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BOOK OF ABSTRACTS

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Speakers' Abstracts

Borhan Ahmadi

International Centre for Theory of Quantum Technologies, University of Gdańsk, Poland

Coherent Charging of Quantum Batteries by an Incoherent Source

Abstract: The transfer of energy from a coherent source to a quantum battery is of significant technological importance. However, perhaps even more crucial is the ability to transfer energy from an incoherent source to a quantum battery and store it in a coherent form. In this study, we propose a novel approach to accomplish this task. Our method involves utilizing indistinguishable two-level fermions as the fundamental units of the quantum battery, collectively interacting with a shared reservoir. Through analytical analysis, we demonstrate that non-zero coherent energy, specified as ergotropy, can indeed be transferred to the battery. Furthermore, we observe that, by increasing the number of cells in the battery, near-perfect ergotropy extraction of the battery occurs. Finally, our analysis intriguingly reveals that the charging power of the battery experiences an enhancement with an increase in the temperature of the reservoir.

Christine Aidala*, Gabriele Carcassi

University of Michigan, The United States

* Presenting person

Classical mechanics as the high-entropy limit of quantum mechanics

Abstract: We show that classical mechanics can be recovered as the high-entropy limit of quantum mechanics. That is, the high entropy masks quantum effects, and mixed states of high enough entropy can be approximated with classical distributions. The mathematical limit $\hbar \to 0$ can be reinterpreted as setting the zero entropy of pure states to $-\infty$, in the same way that non-relativistic mechanics can be recovered mathematically with $c \to \infty$. Physically, these limits are more appropriately defined as $S \gg 0$ and $v \ll c$. Both limits can then be understood as approximations independently of what circumstances allow those approximations to be valid. Consequently, the limit presented is independent of possible underlying mechanisms and of what interpretation is chosen for both quantum states and entropy.

Link to a related paper:
https://arxiv.org/abs/2411.00972

Guido Bacciagaluppi

Utrecht University, The Netherlands

Better than Bohr? Grete Hermann and the 'Copenhagen Interpretation'

Abstract: Within the foundations of quantum mechanics, Grete Hermann is best known for her analysis of causality in quantum mechanics, and for her critique of von Neumann's impossibility proof against the completion of quantum mechanics through hidden variables. I submit further that Grete Hermann is a central figure in understanding the complex of ideas loosely shared between Bohr, Heisenberg and others in the 1930s, and was partly instrumental in their very crystallisation. She was both a critic to whom especially Heisenberg and Weizsäcker responded (the latter also on behalf of Bohr), and the most systematic and articulate exponent of that complex of ideas. A 'Copenhagen interpretation' as generally understood from the 1950s onwards may have been largely Heisenberg's creation, but a systematic view along those lines was arguably formulated already in the 1930s by Grete Hermann.

Nicola Bamonti
Scuola Normale Superiore, Italy

In Search of Cosmic Time: Complete Observables and the Clock Hypothesis

Abstract: This paper considers a new and deeply challenging face of the problem of time in the context of cosmology drawing on the work of Thiemann (2006). Friedmann equations describe the dynamics of the universe with respect to the cosmic time t. However, neither t nor the Hubble parameter H(t) are observables in the Dirac sense, as they fail to commute with the Hamiltonian constraint. Thiemann argues for a radical response to the cosmic problem of time that requires us to modify the classical Friedmann equations by introducing a phantom scalar field. By contrast, we offer a conservative proposal for solution of the problem by bringing together ideas from the contemporary literature regarding reference frames (Bamonti, 2023), complete observables (Rovelli, 2002; Gryb&Thébault, 2023; Bamonti&Gomes, 2024), and the model-based account of time measurement (Tal, 2016). In light of the clock hypothesis, we reinterpret cosmic time as a partial observable \tau, representing the proper time along the Hubble flow of the cosmic fluid understood as a real reference frame. Thus, we construct H(\tau) as a complete observable satisfying Dirac's criterion. Although \tau cannot be directly measured, it is indirectly measured using cosmological data (e.g., CMB power spectra). Our approach thus succeeds in reconciling the demand for observability of cosmic quantities with the preservation of the Friedmann equations as the dynamical equations for the universe.

