hole horizons) and Unruh radiation (observed by uniformly accelerating observers in flat space) by asking: To what extent are they related via the equivalence principle? We argue that the Einstein Equivalence Principle—roughly, the principle that uniformly accelerating systems are locally indistinguishable from systems in a uniform gravitational field—cannot explain the relation between Hawking and Unruh radiation. This is because Hawking and Unruh radiation are not explained by local physics—their explanation involves constraints on global vacuum states imposed by the presence or absence of horizons. The Strong Equivalence Principle—roughly, the principle that, locally, physics can be made to look Minkowskian—fares better. We argue that the Strong Equivalence Principle underwrites an approximate and limited isomorphism between the near-black-hole-horizon geometry and the Rindler geometry, and this allows Hawking radiation to be derived from Unruh radiation. Crucially, in this context, near-horizon physics can be connected to asymptotic physics, which is why a local principle yields global consequences. Our analysis highlights the care required when applying equivalence-principle reasoning to quantum phenomena. We also aim to provide a conceptually clear and quite general presentation of how Unruh and Hawking radiation are related, drawing on the contemporary mainstream theoretical physics literature; consequently, our mathematical rigor matches that of those sources.

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## Some Prehistory of Effective Theories in Physics

David Mwakima

University of Colorado, Boulder, Boulder, USA

### Abstract

**Abstract**

The exchange (Einstein, 1911) that followed Einstein's 1911 Solvay Conference presentation exposes not only the conceptual tensions raised by the emerging quantum hypothesis but also the epistemic and metaphysical commitments (which I argue were based on statistics) that early twentieth-century physicists made about the future of their discipline. By examining how these physicists navigated the ratio of specific heats anomaly, weighed competing model assumptions, and negotiated which foundational principles could be revised or retained; we gain a historically-grounded illustration of a local pragmatist approach to diachronic inquiry, where the notion of a theory being "approximately true" can be understood in terms of what Barrett (2008) calls descriptive nesting relations aimed at eliminating error. In fact, these physicists' attitude during the conference reflects a historically significant pattern in how subsequent theory change has been approached in 20th and 21st century physics using the notion of an effective (field) theory (see Rivat and Grinbaum (2020)). The final contribution of this paper is to show how a Bayesian statistical perspective of this episode can illuminate the pragmatist and evidential reasoning involved in the epistemology of effective theories (see Ruetsche (2022) and Koberinski and Fraser (2023)).

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## Is Dark Matter Falsifiable? Lessons from Small-scale Cosmic Structure

Ethan Nadler

UC San Diego, La Jolla, USA

### Abstract

Abstract

Dark matter plays a central role in cosmology. However, its ontological status remains unclear: cosmological observations tightly constrain the gravitational behavior of dark matter on large scales while radically underdetermining its microphysical nature. Viable dark matter candidates span roughly ninety orders of magnitude in mass and encompass dramatically different physics. This situation has motivated philosophical arguments that dark matter is ontologically “thin,” or even unfalsifiable. On this view, dark matter functions less like a concrete physical entity and more like a placeholder that reconciles discrepancies between theory and data.

I argue that recent observational and theoretical progress in small-scale cosmic structure forces a reassessment of these claims. In particular, certain classes of astrophysical systems—faint dwarf galaxies, strong gravitational lenses, and purely dark halos—now constitute leading tests of dark matter microphysics beyond gravity. These probes do not merely refine parameters within a fixed framework; instead, they have the potential to discriminate among, and in some cases rule out, broad classes of dark matter models including warm, interacting, and non-particle candidates. As a result, the dark matter hypothesis admits meaningful empirical risk.

From an effective field theory perspective, the smallest accessible cosmic scales are intrinsically the most sensitive probes of new dark matter microphysics. I explain how upcoming data will qualitatively advance this regime and analyze what should count as a “detection” of dark matter when the relevant evidence is indirect and gravitational, including the possible detection of dark matter halos with no baryonic content at all. I examine whether this kind of evidence can, in principle, justify treating dark matter as a real physical entity.

More broadly, I claim that dark matter occupies a distinctive position in the philosophy of science. It exemplifies a case where falsifiability and realism must be assessed through converging lines of indirect astronomical evidence, rather than through direct detection or a single decisive experiment. I relate this claim to recent work on dark matter underdetermination and realism, arguing that pessimistic conclusions about dark matter falsifiability rely on an outdated picture of astronomical inference in light of the advances discussed above. I conclude by suggesting how greater philosophical clarity on these issues can, in turn, inform theoretical and observational strategies in cosmology.

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## Revisiting Riemann’s Infinitesimal Conception of Structure: Local Comparability Without Rigid Congruence

Shirleen Nunn

Independent Scholar, Bakersfield, USA

### Abstract

**Abstract**
Foundational discussions of geometry and spacetime have long been shaped by an interpretation of Bernhard Riemann’s 1854 habilitation lecture that emphasizes metric structure derived from rigid congruence. This reading, strongly influenced by Hermann von Helmholtz and later echoed by Henri Poincaré, treats freely movable solid bodies as a necessary precondition for meaningful geometry. As a result, geometries with variable curvature have often been regarded as philosophically suspect or conceptually incomplete. Riemann himself, however, explicitly rejected this assumption, proposing instead that geometry should be grounded in relations among infinitesimal elements whose comparability does not presuppose rigid motion.

This talk revisits Riemann’s original conception and argues that several persistent conceptual difficulties in the foundations of spacetime arise from conflating comparability with congruence. By carefully separating these notions, we show that Riemann’s framework naturally accommodates structures in which no metric or global spatial assumptions are presupposed. In such settings, local relations are well defined, while global structure emerges only through consistency across perspectives—understood as structural compatibility rather than shared realization. On this view, infinitesimal elements function as locally articulated relational units rather than as parts of rigidly transportable bodies.

To make this point concrete, the talk introduces a minimal recursive framework used purely illustratively, with no independent geometric or physical interpretation. The framework is not proposed as a physical theory, nor as a replacement for established geometric or dynamical formalisms. Instead, it serves as an explicit demonstration of how global compatibility can arise from strictly local relations without invoking rigid congruence, global reference frames, or metric assumptions. In this setting, infinitesimal elements play a role analogous to Riemann’s line elements: they are locally comparable, structurally constrained, and globally coordinated only through coherence rather than through congruence.

This reinterpretation clarifies several foundational themes relevant to contemporary philosophy of physics: why global structure need not be simultaneously realized, how locality can be preserved without presupposing spacetime primitives, and why attempts to impose rigid congruence at the foundational level tend to obscure rather than resolve conceptual tensions. The analysis also sheds light on historical misunderstandings surrounding Riemann’s work and suggests that his original vision remains a viable and underexplored resource for current debates at the conceptual frontiers of physics.

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## EEL for the Everettian

Ray Pedersen, Sam Fletcher

University of Oxford, Oxford, United Kingdom

### Abstract

In many approaches to quantum mechanics, the eigenstate-eigenvalue link (EEL) specifies how quantum states ground property ascription. EEL states that a system instantiates the property associated with a particular eigenvalue of an operator just in case the system is in the corresponding eigenstate. In EQM, however, the universal wave function evolves unitarily without collapsing into eigenstates of such operators. Thus, any system of interest hardly ever occupies an eigenstate of any operator that represents a nontrivial property. Despite the invocation of Dennettian functionalism to solve this problem in contemporary versions of EQM, the details remain an open research program (Millhouse 2021). This leaves EQM without an adequate link between its formalism and the emergent physical properties that we would like to associate with decoherent branches. EQM therefore does not yet meet the demands of a realist theory to represent the properties of the systems it describes.