Link to a related paper:
https://arxiv.org/pdf/2411.00541

Michał Banacki
International Centre for Theory of Quantum Technologies, University of Gdańsk, Poland

On steering in the C-algebraic framework*

Abstract: Inspired by the celebrated Tsirelson's conjecture, we study the phenomenon of quantum steering, based on different descriptions of quantum composed systems (given by tensor and commuting approaches). In a typical steering scenario, two parties (i.e. Alice and Bob) share a common system and only Alice steers the local state of Bob's subsystem by random choices of local measurements performed on her subsystem. We discuss such measurement schemes in the most general (infinite-dimensional) setting, where local subsystems of both trusted (Bob) and untrusted (Alice) parties are modeled by certain C*-algebras (as in Algebraic Quantum Field Theory). We perform a systematic analysis of algebras accessible to the trusted party, for which separations between tensor and commuting models may occur. Specifically, using the concept of a universal C*-algebra generated by projection-valued measures (PVMs), we provide equivalent descriptions of both models. We introduce necessary and sufficient conditions for the equivalence of quantum commuting and quantum tensor approach that is stable under extensions of the trusted subsystem by finite-dimensional ancillae. As a result, we provide a large class of C*-algebras for which both considered models are different for all numbers of settings m and outcomes k (except for the trivial case with m=2, k=2). In particular, going beyond previously known results, we show for the first time the existence of a Tsirelson's gap for steering in the case when m=2 and k>2. Moreover, we compare the discussed classes of assemblages (i.e. collections of subnormalized states defining steering) with those constrained only by the no-signaling principle. Specifically, we prove that such a paradigm coincides with the quantum commuting model, i.e. there is no post-quantum steering. Finally, we use this equivalence to establish "no-go" results concerning collections of freely independent self-adjoint unitaries in certain tracial C*-algebras.

Link to a related paper:
https://arxiv.org/abs/2306.14344

Philipp Berghofer
University of Graz, Austria

Quantum Probabilities Are Objective Degrees of Epistemic Justification

Abstract: QBism is one of the most widely discussed "subjective" interpretations of quantum mechanics. Its central claim is that quantum probabilities are personalist Bayesian probabilities and that the quantum state represents subjective degrees of belief. Even probability-one predictions are considered subjective assignments, expressing the agent's highest possible degree of certainty about what they will experience next. For many philosophers and physicists this means that QBism is too subjective. Even those who agree that the wave function should not be reified and that we should look for alternatives to standard ontic interpretations of the wave function, often argue that QBism must be abandoned because it detaches science from objectivity. One problem is that from the QBist perspective it is hard to see how objectivity could enter science.

In my talk, I introduce and motivate an interpretation of quantum mechanics that takes QBism as a starting point, is consistent with its virtues, but allows objectivity to enter from the get-go. I call this the "degrees of epistemic justification" interpretation (DEJI), which understands quantum probabilities as objective degrees of epistemic justification. According to DEJI, quantum mechanics is a machinery that has a subjective input (the wave function that is supposed to encode the agent's experiential input) but an objective output (quantum probabilities understood as degrees of epistemic justification). In this view, quantum mechanics provides the formalism that allows an experiencing subject to answer the following question: Based on my experiential input, what should I believe to experience next? Quantum probabilities, then, are degrees of epistemic justification that encode the answer to this question.

One pressing question for DEJI is to explain where the objectivity of the quantum probabilities comes from. Since the objectivity in question is not ontic in nature (grounded in an ontic interpretation of the wave function) but normative, we are dealing with an unusual account of objectivity. Drawing on the quantum reconstruction program and approaches to experiential justification that emphasize the (re)presentational character of perception, my objective in this talk is to clarify in what sense quantum probabilities, according to DEJI, are objective.

Link to a related paper:
https://arxiv.org/abs/2410.19175

Källan Berglund
Worcester Polytechnic Institute, The USA

Black Hole in Quantum Superposition: Space-time superpositions as fluctuating geometries

Abstract: Superpositions of black holes can be described geometrically using a combined canonical formulation for space-time and quantum states. A previously introduced black-hole model that includes quantum fluctuations of metric components is shown here to give full access to the corresponding space-time geometry of weak-field gravity in terms of suitable line elements with quantum corrections. These results can be interpreted as providing covariant formulations of the gravitational force implied by a distribution of black holes in superposition. They can also be understood as a distribution of quantum matter constituents in superposition for a single black hole. A detailed analysis in the weak-field limit reveals quantum corrections to Newton's potential in generic semi-classical states, as well as new bounds on quantum fluctuations, implied by the covariance condition, rather than the usual uncertainty principle. These results provide additional control on quantum effects in Newton's potential that can be used in a broad range of predictions to be compared with observations.

Link to a related paper:
https://arxiv.org/abs/2405.20193

Alessandro Bisio
University of Pavia, Italy

Higher order maps in general physical theories

Abstract: Sequential and concurrent models of classical or quantum computation, like Turing machines and circuits, describe computation as state changes over time. However, models like Lambda calculus use higher-order operations on functions and are not immediately reducible to a sequence of state transformations.
Physically, this corresponds to consider transformation of transformations, forming the basis of Higher Order Quantum Theory. Here, quantum channels become inputs, enabling “second-order” gates that map channels to channels. This extends recursively, creating a hierarchy of higher-order maps (HOM). This hierarchy is structured by type, which specifies a map’s input and output. This is defined recursively. A quantum state of system A has type A, while a map transforming type x maps into type y maps has type (x->y). To be physically admissible, a HOM must satisfy certain requirements, ensuring compatibility with quantum theory’s probabilistic structure. These are generalizations of Kraus’ conditions for quantum operations. Within this axiomatic framework, we characterize admissible HOMs using the Choi isomorphism, showing that admissible maps lie within a cone of positive operators constrained by linear constrained [1].
Within the hierarchy, some HOMs can be realized as a quantum circuit with open slots, while some others (e.g. the quantum switch) exhibit an indefinite causal order. We prove a result linking a map’s functional description (i.e. its type) to its causal structure via no-signaling relations, based on the compositional structure of HOMs [2].
We then present a generalization of the higher order framework to general physical theories as described by the categorical formalism of Operational Probabilistic Theories (OPTs) [3]. The starting point is to enrich an OPT with the notion of “contraction”. A contraction is a morphism, which resemble a categorical trace, which extends the compositional structure of the OPT beyond the sequential one and it allows to define the hierarchy of HOMs. We prove that an OPT admits an existence of a contraction if and only if it is endowed with the so called Choi states and Choi effects. Therefore, within our framework, the higher-order functionality of an OPT is not an extrinsic element but it is fully determined by its native compositional structure.

References:
[1] AB, P. Perinotti, Proc. R. Soc. A 475 20180706 (2019)
[2] L. Apadula, AB, P. Perinotti, Quantum 8, 1241 (2024)
[3] AB, M. Erba, L. Apadula, P.Perinotti (in preparation)

Noemi Bolzonetti
Utrecht University, The Netherlands

Bohr and Heisenberg: Debate on the Gamma-Ray Microscope

Abstract: On March 27th, 1927, Heisenberg published the paper in which he introduced the uncertainty relations through his well-known gamma-ray microscope thought experiment. Since then, the debates and commentaries over the origin of the uncertainty relations have continued for a century (see, for instance, Bacciagaluppi and Valentini 2009; Beller 1999; Brown and Redhead 1981; Busch 1990; Hilgevoord and Uffink 1985,2024; Jammer 1974; Uffink 1990).
Going back to 1927 through a selection of letters – including an unpublished letter from Jordan to Rosenfeld – this talk aims to add a crucial piece to this century-old puzzle by shedding new light on the differences between Heisenberg and Bohr's conceptual basis of the uncertainty relations. According to the received view, Bohr derives the uncertainty relations from the wave-particle duality of light. By contrast, it is commonly stated that Heisenberg based them on the discontinuity in the interaction between the electron and the light quantum, i.e., the uncontrollable change resulting from the Compton effect (cf. Camilleri 2009). I will challenge the received view by arguing that: (i) Bohr’s derivation of the uncertainty relations fundamentally relies on the use of classical concepts, consistent with their central role in his broader interpretation of quantum mechanics. (ii) The supposed contrast rooted in the wave-particle duality of light may stem from Heisenberg’s 1927 misrepresentation (or misinterpretation) of Bohr's ideas on the gamma-ray microscope. This misrepresentation may have influenced the reception of Bohr’s interpretation, particularly regarding his ideas on the conceptual justification for the uncertainty relations, and contributed to obscuring the deeper significance of Bohr's complementarity principle – fully comprehensible only in light of (i).

Silvester Borsboom
Radboud University, Radboud Center for Natural Philosophy, The Netherlands

Global Gauge Symmetry Breaking in the Abelian Higgs Mechanism

Abstract: The aim of this talk, which is based on the eponymous article together with Sebastian de Haro, is to resolve the incompatibility between two extant gauge-invariant accounts of the Abelian Higgs mechanism: the first account uses global gauge symmetry breaking, and the second eliminates spontaneous symmetry breaking entirely. We resolve this incompatibility by using the constrained Hamiltonian formalism in symplectic geometry. First we argue that, unlike their local counterparts, global gauge symmetries are physical. The symmetries that are spontaneously broken by the Higgs mechanism are then the global ones. Second, we explain how the dressing field method singles out the Coulomb gauge as a preferred gauge for a gauge-invariant account of the Abelian Higgs mechanism. Based on the existence of this group of global gauge symmetries that are physical, we resolve the incompatibility between the two accounts by arguing that the correct way to carry out the second method is to eliminate only the redundant gauge symmetries, i.e. those local gauge symmetries which are not global. We extend our analysis to quantum field theory, where we show that the Abelian Higgs mechanism can be understood as spontaneous global U(1) symmetry breaking in the C^*-algebraic sense.