Everett (1956) and Saunders (1998) both developed state-relative links intended to ground property ascription in an Everettian setting. Since the off-diagonal terms in reduced density matrices almost never strictly vanish, however, any successful link must tell us how systems represented by mixed states instantiate the properties associated with eigenvalues corresponding to eigenstates. The mixed state is not identical to any eigenstate, and so the property instantiated by the system is not identical to the property associated with the relevant eigenstate. EEL therefore cannot straightforwardly apply; an Everettian EEL requires a notion of approximation. A further challenge arises with Wallace's (2019) objection to an Everettian EEL based on Hegerfeldt's theorem, which aims to show that EEL implies there can be no substantive change in a system's properties under unitary dynamics. We argue that this objection tacitly presupposes a time-independent Hamiltonian, thereby restricting its scope to closed systems while leaving open the possibility of a link relativized to interacting subsystems. These considerations motivate the need for a link that is branch-relative, subsystem-relative, and governed by a principled account of approximation.

We propose an Everettian EEL that correlates properties with the eigenstates of branch-relative subsystems whose effective dynamics are governed by interaction with an environment. The link licenses determinate property ascription when a subsystem's branch-relative state is an eigenstate of an operator that represents a nontrivial property. Although subsystems in general will then instantiate properties that are slightly different from what we attribute to them, these properties will be close enough in their extensions in state space to be physically indistinguishable. This appeal to indistinguishability in attribution parallels the same in accounts of emergent branches in decoherence, rather than permissively weakening of EEL. As a result, the proposal differs fundamentally from Albert and Loewer's (1996) fuzzy link: instead of putting vagueness in the link itself, it employs approximation in the attribution of which property a subsystem instantiates. By connecting the universal wave function to branch-relative emergent properties, the proposal supplies a representational link that enables EQM to qualify as a realist theory.

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## How to make semiclassical gravity consistent?

Francisco Pipa

School of Mathematics and Physics, University of Queensland, Brisbane, Australia

### Abstract

We argue that semiclassical gravity can be made consistent if quantum systems source gravity only when they participate in non-gravitational interactions that lead to environment-induced decoherence. Outside such decoherence-based events, systems do not contribute their stress-energy to the semiclassical equations, so regions lacking these interactions may remain (approximately) flat. The proposal is testable by probing the gravitational field sourced by systems, which should depend entirely on environment-induced decoherence due to matter fields; by gravity not mediating entanglement in the Bose-Marletto-Vedral (BMV) experiment; and by how the reversibility of the initial state in this experiment would depend solely on this decoherence, distinguishing it from competing approaches. We propose a kind of decoherence-inducing interaction that leads systems to source gravity, modeling decoherence as chains of causally ordered, localized interactions between quantum matter fields, which select the states and observables that source gravity. We argue that these interactions lead to the emergence of gravity. One way to see this is to note that these chains consist of timelike and lightlike separated events, whose causal order determines the metric up to a local conformal factor (Hawking-King-McCarthy-Malament theorem), and that when the number of events can be associated with the four-volume of spacetime, it provides the remaining information to fix the metric. Another way to understand this emergence is to note that these events can be correlated, so that the metric can be understood as arising from these interactions. This framework is conservative: it does not modify standard quantum theory while providing a consistent semiclassical theory of gravity. We will further discuss other potential payoffs of this approach.

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## Bohrian Measurement Problem: Language, Semantic Communication, and Quantum Theory

Varun Immanuel Premkumar

University at Albany, Albany, USA

### Abstract

To supplement familiar approaches in quantum theory—interpretation, modification, and reconstruction—we take a different route in this work. We explore the consequences of keeping standard quantum theory with Bohr's minimal operational interpretation. We also retain higher-level empirical regularities, which become relevant at higher levels of complexity. These are regularities concerning how experimenters communicate in ordinary language about their operational interventions. We call such systems "language-bearing systems"—they include computers, humans, robots, and other systems that can communicate meaningful information using natural language and navigate the world.

We consider the reverse of existing methods. In place of aiming to explain definiteness and intersubjective agreeability of facts, we treat these as empirical regularities in nature, applicable to language-bearing systems. This is similar to regarding the laws of evolution by natural selection as fundamental laws that apply to complex systems such as organisms and technologies, even though they supervene on known elementary particles.

We do not take classical mechanics as primitive. Classical mechanics remains an effective theory whose origin must be explained jointly in terms of quantum theory and higher-level features of language-bearing systems. To this end, we distinguish three senses of "measurement": comparison with a calibrated standard (coincidence measurement), measurement as information copying (correlation measurement), and measurement as quantum-state determination (tomography). This distinction leads us to the general features that language-bearing systems share when they engage in experimentation.

This approach leads us to three primitive "modes of existence" which can be seen as ontological categories, not as substances. These include potentialities (a generalized version of Heisenberg’s idea, covering even classical electromagnetic fields in vacuum), actualities (such as detector clicks), and language-bearing systems. All are supervenient on the known particles of the standard model, yet each is still irreducible. Importantly, these three modes are defined by function rather than by length scale.

These developments, combined with the Dirac-von Neumann postulates of quantum theory, suggest three distinct kinds of emergences of classical dynamics. These emergences correspond to the three modes of existence; two are already known. One is for potentialities, in which classical dynamics arises from environment-induced decoherence. Another concerns computational processes inside language-bearing systems, where classical computing emerges via Dorit Aharonov’s noisy quantum computer model. Finally, for actualities, we derive the natural occurrence of a class of dynamics previously studied in engineered contexts, namely the measurement-induced entanglement phase transition MITP, which serves as a mechanism for the emergence of classical mechanics.

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## From Quantum States to Spacetime Structure: A Relational–Modal Ontology for Fundamental Physics.

Mosaab Raad

Department of Philosophy, Lebanese University, Beirut, Algeria

### Abstract

Abstract

Contemporary foundational physics faces a persistent tension between the formal success of quantum theory and the conceptual opacity surrounding the ontology of quantum states and the status of spacetime. Quantum mechanics is most naturally formulated in terms of abstract state spaces and operator algebras, while spacetime continues to function as the primary arena for physical processes. This talk develops a unified philosophical framework in which both quantum states and spacetime emerge from a deeper relational–modal structure, challenging the assumption that either Hilbert space or spacetime geometry is fundamental.

The central proposal is that the basic ontology of physics consists neither of objects nor of spacetime events, but of modal relations: structured patterns of physical possibility and constraint – that is, which transitions between physical situations are allowed, and with what weights. Quantum states are interpreted as codifications of this modal structure, rather than as descriptions of substances or fields. Spacetime, in turn, is reconstructed as a higher-level organization of relatively stable modal relations that exhibit approximate locality, dimensionality, and causal ordering.

Within this framework, the measurement problem is reframed: instead of asking how definite outcomes arise from a superposed physical state, we ask how robust modal patterns give rise to effectively classical regimes. Decoherence is reinterpreted as a dynamical sharpening of modal constraints rather than a physical collapse or literal branching, thereby preserving the empirical content of quantum theory without additional ontological postulates such as wavefunction collapse or a many-worlds ontology. Quantum nonlocality, as witnessed in violations of Bell inequalities, is likewise understood as the manifestation of globally constrained modal structure that is not decomposable into independent local substructures, rather than as evidence for superluminal influences.

Turning to spacetime, the talk argues that geometric notions such as distance, dimension, and curvature should be viewed as coarse-grained descriptors of large-scale regularities in modal connectivity. This perspective resonates with emergent spacetime programs in quantum gravity, while remaining neutral on specific microphysical models. It also advances beyond existing relational approaches (e.g. Esfeld 2001; Dorato 2000) by explicitly

integrating quantum modal structure with emergent spacetime geometry within a single ontological framework.