Link to a related paper:
Based on my master thesis: https://philsci-archive.pitt.edu/24403/. The article itself will be uploaded soon.

Lorenzo Braccini
University College London, The United Kingdom

Collective Nonclassicality of a Macroscopic Qubit-Ensemble via Measurement-Induced Disturbance

Abstract: An experimental proposal is presented for testing the nonclassicality of an ensemble of qubits measured collectively by a single cavity, effectively performing a parity measurement on the ensemble. Although the qubit ensemble and the electromagnetic field are both initially prepared in classical-like states, the action of sequential measurements allows violating the classical notion of macrorealism (MR), via quantum measurement-induced disturbance, irrespective of the ensemble size. This proposal can experimentally verify that Bohr's correspondence principle is not fundamental, but a consequence of practical limitations (decoherence and noise). The protocol is adapted to collectively detect the quantumness of a quantum computer (QC) using only two measurement qubits. Violation of MR is detected up to 40 qubits in IBM quantum computers. This scheme can be realized using different physical systems, and conclusions on its experimental implementation can be drawn.

Marcoen Cabbolet
Vrije Universiteit Brussel, Belgium

The 100th birthday of quantum theory. Time to move on.

Abstract: The probabilistic description of nature that quantum theory provides us with has thus far withstood all tests: without exaggeration we can say that the empirical successes of quantum theory, obtained from measurements on microsystems, are unrivalled by any other theory. Yet there is still doubt as to whether quantum theory is the final answer with regard to the fundamental workings of the universe. First of all, a fundamentally probabilistic universe is hard to swallow if one is in the 'God-does-not-play-dice' camp, and even harder if one is in God's camp. But not only that: mainstream research programs aimed at uniting gravity with the other interactions in the framework of quantum theory have become degenerative, in the sense that they have reached a stalemate: no substantial progress has been made for decades in a row. That being said, we can solve open foundational issues in physics by moving on to a fundamentally new research program: the purpose of this talk is to give an outline of this research program without throwing formulas at the audience.
It's core is a set of generalized process-physical principles, which give a description of the (discrete) elementary processes by which the smallest physical systems evolve in time, originally published in [1,2,3]. Under the special condition that the

evolving physical system has only one component, this reduces to a particularly simple process theory, the special theory of elementary processes (STEP), which I will briefly sketch using pictures.
It's auxiliary hypothesis is a mathematical model of the STEP: this yields a relativistic model of an elementary process in the temporal evolution of a one-component system, during which a gravito-electromagnetic interaction takes place between the system and its spatiotemporal environment at Planck scale [4]. I'll briefly sketch the principle of the gravito-electromagnetic interaction under non-relativistic conditions using pictures.
The heuristics are to show that general relativity (GR) and quantum electrodynamics (QED) are approximations of the gravitational and the electromagnetic aspects of this gravito-electromagnetic interaction. Using pictures, I'll briefly show why our knowledge of the whereabouts of a one-component system is fundamentally probabilistic, despite the fact that the elementary processes by which it evolves in time are deterministic.

References:

[1] M.J.T.F. Cabbolet, Ann Phys. 522, 699-738 (2010)
[2] M.J.T.F. Cabbolet, Ann Phys. 523, 990-994 (2011)
[3] M.J.T.F. Cabbolet, Ann Phys. 528, 626-627 (2016)
[4] M.J.T.F. Cabbolet, Preprint (2024):
https://researchportal.vub.be/nl/publications/model-of-a-gravito-electromagnetic-interaction-with-gravitational

Lorenzo Catani
International Iberian Nanotechnology Laboratory (INL), Portugal

An extended Wigner's friend no-go theorem inspired by generalized contextuality

Abstract: The renowned Local Friendliness no-go theorem demonstrates the incompatibility of quantum theory with the combined assumptions of Absoluteness of Observed Events – the idea that observed outcomes are singular and objective – and Local Agency – the requirement that the only events correlated with a setting choice are in its future light cone. This result is stronger than Bell's theorem because the assumptions of Local Friendliness are weaker than those of Bell's theorem: Local Agency is less restrictive than local causality, and Absoluteness of Observed Events is encompassed within the notion of realism assumed in Bell's theorem. Drawing inspiration from the correspondence between nonlocality proofs in Bell scenarios and generalized contextuality proofs in prepare-and-measure scenarios, we present the Operational Friendliness no-go theorem. This theorem demonstrates the inconsistency of quantum theory with the joint assumptions of Absoluteness of Observed Events and Operational Agency, the latter being a weaker version of noncontextuality, in the same way that Local Agency is a weaker version of local causality. Our result generalizes the Local Friendliness no-go theorem and is stronger than no-go theorems based on generalized noncontextuality.