Philosophically, the proposal occupies a middle ground between structural realism and modal realism: it affirms the reality of structure and modality without reifying abstract mathematical objects or invoking Lewis-style possible worlds. The resulting picture reconceives the task of fundamental physics as the discovery of the minimal modal architecture capable of generating both quantum phenomena and effective spacetime geometry.


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## Heuristics of supergravity

James Read

University of Oxford, Oxford, United Kingdom

### Abstract

Supersymmetry is a postulated symmetry in which bosonic (integer spin) fields are sent to fermionic (half integer spin) fields and vice versa. Despite not being empirically confirmed in any way in particle physics experiments such as those at the Large Hadron Collider, it remains a mainstay on 'beyond the Standard Model' theoretical physics. Technically, one way in which to implement supersymmetry is by enriching the spacetime manifold with extra 'Grassmann-valued' (i.e., anti-commuting) coordinates, to arrive at the structure of so-called ‘supermanifold’ (see Menon (2021) for a philosophical introduction).

Standard supersymmetric field theories, however, are still set in flat spacetime: as such, they are the supersymmetric analogues of special relativistic field theories. If one wishes to combine gravitational effects with supersymmetry, one must move to curved superspaces---in doing this, one arrives at so-called 'supergravity' theories.

Supergravity is not just a theoretical plaything: it is a crucial stepping stone towards a full theory of quantum gravity. Indeed, it's well known amongst theorists that the low-energy limit of 11-dimensional 'M-theory' is a supergravity theory. Given its importance in theoretical physics, it is incumbent upon us to understand the structure of supergravity theories; their moving parts, and their ontological commitments. Technically, however, the formalism of supergravity theories is forbidding (see Dall’Agata & Zagermann (2021) for arguably the conceptually clearest introduction to the topic); relatedly, the metaphysical upshots of such theories are not at all straightforward to glean. (For example, even in the context of supersymmetric theories, the ontology of spacetime points differs vastly from settings without supersymmetry: see Huggett et al. (2021) for a warmup in the context of non-commutative geometry.)

In this talk, I propose to clarify the theoretical architecture of supergravity theories by beginning not with the geometrical formalism, but rather with the kind of reasoning which Hetzroni & Read (2023) have argued is involved in the heuristics of moving from special relativity to general relativity—namely, inductive arguments involving minimal modifications to the theory which came before. (Hetzroni & Read (2023) argue that this reasoning can be found in Einstein’s first review of general relativity (1916), and is also consistent with Bell’s (1976) famous injunction against “premature philosophising about space and time”).

More specifically: I will show how these kinds of heuristics—the centrepiece of which being a device which Hetzroni & Read call the ‘methodological equivalence principle’—can also be employed in order to move from a flat-spacetime supersymmetric theory to the structure of a supergravity theory. Doing so will render each part of a supergravity theory both natural and inevitable, whereas arguably in textbook presentations the motivation for such parts is obscure. In turn, this will facilitate much clearer answers on what the world is like according to supergravity.

(Based upon joint work with Guy Hetzroni.)

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## Can we pause the elimination of inertial frames?

Yifei Ren

Western University, London, Canada

### Abstract

I want to argue that Machian relationalists, Julian Barbour and his collaborators, cannot coherently hold the view that a conformal 3-geometry is primitive in their ontology (Barbour, 2011), yet inertial frames are not (Barbour and Bertotti, 1982).

The Machian relationalist interprets an inertial frame as a system where total linear and angular momenta vanish (1982). Such a frame can be picked out via a conformal 3-geometry action principle, which corresponds to geodesics in the space (Barbour, 2011). On this view, a conformal 3-geometry and action principles are more fundamental than inertial frames.

If the Machian takes a conformal 3-geometry as primitive, then they are also committed to an affine structure, in which straightness and parallelism of lines are defined. In general relativity, straight lines (geodesics) are physically interpreted as the paths of force-free particles.

An inertial frame is a standard relative to which motion and rest may be measured (DiSalle, 2020). In general relativity, the paths of free-falling particles define the standard relative to which motion and rest are measured; thus, free-falling particles determine what counts as inertial frames. An inertial frame is a privileged state of motion (DiSalle, 1995)—the state of motion relative to which comparisons of other motions are made possible.

Hence, if the Machian takes affine structure as primitive, then in general relativity, they are required to take the paths of free-falling particles as primitive. This in turn requires taking inertial frames as primitive, which commits them to privileged states of motion. I claim that the existence of privileged states of motion conflicts with the relationalist philosophical motivation that all motions are purely relative. I argue that relationalists who stay true to this principle cannot coherently include conformal geometry in their primitive ontology.

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## Heat As Gauge

Bryan W Roberts

London School of Economics, London, United Kingdom

### Abstract

It is sometimes possible to shed light on one physical theory by casting it in the language of another, thus allowing conceptual tools to be shared between them. For example, philosophers have done so by arguing that thermodynamics is a special case of control theory (Wallace 2014, Myrvold 2020). The purpose of this paper is to do so by showing how classical thermodynamics is a special case of gauge physics.

In particular, it is well known that a gauge connection has vanishing curvature if and only if it is integrable, and that heat is integrable if and only if it can be locally expressed as TdS. In this paper we combine these two facts: viewing heat as a gauge connection, we show that vanishing thermal curvature is equivalent to the local existence of entropy and temperature functions. In other words, heat defines a connection on a line bundle over work configurations, which admits a local integrating factor whenever its curvature vanishes.Identifying equilibrium with the presence of a flat gauge connection in this way opens up new possibilities for formulating non-equilibrium thermodynamics as a gauge theory with a connection that is curved. The proof of a conjecture of Jauch (1972) regarding the existence of entropy and temperature follows as a special case.

As an example of how this framework can be fruitfully used, we show that geometric or 'Berry' phase, familiar from gauge theories with non-trivial holonomy structure, has a formal analogue in thermodynamics. Experiments have shown that fluctuations give rise to anomalous heat transfer from cold to hot regions, in apparent 'violation' of the second law. Recent work in stochastic thermodynamics has shown that some of these anomalies may be resolved through the introduction of a formal 'geometric phase' contribution to heat (Ren et al. 2010, Liu et al. 2024). Our framework provides a theoretical basis for these results in gauge physics.

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## Circling Back to Holonomies

Madeleine Roberts, Hans Halvorson

Princeton University, Princeton, USA

**Abstract**

The holy grail of “science-informed metaphysics” is an experiment whose outcome changes a fundamental plank of our metaphysical outlook. Such was the case with the violation of Bell's inequality, and such is the case—according to its discoverers—with the Aharonov-Bohm (AB) effect. Nevertheless, after more than sixty-five years of discussion, there is still fundamental disagreement about the philosophical upshot of the phenomenon.

According to the traditional framing, the task of explaining the AB effect forces us into a dilemma: we must either reify gauge-variant properties, or concede a violation of locality. Philosophers have sensed this dichotomy is faulty, and a clear consensus has emerged that nonlocality, in one sense or another, is unavoidable. Unfortunately, this consensus is based on shared sentiment rather than rigorous arguments.

Based on joint work with Hans Halvorson, this talk revisits the AB effect, prioritizing conceptual clarity over falling neatly into the categories of the traditional dilemma. Starting from the assumption that one's commitments about what is real should harmonize with one's commitments about physical equivalence between models, we consider notions of physical equivalence between models of three closely related theories: (1) QM plus classical EM in R^2, (2) QM on S^1, and (3) classical EM on S^1. Through this analysis, we draw lessons from the AB effect for our metaphysical understanding.