Link to a related paper:
https://arxiv.org/abs/2502.02461

Carlo Cepollaro
University of Vienna / Institute for Quantum Optics and Quantum Information (IQOQI-Vienna), Austria

The classical limit of quantum mechanics through coarse-grained measurements

Abstract: A long-standing question in the foundations of quantum mechanics is how classical behavior emerges from a theory that is fundamentally quantum. In this talk, I will present a framework that addresses this question by focusing on the role of coarse-grained measurements: those in which individual quantum outcomes are not resolved, but grouped into broader, finite-resolution “slots”. This approach offers an alternative to standard treatments based on the formal limit $\hbar \to 0$, or on decoherence, and highlights how classical structures can emerge purely from the way we observe quantum systems through limited-resolution instruments.
I'll show that when these coarse-grained slots in phase space are much larger than Planck's constant, the structure of quantum kinematics effectively reduces to classical probability theory. Observables commute, and states behave like

classical distributions. This transition is not just a mathematical limit, but a physically meaningful consequence of the limitations inherent in realistic measurements.
The analysis goes further: by considering dynamics under coarse-grained observation, and by linearizing the quantum Hamiltonian around the classical values associated with each slot, we recover classical Hamiltonian dynamics governed by the Liouville equation. Strikingly, the classical Hamiltonian that emerges in this way is precisely the one from which the original quantum Hamiltonian could have been obtained via canonical quantization. This closes what we refer to as the quantization–classicalization cycle: the classical system is first quantized according to standard rules, yielding a quantum Hamiltonian; then, by considering coarse-grained measurements and dynamics, one recovers the same classical structure from which the quantum theory originated. This circular consistency is nontrivial and conceptually reassuring, reinforcing the internal coherence of quantum mechanics as a fundamental theory.
I will also discuss the role of the Ehrenfest time in setting the boundary of classical behavior, with examples drawn from various physical systems. This framework helps clarify under what conditions and for how long classical descriptions of quantum systems are valid.
Overall, the approach offers a clean and operational account of the quantum-to-classical transition and sheds light on the consistency, completeness, and empirical adequacy of quantum mechanics as a foundational framework.

Link to a related paper:
https://arxiv.org/abs/2503.15642

Erik Curiel
Bonn Universität, Germany / Harvard Univesity, The United States

The Dynamics of Classical Physics Determines the Geometry of Newtonian Spacetime; That of Quantum Physics Does Not

Abstract: I describe a few theorems that show that, in classical mechanics (Newtonian and Lagrangian mechanics), the intrinsic structure of the dynamics naturally distinguishes the concept of interaction from that of evolution, and, correlatively, position from momentum. One gets for free, moreover, a characterization of "free" evolution (or "isolation"). I show that the theorems allow one to entirely reconstruct the full 4-dimensional spacetime structure of Newtonian physics from classical dynamics. None of this is possible in Hamiltonian mechanics or quantum mechanics. Thus, in quantum mechanics, the distinction between interaction and evolution needs to be imposed by fiat, and the dynamics needs to be hooked up to background spacetime structure "by hand", all in ways not required in classical mechanics. I conclude by discussing what I take to be the lessons for all this with regard to the Measurement Problem: not only is the idea of "measurement" problematic in quantum theory, but the entire idea of "interaction" per se in quantum theory is more deeply problematic than has been recognized. There may also be some lessons for quantum gravity somewhere in here, but who really knows?

Marek Czachor
Gdańsk University of Technology (GUT), Poland

Heisenberg-Born-Jordan oscillators 100 years after: Field quantization revisited

Abstract: Heisenberg, Born and Jordan quantized electromagnetic fields already in 1925, a few months before Schroedinger understood the role of eigenvalues in quantum mechanics. One of the assumptions they implicitly made may be nowadays regarded as unphysical, and yet it is still implicitly present at the "zeroth axiom" of field quantization. Fixing the unphysical element makes quantum fields much less singular and removes at least a part of the divergences. I will review some of the results obtained in this modified formalism so far.