Along the way, we consider the holonomy interpretation (see e.g. Belot 1998 and Healey 2007). Previous presentations of this interpretation have not lived up to standards of ontological clarity (vide Maudlin 2018) and have thereby been vulnerable to criticisms that are misdirected (pace Jacobs 2023). Our investigation offers a much-needed clarification of what exactly it means to say that holonomies are “real,” as well as the oft-repeated assertion that they involve a kind of nonlocality. The upshot of this discussion is a revision and revitalization of the holonomy interpretation as a viable response to the AB

effect. We claim that holonomies should not be seen as properties of (nonlocal) loops, but as labels for superselection sectors.


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## Low-Weight Branches and Humeanism About Laws

Jerome Romagosa

University of California, Davis, Davis, USA

### Abstract

Many have worried that Everettian Quantum Mechanics (EQM) is not susceptible to ordinary scientific confirmation and disconfirmation from empirical evidence. Everettians such as Wallace (2012) have offered decision-theoretic strategies for Everettian probability, that if successful, provide an account of empirical (dis)confirmation in EQM. I argue, however, that such strategies are in tension with a common epistemological motivation for Humeanism about laws of nature: that Humean laws are knowable via knowledge of occurrent matters of fact. Put roughly, Humeanism about laws holds that laws of nature are merely the best summaries of patterns of events—they describe, but do not "produce'' their instances. The Everettian multiverse entails the existence of low-weight branches in which the relative frequencies of experimental outcomes do not align with the statistical predictions made by the Born rule. If EQM is to be subject to ordinary sorts of empirical confirmation and disconfirmation, agents in low-weight branches must take their empirical evidence to disconfirm EQM (and quantum mechanics in general). So in these "unlucky'' low-weight branches, knowledge of fundamental laws of nature is impossible, despite the fact that agents in such branches can have the same sort of knowledge about occurrent matters of fact—such as the relative frequencies of experimental outcomes—that agents possess in Born-typical branches.

I then show that while an infinite universe with fundamental stochastic laws could generate similarly "unlucky" agents, the Everettian case is uniquely problematic. Low-weight branches are ineliminable parts of the overall Everettian mosaic: their existence is required for a complete Everettian universe, since we cannot make sense of the entire quantum state without its low-weight components. Accepting EQM means committing to the claim that low-weight branches exist, and that one has counterparts—agents with qualitatively identical pasts as oneself—in such branches who cannot accept EQM on pain of irrationality. In contrast, we do not need low-probability results or regions of spacetime to make sense of fundamental stochastic laws in non-Everettian infinite universes. While the Everettian is committed to a claim like 'everything Schrödinger's equation says happens does in fact happen', an infinite universe with stochastic laws does not itself entail that 'everything possible does in fact happen'. Accepting EQM thus means accepting that there are agents—counterparts of oneself with qualitatively identical pasts—who are rationally required to reject the true description of their own situation, and hence for whom empirical observation cannot be a guide to the laws of nature.

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## Spatial Topology and Conventionality

Patrick Ryan

New York University, New York, USA

### Abstract

In this talk, I consider the prospects of a conventionalist position concerning the spatial topology of the universe. Much contemporary cosmological research devoted to ascertaining the topology of space (viz., whether it is simply- or multiply-connected) assumes the Cosmological Principle (CP), i.e., the claim that on average and at large scales the universe is spatially isotropic and homogeneous around every point (Lachièze-Rey and Luminet 1995). This has the effect of focusing attention upon a particularly well-behaved class of cosmological models, viz., the FLRW models. However, CP is a very strong constraint on our cosmological theorizing, and its justification is fraught with difficulties (Beisbart 2009). As such, it has recently been suggested that a more accurate reflection of our observational situation would be to assume "approximate local isotropy" around each spatial point (Ringström 2013). Unfortunately, there is then a sense in which one cannot draw any conclusions about spatial topology from observations (Ringström 2013; Belot 2023). I will argue that these considerations result in a severe form of topological underdetermination, one that is neither transient nor amenable to resolution by appeal to canonical theoretical virtues. Consequently, I argue that the most promising philosophical response to this underdetermination is to adopt a topological conventionalism. Such a position has many virtues; in particular, it is a "selective anti-realism" that does not require that we relinquish realist commitment to all aspects of a given spacetime theory (Dürr and Read 2024). It also allows us to make sense of the "transcendence" of topological structure, namely, that it functions (along with further spacetime structure) as a condition of the possibility of meaningful, local physical laws. Time permitting, especially in light of the latter point, I consider whether a neo-Kantian approach along the lines of Friedman's relativized a priori could be a reasonable response to our topological underdetermination.

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## Is the Standard Model an Effective Field Theory?

Dominic Ryder[1], Michael Miller[2]

[1]LSE, London, United Kingdom. [2]University of Toronto, Toronto, Canada

### Abstract

Empirically successful quantum field theories are understood by contemporary physicists as effective field theories. This includes, but is not limited to, the Standard Model of Particle Physics, our most fundamental theory of matter and non-gravitational forces. The effectiveness of theories has recently received substantial attention in the philosophy of physics literature. The attribution of effectiveness has been regarded as important to a wide range of topics in philosophy, including but not limited to: ontology (Wallace, 2011), scientific realism (Williams, 2019), and reduction and emergence (Bain, 2013). It is therefore surprising that little-to-no attention has been paid to two foundational questions: What does it mean to be an effective theory, and why should one believe that the Standard Model is effective? In this talk, answers to these questions are provided.

At least two distinct notions of effectiveness are often conflated. Effective$_1$ is associated with the use of the mathematical methods of modern Effective Field Theory, and effective2 is associated with having a limited domain of applicability due to theory breakdown. We show that, contra suggestions in the physics and philosophy of physics literature, effective$_1$ does not imply effective2; in fact they are independent. In this talk we focus on the claim that the Standard Model is effective$_2$ because the Standard Model is trivially effective$_1$ and because effective$_2$ is the epistemologically consequential notion.

We disambiguate further senses of effective$_2$ corresponding to different notions of breakdown: breakdown of empirical adequacy, breakdown of the physical picture, and breakdown of calculational methods. Each sense of breakdown comes in two degrees of severity: those that necessitate a new physical framework, and those that do not. We now analyse the claim that the Standard Model effective$_2$, where effective2 ranges over its six senses.

We provide a novel taxonomy of the reasons to construe the Standard Model as effective$_2$: 1. UV-incompleteness, 2. quantum gravity, 3. arguments from humility and history, 4. unexplained empirical observations, and 5. unexplained theoretical observations. On analysing the strength and target of each, we find significant inhomogeneity. For instance, unexplained empirical observations guarantee empirical adequacy breakdown, but don’t motivate framework change. History and humility on the other hand strongly motivate empirical breakdown and framework change, but don’t guarantee either.

UV-incompleteness is itself a heterogeneous taxa. We show that if it is evidenced by non-renormalizability then it fails to imply empirical or physical picture breakdown. If it is

evidenced by a Landau pole then this evidence can be either perturbative or non-perturbative; the former is suggestive of empirical and physical picture breakdown but does not guarantee them, and the latter guarantees both but we have no such evidence.

We conclude that the claim "the Standard Model is an effective theory" is ambiguous without specification of the sense of effectiveness. It is trivially true on some senses, interestingly true on others, and surprisingly doubtful on further senses. This talk seeks to clarify the epistemology status of the Standard Model by parsing these senses and analysing the arguments for each.

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## The Process of Particle Localization in a Quantum Theory of Fields

Charles Sebens

Caltech, Pasadena, USA

### Abstract

In non-relativistic quantum mechanics, if you have a particle that is in a superposition of two distant locations and look for it at one location, it appears to collapse to a single location. Bohmian mechanics says that it was already at that location before measurement. The many-worlds interpretation says that we get a superposition of branches in which the particle is either in one location or the other. I seek to better understand the relation of particles to fields by asking how relativistic quantum field theory handles such measurements, given that what you do in one region cannot alter the reduced density matrix state of a distant region (by the locality of the theory's unitary dynamics; Chua and Sebens, forthcoming). This independence can be seen in EPR-Bohm measurements of entangled spin states, an example that serves as a useful analogy for what happens during position measurements in quantum field theory.

In quantum field theory, one way to represent the quantum state is as a wave functional over classical field configurations (Sebens, 2022). The wave functional can be squared to get a probability distribution over field configurations. A challenge facing this field formulation of quantum field theory is to explain particle-like behavior in measurements like the one described above. To describe that setup, the non-relativistic quantum wave function with peaks at the two locations is replaced by a wave functional peaked around field configurations that have lumps at both locations (Valentini, 1992; Struyve, 2010). The particle has pieces in two different places. When you look for the particle in one place, what happens to the distant piece?

Taking a Bohmian approach, one can add to the ontology a field (in a particular true configuration) that is guided by the wave functional. This field might start with small lumps at both locations and then evolve into a configuration with either a big lump or no lump at the observed location, reflecting whether the particle was found there or not. At the distant location, there would be a (somewhat surprising) persisting small lump. That lump is already destined to either grow or disappear when one looks for a particle there (depending on the result of the earlier observation).

Taking a many-worlds approach, there is only the wave functional. There are two ways to describe the evolution of this wave functional in terms of branching worlds. On the view that branching is local, looking for the particle at one location yields branches there (where the particle is either found or not), but does not cause any branching at the other location. On the view that branching is global, the measurement leaves you with two branches: one branch described by a part of the wave functional that is peaked at a field configuration with a big lump at the observed location and no lump at the other location, and another branch peaked at a configuration with no lump in the observed region and a big lump at the other location.

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## Toward a Foundation for Cosmo/Astrostatistics: Deideaization from Structure Formation to the Cosmos

Tianzhe Cozette Shen

University of Arizona, Tucson, USA

### Abstract

In the widely accepted cosmological model containing cold dark matter, structure formation is described as bottom-up and hierarchical. In the very early Universe, low mass objects were formed, and through their colliding and merging, or "clustering", larger systems, from galaxies to galaxy clusters to superclusters, were formed over time. Objects at each astronomical scale are usually modeled and studied separately. Galaxy clusters are of particular interest because (1) they are believed to be dominated by (cold) dark matter, and (2) to model their formation, certain idealizations are necessary for both the clusters and their background—the Universe. Kaiser (1986) developed a model for (rich) clusters intended to predict the statistical nature of clusters at any epoch with purposely simplified/idealized cosmological assumptions. According to this model, clusters are formed in a scale-free gravitational spherical collapse in an Einstein–deSitter Universe with $\Omega_m$=1. They are self-similar objects, by which their physical properties are expected to simply scale with mass and redshift, leading to a power-law-form relation between physical properties X and Y, generally expressed as $Y=AE(z)^{\gamma}X^{B}$.

Such relations, called scaling relations, can be established empirically via observations (commonly X-ray). They are frequently used to probe cosmological parameters (Migkas 2025), and more importantly, to test for "departures from the self-similar expectations", elucidating other potentially contributing (astro)physical processes not included in the self-similar models. (Lovisari & Maughan, 2022) Plausibly, the empirical studies of galaxy cluster scaling relations can be taken as essentially part of a deidealization process, leading to more realistic cluster models.

However, since both Kaiser's model and the scaling relations are statistical by nature, cosmological inferences made upon the deidealized cluster models do not necessarily amount to proper deidealization of the idealized cosmology assumed in Kaiser's model. In other words, there is an epistemic gap between the scaling relations and the cosmological inferences made upon. Moreover, while statistical models do not typically go beyond the modeled systems themselves, in the case of galaxy cluster scaling relations, we indeed are trying to make inferences beyond clusters, but we seem not to have a reasonable foundation to ground such inferences. This raises serious interpretative and foundational challenges to this method, deviating from general philosophical debates on statistical modeling in science. Furthermore, since scaling relations have also been commonly established at other scales (e.g., stars and galaxies), structurally similar challenges arise from this general method.

Another crucial part of this process involves computational studies, particularly via cosmological simulations, in which one can turn on and off different (astro)physical

processes—some being cosmologically relevant—to produce scaling relations of cluster analogs and then compare the simulated relations with observed ones. However, this is far from closing the gap, because (1) such a simulation can only work with known (astro)physical processes, and (2) the concept of robustness is not (yet) methodologically well-established in the context of cosmology.

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## The Path Dependence of Inter-theoretic Relations

Kabir Bakshi

HPS, University of Pittsburgh, Pittsburgh, USA

### Abstract

This paper argues that inter-theoretic relations in science are path dependent: the relation between two theories depends not only on the content and form of those theories but also on the intermediate theories -- which I call "inbetweeners" -- through which the relation is established. I develop this argument by working through the problem of defining thermodynamic work in quantum thermodynamics, a problem that has generated sustained debate in contemporary physics.

I begin by surveying the centrality of work to the theoretical edifice of thermal physics and presenting two prominent definitions of quantum work: the Two Point Measurement (TPM) definition, which treats quantum work as a classical stochastic variable, and the operator of work definition, which treats it as a Hermitian observable. No-go theorems demonstrate that no definition of quantum work can simultaneously satisfy three reasonable desiderata — generality, consistency with the First Law of Thermodynamics, and recovery of classical thermodynamic work distribution in an appropriate limit (Perarnau-Llobet et al. 2017).

Building on David Chalmers' work on the philosophy of verbal disputes, I diagnose the debate over "what is quantum work?" as a verbal dispute (Chalmers 2011). However, I argue that the underlying dispute over the nature of the inter-theoretic relation between classical and quantum thermodynamics is not merely verbal but substantive, involving genuine disagreements about which theoretical structures and laws must be preserved in the transition to the quantum regime.

I then locate the source of this substantive dispute in the choice of inbetweener theory. The TPM approach routes the inter-theoretic relation through stochastic thermodynamics, treating work as a classical stochastic variable and justifying the definition via semiclassical methods (Jarzynski et. al. 2015). The operator approach, on the other hand, routes it through quantum mechanics, treating work as a quantum observable justified by formal analogy with the classical First Law. These different paths yield different theories of quantum thermodynamics, different definitions of quantum work, and different theoretical commitments.

I argue that this case reveals the inadequacy of existing philosophical accounts of inter-theoretic reduction, including neo-Nagelian, Nicklesian, and pluralist approaches, all of which treat the relation as a two-place relation between reducing and reduced theories alone (Palacios 2022). I advocate instead for a path-dependent approach to reduction that recognizes the constitutive role of inbetweener theories. I close by drawing connections to circulatory models of knowledge production in history of science and extracting further lessons for debates over pragmatism in quantum thermodynamics, the emergence of verbal disputes across theoretical regimes, and conceptual engineering in philosophy of language.