Link to a related paper:
https://arxiv.org/abs/1209.3465

Debarshi Das
University College London, The United Kingdom

Mass-Independent Scheme to Test the Quantumness of a Massive Object

Abstract: The search for empirical schemes to evidence the nonclassicality of large masses is a central quest of current research. However, practical schemes to witness the irreducible quantumness of an arbitrarily large mass are still lacking. To this end, we incorporate crucial modifications to the standard tools for probing the quantum violation of the pivotal classical notion of macrorealism (MR): while usual tests use the same measurement arrangement at successive times, here we use two different measurement arrangements. This yields a striking result: a mass-independent violation of MR is possible for harmonic oscillator systems. In fact, our adaptation enables probing quantum violations for literally any mass, momentum, and frequency. Moreover, coarse-grained position measurements at an accuracy much worse than the standard quantum limit, as well as knowing the relevant parameters only to this precision, without requiring them to be tuned, suffice for our proposal. These should drastically simplify the experimental effort in testing the nonclassicality of massive objects ranging from atomic ions to macroscopic mirrors in LIGO.

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Phys. Rev. Lett. 132, 030202 (2024), https://doi.org/10.48550/arXiv.2211.10318

Sebastian De Haro
University of Amsterdam, The Netherlands

The Geometric View of Theories

Abstract: Recent work on inter-theoretic relations has emphasised the need for a structured view of theories, as a development of the semantic conception of theories (Halvorson 2012 and Halvorson and Tsementzis 2017). Lehmkuhl (2017) also calls for a ‘theory of theories’ (cf. Fletcher, 2016). On the standard semantic conception, a theory is a set of models, each defined through a set-theoretic structure: this view is sometimes called “flat”, because there is no further structure on the set of models. By contrast, the structured view of theories that the recent literature advocates endows the set of models with further structure. This prompts two questions: What structure should one define on a set of models? What scientific motivation is there to introduce such structure?

I will argue that there is a large class of examples in physics where the structure on the set of models is, at its simplest, a differentiable manifold. I will endorse De Haro’s (2020) idea of lifting the use of ‘theory’ and ‘model’ “one level up”, with dualities as isomorphisms between models of a single theory. Then I will extend De Haro and Butterfield’s (2025) notion of duality in physics to the case of a quasi-duality, a map that falls short of being an isomorphism. I will argue that quasi-dualities between models can be seen as transition functions between open sets on the theory’s state-space, and the other conditions for having a manifold are also satisfied.

I will illustrate this idea with an example from quantum field theory, namely the Seiberg-Witten theory, where the state-space can be covered by three open sets. The resulting state-space is a differentiable manifold: a Riemann surface with three punctures, endowed with metric and symplectic structure. This example is representative for quantum field theories, statistical mechanics and string theories. This simplest case, of a physical theory as a manifold, needs to be generalized, in more realistic examples, to include algebraic varieties, and fibre bundles over them, with physical quantities living in the fibres.

On this geometric view of theories, a physical theory is a set of models with both topological and geometric structure. This structure is induced from the structure of the configuration space of fields, and the dynamics and quantities thereon, especially from the action or the free energy (depending on the specific examples). I will also highlight some of the interpretative questions that arise with such structures.

Link to a related paper:
https://arxiv.org/abs/1707.06681

Flavio Del Santo
University of Vienna, Austria

Which features of quantum physics are (not) fundamentally quantum

Abstract: What is fundamentally quantum? We argue that most of the features, problems, and paradoxes – such as the measurement problem, the Wigner's friend paradox and its proposed solutions, single particle nonlocality, and no-cloning – allegedly attributed to quantum physics have a classical analogue if one is to interpret classical physics as fundamentally indeterministic. What really characterizes non-classical effects are incompatible physical quantities, which, in quantum quantum theory are associated to the fundamental constant $\hbar$.

Link to a related paper:
https://arxiv.org/abs/2409.10601

Hippolyte Dourdent
ICFO, Spain

Simulating Noncausality with Quantum Control of Causal Orders

Abstract: Logical consistency with free local operations is compatible with non-trivial classical communications, where all parties can be both in each other's past and future—a phenomenon known as noncausality. Noncausal processes, such as the "Lugano (AF/BW) process", violate causal inequalities, yet their physical realizability remains an open question. On the one hand, the Lugano process is purifiable (unitarily extendible), a property considered as a criterion for physical implementability, and admits a realization through time-delocalized subsystems, observer-dependent local events, and in a routed quantum circuit. On the other hand, a fine-grained analysis suggests that violation of causal inequalities cannot occur in a fixed spacetime satisfying relativistic causality, instead relying on interactions with a closed timelike curve. Whether the Lugano process emerges in general relativity or arises at the interface of quantum theory and gravity, and by extension, how to implement or observe a local realization of the SHIFT measurement, remains a priori unknown. In contrast, the quantum switch—a physically realizable process with indefinite causal order—can only generate causal correlations. Building on a recently established equivalence [Kunjwal & Baumeler, PRL 131, 120201 (2023)] between the SHIFT measurement, which exhibits nonlocality without entanglement, and the Lugano process, we demonstrate that the SHIFT measurement can be implemented using the quantum switch in a scenario with quantum inputs. This shows that the structure of the Lugano process can be simulated by a quantum switch and that successful SHIFT discrimination witnesses causal nonseparability rather than noncausality, refuting prior claims. We further investigate this connection, deriving a quantum circuit with quantum control of causal orders similar to the quantum switch from a unitary extension of the Lugano process matrix. Finally, we identify a broad class of "superposition of classical communications" derived from classical processes without global past capable of realizing similar causally indefinite measurements. We examine these results in relation to the ongoing debate on implementations of indefinite causal orders.