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## No Thermalization without Quantum Representation

Brett Park, Kabir Bakshi

History and Philosophy of Science, University of Pittsburgh, Pittsburgh, USA

### Abstract

Statistical Mechanics provides a microphysical underpinning for thermodynamic phenomena. What the best way to understand statistical mechanics is has been a theme of sustained interest and importance in philosophy of physics. This question, however, is also of great interest in general philosophy of science, given that the inter-theoretic relation between thermodynamics and statistical mechanics (whatever it maybe) is taken to be the paradigmatic example of reduction in science (Palacios 2022). Two competing approaches to statistical mechanics have become established and entrenched in the philosophy literature. On the first, statistical mechanics deals with particular systems which occupy particular microstates and how those microstates change with time. This is Boltzmannian Statistical Mechanics (Frigg and Werndl 2024). On the second, statistical mechanics deals with an ensemble of systems and how the probability distribution of various quantities of the ensemble changes with time. This is Gibbsian Statistical Mechanics (Wallace 2020).

The recent decade has been witness to sustained discussions in the philosophy of science literature over which of these two is the better or the more fundamental approach to understand statistical mechanics. In this paper, we argue that the distinction between these two approaches fades away in Quantum Statistical Mechanics. Since quantum physics is a more fundamental theory than classical physics, we conclude that the Boltzmann-Gibbsian dichotomy must be dispensed with.

The major reason why the distinction fades in quantum mechanics concerns thermal fluctuations in and the approach to equilibration of quantum systems. We argue that neither the Boltzmannian nor the Gibbisan approach fully capture thermal fluctuations in quantum systems as presented in the Eigenstate Thermalization Hypothesis (ETH) – a recent influential proposal of the mechanism of thermalization in quantum systems (Deutsch 1991; D'Alessio et al 2016). Instead, we show that the results of thermalization and fluctuation in the ETH framework can only be understood through a composite approach, an approach that appeals to both Boltzmannian and Gibbsian elements. In other words, we argue that the Boltzmannian notion of fluctuation, as the dynamical fluctuation of individual systems away from equilibrium, and the Gibbsian notion, as differences from the equilibrium value upon projective measurement, are both essential to understanding ETH. Differences between the Boltzmannian and Gibbsian approaches to understand statistical mechanics turn out to be largely semantic in quantum statistical mechanics.

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## Everettian chance in no uncertain terms

Jer Steeger[1], James Read[2]

[1]University of Bristol, Bristol, United Kingdom. [2]University of Oxford, Oxford, United Kingdom

### Abstract

#### Abstract

The current landscape of views on chance in the Everett interpretation is rocky. Everettians (Wallace 2012, Sebens and Carroll 2018, McQueen and Vaidman 2019) agree that chance values should be derived using principles governing uncertain or partial belief, but they cannot agree on how. Critics (Dawid and Thébault 2015, Mandolesi 2019) maintain that any such approach is circular. We smooth the landscape by shifting focus from what Everettians take to be uncertain to what they should think is certain: namely, the conditions under which branches are isolated. Our approach to isolation resolves the main tensions among the different Everettian chance derivations while clarifying how they avoid circularity.

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#### Preprint

https://philsci-archive.pitt.edu/id/eprint/26677

## Invariance, Congruent Transport, and the Adaptation of Matter to Spacetime

Adán Sus

Universidad de Valladolid, Valladolid, Spain

### Abstract

Much has recently been discussed about the relation between spacetime and dynamical symmetries, or more generally about the commitments involved in interpreting certain objects (e.g. the metric of GR) as representing the chrono-geometry of physical spacetime. Far from being settled, however, I believe there is still much more to be said. One way of formulating the central issue in dispute concerns what is presupposed when one claims that, in the context of a theory, spacetime has such-and-such a geometry: to what extent this claim assumes that matter dynamics is adapted to that geometry, and what an acceptable account of this relation of adaptation amounts to.

The main aim of this talk is to develop an account of this relation that goes beyond those offered by the two main approaches: the geometrical (GA) and the dynamical (DA). Their limitations have already been noted in the literature. An unqualified GA would implausibly hold that a primitively determined spacetime geometry constrains dynamics, while defenders of the DA—at least in the context of GR—typically invoke the requirement that matter laws implement some notion of local symmetry, perhaps nomologically imposed through the strong equivalence principle, as expressing the fact that matter "surveys" spacetime geometry. As has been convincingly argued in various places, these accounts face serious difficulties.

The alternative I propose, inspired by Weyl's formulation of the so-called problem of space—the question of how the geometry of physical space is determined in a relativistic context—and close to a methodological reading of the gauge argument, aims to capture an idea of adaptation according to which quantities that are, in a specific sense, empirically determinable must advert to physical geometry; here, "physical" means that it is this geometry that provides the rule for comparing such quantities. This idea is initially informal, and the proposal consists in giving it more precise and formal content, which can be summarized as follows.

The account begins by identifying physically relevant quantities as those invariant under the spacetime symmetry group at each point, and then requires that these quantities be congruent when transported to nearby points according to the rule defined by the affine connection compatible with the spacetime metric. This imposes that the standards for comparing lengths and angles of vectors representing physical matter quantities are fixed by the spatiotemporal structures of the theory, as captured by Weyl's principles for determining physical spacetime. What we are doing is imposing the conditions of local congruence that Weyl requires for vectors, in the determination of the geometry of physical space, on the matter quantities they are supposed to represent, and interpreting such

quantities as empirically determinable. I then discuss the implications of these conditions for the formulation of matter equations of motion, and how they allow us to distinguish theories that are well adapted to spacetime geometry from those that are not. In the final part of the talk, I address some interpretive issues, in particular the distinction between internal and external symmetries.

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## Go Results for Unsharp Particle Localization

Noel Swanson

University of Delaware, Newark, USA

### Abstract

Unifying relativity and quantum mechanics precludes familiar notions of particle localization due to two clusters of no-go results, *Hegerfeldt-type theorems* (Hegerfeldt 1974, 1985, 1998) and *Malament-type theorems*(Malament 1996, Busch 1999). Halvorson and Clifton (2002) unify these two clusters into a single set of sharpened no-go results that apparently rule out both sharply localized particle states (detectable in bounded spatial regions with probability 1) and unsharply localized particle states (detectable in bounded spatial regions with probability less than 1). The latter conclusion is especially puzzling. It flies in the face of experimental practice in physics where particles are modeled using wavepackets with exponential tails. Moreover, it is at odds with recent constructions of position POVMs in the Klein-Gordon model (Terno 2014, Moretti 2023). As Barrett (2002) argues, it also conflicts with our common sense picture of an emergent classical reality. If particles cannot even be unsharply localized, how can well-localized macroscopic objects composed of such particles emerge?

In this talk I explain how we can square unsharply localized particles with the Halvorson-Clifton no-go theorems. The key is to disentangle Hegerfeldt-type theorems and Malament-type theorems. Although they overlap, they rely on different root lemmas and depend on subtly different assumptions. In particular, microcausality plays a key role in Malament-type theorems but not Hegerfeldt-type theorems. From this vantage point, the upshot of Malament-type theorems is that particle position operators cannot be local observables, whereas Hegerfeldt-type theorems place additional constraints on quasi-local and global position operators.

This is remarkably similar to the “for all practical purposes” solution advanced by Halvorson and Clifton at the end of their own paper according to which particle detectors are modeled using quasi-local operators which can be approximated by uniform sequences of local operators. They conclude “particle detections can always be simulated by purely local measurements; and the appearance of (fairly-well) localized objects can be explained without the supposition that there are localizable particles in the strict sense’’ (p. 22). The difference is that a clearer picture of the Hegerfeldt-type theorems now allows us to give a more metaphysically robust interpretation of unsharply localized particle states using ideas from Terno (2014) and Moretti (2023). They are excitations of a quantum field with energy-momentum concentrated in a bounded region and tails stretching off to spatial infinity. Although the structure of these tails is model-dependent, in order to avoid the superluminal wavepacket spreading entailed by Hegerfeldt-type theorems, they generally have to be sub-exponential. The associated position POVMs can discriminate the structure of these tails, and thus violate microcausality. In accordance with Malament-type theorems, they cannot be local observables.

This helps make sense of conventional experimental practice, while at the same time subtly refining it, linking rigorous constructive results concerning universal QFTs to the effective

field picture. It also gives us better tools to respond to Barrett (2002). Local measurements don't merely simulate quasi-local particle detectors for all practical purposes, rather local quantities approximate well-defined global quantities which characterize the location of bumps in the quantum field with a particular shape.

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## 100 Years of the Born Rule

Diana Taschetto[1], Ricardo Correa da Silva[2]

[1]Utrecht University, Utrecht, Netherlands. [2]Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany

### Abstract

Quantum mechanics is perhaps the most successful physical theory we have ever had in terms of predictive power—and it is hardly an overstatement to say that the Born rule is almost single-handedly responsible for its predictions. The task of understanding how the mathematical formalism is related to the physical world, and why probabilities arise in quantum theory, is therefore tied to the task of understanding the Born rule, its origin and its nature—but the connection does not by itself determine the arrow of explanation. The traditional assumption that the Born rule was originally postulated rather than derived—as if it were somehow handed down from heaven—has to some extent mystified the physics behind it and has thereby fixed a very definite direction of explanation in foundational discussions: it apparently follows from it that one must first resolve the interpretative questions so that an understanding of the nature of the Born rule will follow. But this assumption about the Born rule amounts to a historical claim—and it may be mistaken. In which case, discussion is long overdue. In this talk, we share some of the findings of a new and very rigorous mathematical investigation of the conceptual development of quantum mechanics that has led to the identification of important facts constitutive of the Born rule which up to now have remained hidden from sight. We discuss a half-forgotten theorem proved by Ehrenfest in 1914 that fixed, in point of historical and theoretical fact, strict conditions as necessary and sufficient for the statistical construal of the second law of thermodynamics to be valid in the quantum theory. These conditions reveal fundamental physics now buried in the past: they lie, as we show, at the foundation of the proposition that, in the quantum theory, probabilities are completely determined by the modulus squared of the amplitude associated to the state of the system. The fact Max Born introduced the so-called Born rule in 1926 nonchalantly, in a footnote, and the fact his interpretation of the wave function was received without any surprise by many of his contemporaries—“we never imagined it could be anything else,” said Bohr—seem thereby unsurprising. For there were no wave functions before 1926 of course, but, in its form, the rule itself had been long fixed—it is there, sitting in Max Planck’s 1913 *The Theory of Heat Radiation,* for anyone who cares to look.

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## Typicality in Science and Physics

Lem Tsikas

University of Bristol, Bristol, United Kingdom

### Abstract

"Typicality" is an idea widely used in science (see e.g. Wilhelm, 2022). We talk about (for example) the typical behaviour of animals, the typical duration of a storm, the typical number of motor-related injuries in a year, the typical distance between stars in a galaxy, or the typical behaviour of a gas. Claims involving typicalities such as these cannot be falsified by individual violations of the general rule. As such it is required (and intuitively obvious) that the general rule must take a probabilistic form, and this can be explicit or implicit (Maudlin, 2011).

If individual instances of violations do not falsify claims of typicality, then what relation do they bare to them? I'll argue here that the best way to understand this is that typicality statements tell us which behaviour requires explanation and which does not. It is a secondary property of the behaviour, in that it relates really to the whole set of possible behaviours. Out of these, the typical behaviours are the ones for which the question "why did it do that?" is not interesting, and its answer is not informative.

This places typicality within physics in a unique position, since in (parts of) physics we think we deal with explanations that go "all the way down", i.e. have some element of fundamentality to them. Therefore, actual non-typical physical behaviour cannot be explained via recourse to some lower-level mechanism that sometimes makes atypical behaviour likely; in physics, such behaviour is just unlikely and that's that, so persistent observations of atypical behaviour gives us far stronger reasons to reject the purported typicality statement than in other areas of science.

I'll then take a look into how typicality works specifically within the context of statistical mechanics, and how this relates to stat mech's usage in reducing thermodynamics (see Albert, 2003 for discussion). I will essentially conclude that normal thermodynamic behaviour should be viewed as the unique large scale behaviour of systems that does not require explanation; it is the norm, and only deviations from the norm must be explained (but such deviations do not occur other than as statistical outliers, since nothing can consistently bring them about).

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## Quantum (non)separability: The T-Shirt, The Hamiltonian, and Bounded Memory

Lev Vaidman

Tel Aviv University, Tel Aviv, Israel. Institute for Quantum Studies, Chapman University, Orange, CA, USA

### Abstract

In 2000, Deutsch and Hayden (DH) [1] claimed that replacing the Schrödinger wavefunction with "descriptors" renders quantum mechanics (QM) separable. Bédard [2] found it striking that DH had received fewer than 200 citations by 2021, yet interest has surged recently, now exceeding 300 (e.g., [3,4]). This talk critically examines the separability claims of the DH formalism.

The Schrödinger ontology—a wavefunction evolving via dynamical laws—is demonstrably nonseparable; the state of remote entangled systems cannot be factorized into local descriptions. The DH ontology, conversely, relies on local descriptors (sets of operators) and an initial global wavefunction, arguing this yields a picture where empirical evidence is fully explained locally.

I argue that the DH separability claim is less substantive than it appears. Local descriptors essentially encode the unitary evolution from the initial time. Since dynamical laws (the Hamiltonian) are global and compact—simple enough to be "put on a T-shirt"—one could construct a "trivially separable" Schrödinger picture by attaching the initial wavefunction and the "T-shirt" to every local system. In this view, every system simply carries the global instructions. Thus, the recent surge in citations for DH, effectively replacing the compact T-shirt with a vast set of complex descriptors, may be unwarranted regarding ontological separability alone.

However, the DH approach demonstrates a crucial advantage in a specific context: a model of the Universe as a network of local systems with externally introduced gates. This scenario requires a different form of "trivial separability" than the global T-shirt. Here, it suffices for every local system to maintain a record of only its own past gates, but this demands unbounded memory as the history accumulates indefinitely. In contrast, DH descriptors describe the transformation of the state; they succeed in capturing the relevant history without recording the sequence of gates, thus explaining empirical evidence (given the initial global wavefunction) within bounded resources.

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## Defining superdeterminism and its negation

Mordecai Waegell

Chapman University, Orange, USA

### Abstract

Bell's theorem (Bell 1966) is best understood as showing that at least one in a list of seemingly plausible assumptions about reality must be wrong. One of these assumptions has been called `no superdeterminism' (Bell 2001), which is intended to rule out correlations between measurement settings and the independently prepared systems that will be measured, but a good general definition of this assumption has only recently appeared in the literature (Waegell & McQueen 2025). This is important because there has been recent interest in superdeterministic theories as a way to satisfy Bell's theorem while obeying local causality. The new definition identifies any systematic violation of statistical independence when vetted random sampling procedures are employed, as superdeterminism. Three categories of superdeterminism are discussed, where the entanglement correlations predicted by quantum mechanics are not strictly obeyed: fine-tuned initial conditions in deterministic theories, where entanglement correlations arise only due to the special initial conditions; statistic flukes, where the entanglement correlations arise due to indeterminism; and nomic restrictions, where measurement settings that would reveal violations of the entanglement correlations are physically impossible. The present work formally develops the structural requirements for non-superdeterministic theories and establishes the minimal conditions needed to show that a proposed physical theory is not superdeterministic. This is done by developing the concept of `generalized response functions' that show how a prepared sample responds to different measurements. This requires careful discussion of preparation procedures, measurement procedures - including random selection procedures, and the notion of representative samples. This analysis also makes it easy to see how superdeterminism is contextual.