Link to a related paper:
https://arxiv.org/abs/2502.15579

Jan Dziewior
Ludwig-Maximilians-Universität München (LMU Munich) / Max-Planck-Gesellschaft (MPQ), Germany

The Meaning of Weak Values

Abstract: Weak values have been introduced over thirty years ago by Aharanov, Albert, and Vaidman. While since then this concept has proven practically useful, in particular for metrological applications measuring small parameters, weak values have also consistently been accompanied by foundational controversy. In connection with the two-state-vector formalism they have been interpreted as descriptions of quantum systems in between measurements, it was claimed they provide ""resolutions"" of paradoxes, and they have been suggested as indicators of past presence of quantum particles. Furthermore, an operational definition of particle velocity based on weak values has been proposed, which coincides with

the trajectories of Bohmian mechanics. However, the validity, consistency, and usefulness of such claims have been disputed.
Here, it is argued that in a time-symmetric framework weak values are the natural candidates for an ascription of physical properties to quantum systems. It is suggested that the meaning of any weak value (also complex ones) is best established on strictly operational grounds by its experimental signature without the need for ontological claims. The arguments are substantiated by an analysis of three experimental studies, which all aim to illustrate crucial features of weak values, i.e., the operational similarity of some weak values to eigenvalues, the possibility to measure a weak value on a single pre- and postselected system, and the universality of modification of local interactions for spatially pre- and postselected quantum systems. It becomes clear that weak values are neither ""merely"" statistical nor ""simply"" the results of perturbation theory, but that such properties are necessitated by the constraints imposed by the laws of quantum mechanics on a time-symmetric approach. These results allow to evaluate the relevance of weak values for the resolution of various paradoxes as well as to elucidate their relationship to Bohmian velocity and concepts of particle presence."

Giorgos Eftaxias

Quantum Universe Center, Korea Institute for Advanced Study (KIAS), South Korea

Advantages of multicopy nonlocality distillation and its application to minimizing communication complexity

Abstract: Nonlocality has been proved a resource for various information-processing tasks, a fact that naturally raised its distillation endeavours. Here we introduce several nonlocality distillation schemes, some are sequential algorithms that repeatedly discover optimal two-copy protocols, while others are genuine three-copy protocols. The impact of our schemes is twofold. On the one hand, they unlock the distillability of quantum correlations not known to be distillable before, this way, they offer practical distillation of observed correlations by easy means. On the other hand, they uncover more non-signalling correlations that trivialize communication-complexity, and others that defy information-causality. This brings us closer to an understanding of the sets of nonlocal correlations that can be recovered from information-theoretic-axioms, which in turn, enhances our understanding of what is special about quantum theory.

Link to related papers:

[1] Eftaxias, G., Weilenmann, M. and Colbeck, R., 2023. Advantages of multicopy nonlocality distillation and its application to minimizing communication complexity. Physical Review Letters, 130(10), p.100201
[2] Eftaxias, G., Weilenmann, M. and Colbeck, R., 2023. Multisystem measurements in generalized probabilistic theories and their role in information processing. Physical Review A, 108(6), p.062212

Marco Erba

International Centre for Theory of Quantum Technologies (ICTQT), University of Gdańsk, Poland

The composition rule for quantum systems is not the only possible one

Abstract: Quantum theory provides a significant example of two intermingling hallmarks of science: the ability to consistently combine physical systems and study them compositely; and the power to extract predictions in the form of correlations. A striking consequence of this facet is the violation of a principle termed 'local realism', which has been experimentally demonstrated via Bell tests. The prediction of this phenomenon originates as quantum systems are prescribed to combine according to the composition postulate, i.e. the tensor-product rule. This rule has also an operationally salient formulation, given in terms of discriminability of states via local measurements. Yet, both the theoretical and the empirical status of such postulate has been constantly challenged over the decades: is it possible to deduce it from the remaining postulates?
In arXiv:2411.15964, we solve this long-standing problem by answering in the negative. By leveraging a category-theoretic treatment, we formulate a family of operational theories that are solely distinguished from standard quantum theory by their system-composition rule, while, at the same time, they cannot be told apart by standard Bell-like experiments. Quantum theory is thus established to genuinely embody more content than quantum correlations. This construction applies to both the Hilbert-space and the density-operator formulations of quantum theory. As a result, foundational