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## Quanta and Particles in Effective Field Theory

David Wallace

University of Pittsburgh, Pittsburgh, USA

### Abstract

I explore the relation between field and particle in quantum field theory (QFT) from an effective-field-theory perspective.

In noninteracting QFT, and also in nonrelativistic QFT, there is an exact duality between field and particle descriptions, with the field operators being interpretable as creation operators for quanta of the field Hamiltonian and those quanta in turn being interpretable as (quantum) particles in as full a sense as we might wish. This duality breaks down when relativistic interactions are considered; the breakdown can be seen abstract through results like Haag's Theorem but also shows up concretely in the breakdown of the creation-operator interpretation of the fields and the zero-quanta interpretation of the vacuum.

An "interacting quanta" interpretation of a relativistic QFT remains viable in those regimes whether the theory is weakly interacting; the interaction term can then be seen as generating transitions between quanta. This interpretation bears a strong resemblance to the familiar heuristic accounts of `virtual particles', `particles appearing and disappearing in the vacuum', etc, that one finds in the semipopular literature. But the notion of `particle' here is extremely thin: quanta have unclear localization properties, lack robust stability, have properties that are somewhat conventional, and the vacuum (i.e., the field ground state) is not a zero-quanta state but a superposition of states with many different numbers of quanta.

More robust notions of `particle' can, however, be found in relativistic QFT. I discuss two: the resolution of scattering processes into superpositions of localized states (analyzed via the LSZ formalism) and the presence of stable particles interacting via long-range forces in nonrelativistic physics (analyzed via nonrelativistic effective field theory). Both notions of particle are nonperturbative in the formal sense (they do not involve treating the Hamiltonian as a perturbation of the free-particle sense, but they are still approximate, regime-dependent, and limited – but nonetheless substantive – notions of particle. I conclude by considering their relation to one another and to other emergent notions of particle in QFT.

[At least: this is the extended abstract for the written paper! Depending on how long the talk slot is, it might be a bit of a whistlestop tour.]

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## Decoherence and the Definite

Quinton Wood

New York University, New York, USA

**Abstract**

Where do developments in decoherence situate us with respect to the measurement problem? Schlosshauer and Fine (2007) disentangle the measurement problem into various separate issues. Decoherence researchers have made great progress in addressing the problem of the preferred basis and the problem of the non-observability of interference. However, there is still much controversy regarding the 'general problem of outcomes.' This is the problem of explaining why we see just one outcome when measuring a state with respect to an observable that the state is not an eigenstate of. Decoherence is a dynamical process whereby a system, in interacting with its environment, loses its coherence along certain bases selected by its environment. This causes the reduced density matrix of the system to be formally similar to a proper mixed state density matrix – a density matrix where the probabilities typically represent ignorance. Does the formal similarity between (a part of) the state of a decohered system and a proper mixed state entail a satisfying resolution to the general problem of outcomes? (See Wallace 2012). Does this disparage the project of interpreting quantum mechanics? (See Crull 2015, Zurek 2002). I argue that decoherence provides a framework for solving the general problem of outcomes only when supplemented with at least a minimal interpretational background. These questions then ultimately reduce to controversies about the roles of observation and ontology in physical theories. I begin by arguing that the general problem of outcomes turns on the notion of definiteness – a notion inherent to the decoherence program but seldom given a full account. I show how we get a straightforward grasp of the notion by appealing to a canonical argument about the nature of superpositions via Stern-Gerlach magnet experiments and counterfactual reasoning. This will reveal the role of the interpretations of quantum mechanics as explaining which states will fall into the 'definite' category with respect to each observable. However, as the diversity of interpretations suggests, the notion of definiteness is polysemous; I identify an ontological version of the notion and a subjective version of 'apparent definiteness' that is relativized to observers. I then further distinguish a weaker form of apparent definiteness established by connecting our experimental evidence to a system's dynamics. I conclude that, in order to count as solving the general problem of outcomes, an interpretation will at least need to match empirical evidence about which states to classify under the weaker form of apparent definiteness. It follows that the tools provided by decoherence do not suffice for the formalism of quantum mechanics alone to solve the general problem of outcomes; weak claims about the nature of definiteness must be supplemented. The scientific adequacy of this supplementation depends on whether a physical theory should aim to capture appearances alone or should instead aim to describe an underlying reality. I discuss the consequences for each option by connecting to classical debates about intertranslatability in science.

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## Symmetry Undermines Separability

Yongwoo Yi

LMU Munich, Munich, Germany

### Abstract

In quantum mechanics, global U(1) phase transformations of the wave function leave all empirical predictions invariant. Absolute phase is therefore widely regarded as surplus structure, while relative phase is physically significant. I argue that two major approaches to symmetry, reduction and sophistication, both imply that wave function realism cannot sustain a separable metaphysics in the presence of this symmetry.

Following Ney, a metaphysics is separable iff (i) it posits objects or entities instantiated at distinct regions, each possessing its own state, and (ii) all categorical facts about a composite region are determined by the categorical facts about its subregions. Proponents of wave function realism, especially the wave-function-as-a-field-in-configuration-space view, have argued that their position satisfies these conditions and thereby enjoys an advantage over rival interpretations.

However, it remains unclear whether wave-function realism can maintain separability once global U(1) symmetry is properly taken into account. For its metaphysics to be separable, facts about the relative phase between two distinct regions, R1 and R2, must be determined by facts about the states instantiated at R1 and R2 individually. I argue that neither of the two dominant responses to symmetry can meet this requirement, thereby undermining a central argument for wave function realism.

First, reduction *eliminates* symmetry by formulating the theory solely in terms of symmetry-invariant quantities. In the present context, global U(1) symmetry is removed by formulating physical states with rays in projective Hilbert space. Accordingly, absolute phase is eliminated from the ontology. Once absolute phase is eliminated, however, facts about the relative phase between subsystems can no longer be recovered from facts about the subsystems' states, which lack the relevant local correlates. The projective formalism thus renders relative phase an irreducibly global feature of the composite system, undermining separability under the corresponding metaphysics.

By contrast, on the sophistication approach, often combined with an anti-quidditist metaphysics, symmetry-variant quantities are retained in the formalism, but all symmetry-related models are taken to represent a *single* physical possibility. In our setting, absolute phase remains part of the formalism, but all wave functions related by global U(1) transformations are physically equivalent. Crucially, I argue that this representational strategy should be accompanied by a rejection of definite values for symmetry-variant quantities. The motivation is twofold: first, if such quantities possessed determinate values, differences in those values would correspond to distinct physical possibilities; second, any assignment of a particular value would be arbitrary. Applied to global phase, this suggests that the absolute phase of a wave function does not correspond to any determinate physical value. Consequently, determinate facts about the relative phase between two regions cannot be grounded in facts about the states instantiated at those regions. Separability is therefore violated once again.

I conclude that under either treatment of global phase symmetry, reduction or sophistication, wave function realism fails to deliver a separable metaphysics. More generally, the argument suggests that symmetries pose a systematic challenge to

separability: once symmetry-variant structure is eliminated or deprived of determinate magnitude, the supervenience of global facts on local facts is often undermined.

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