programmes based on single-system principles only, or on mere Bell-like correlations, are operationally incomplete, showcasing the importance of mereological aspects in physics. On the experimental side, ascertaining the independence of postulates is a fundamental step to adjudicate between quantum theory and alternative physical theories: hence, the composition postulate deserves to be experimentally scrutinised independently of the other features of quantum theory. Our construction provides an infinite family of theories of quantum processes, but it can be applied to any operational probabilistic parent theory. Finally, in addition to the results that can be found in arXiv:2411.15964, we would also like to formalise the idea that these theories cannot be seen as subtheories of standard quantum theory, and to illustrate work in progress about the experimental testability of quantum composition. These results naturally elicit a number of intriguing questions—of applied-categorical, foundational, and experimental interest—which are inquired.

Link to a related paper:
https://arxiv.org/abs/2411.15964

Peter Evans
University of Queensland, Australia

Reading out a quantum clock: what does measurement mean for time?

Abstract: A good clock is a physical dynamical system driven far from thermal equilibrium that maintains a stable and periodic oscillation, coupled to an auxiliary system that counts this oscillation. Stability arises from being driven to overcome friction, and so a good clock must be an open, nonlinear, dissipative physical system, and subject to noise, which renders the period of oscillation a stochastic variable.
The atomic clocks used to coordinate UTC (so-called caesium fountains) operate at microwave frequencies and so are typically considered classical: reading out such a clock requires counting microwave oscillations, and the energy of a microwave photon is so low that single photon detectors are impracticable. Instead the electric field itself is measured to count the ticks, which can be described entirely classically and where phase noise is determined by classical voltage noise in the nonlinear driving circuit. As a result, 'reading out' the time on such a clock does not affect the operation or the precision of the clock.
Optical clocks operate the same as caesium atomic clocks except they employ lasers at optical frequencies, coupled to some suitable atom held in an optical dipole trap. However, lasers are still subject to noise, and since optical photon energy is much larger than room temperature thermal excitations, such noise is quantum arising from spontaneous emission. Whilst the high frequencies of optical lasers poses a practical challenge for counting the cycles of an optical clock (so-called 'frequency combs' are currently used), such clocks display all the principles of physical clocks operating in a quantum system: far-from-thermal equilibrium, dissipative steady-state oscillations, phase diffusion, and an explicit counting mechanism. The quantum nature of an optical clock arises through the noise of counting the oscillations: the direct measurement of the electric field leads to phase noise arising purely from the Heisenberg uncertainty principle. In quantum clocks, then, the measurement used to generate the count provides a critical point of difference to classical clocks.
In this talk we analyse the relationship between the oscillator and counter in both classical and quantum clocks, and the role played by measurement when reading out a clock. We consider in this context the possibility of coherent feedback in a quantum clock. We show that quantum clocks provide a neat illustration of the relational nature of time.

Johannes Fankhauser
University of Innsbruck, Austria

Epistemic Horizons From Deterministic Laws: Lessons From a Nomic Toy Theory

Abstract: Quantum theory has an epistemic horizon, i.e. exact values cannot be assigned simultaneously to incompatible physical quantities. As shown by Spekkens' toy theory, positing an epistemic horizon akin to Heisenberg's uncertainty principle in a classical mechanical setting also leads to a plethora of quantum phenomena. We introduce a deterministic theory – nomic toy theory – in which information gathering agents are explicitly modelled as physical systems. Our main

result shows the presence of an epistemic horizon for such agents. They can only simultaneously learn the values of observables whose Poisson bracket vanishes. Therefore, nomic toy theory has incompatible measurements and the complete state of a physical system cannot be known. The best description of a system by an agent is via an epistemic state of Spekkens' toy theory. Our result reconciles us to measurement uncertainty as an aspect of the inseparability of subjects and objects. Significantly, the claims follow even though nomic toy theory is essentially classical. This work invites further investigations of epistemic horizons, such as the one of (full) quantum theory.

Link to a related paper:
https://arxiv.org/abs/2406.17581

Jonathan Fay
University of Bristol, The United Kingdom

On Reissner's hypothesis: The current status of Machian theories for the unification of gravity and inertia

Abstract: The combination of Mach's hypothesis concerning the material origin of inertia in mass-interactions and Einstein's equivalence hypothesis on the unity of inertia and gravity raises the intriguing possibility that gravity may be explained entirely as the dynamical part of a relativized law of inertia. This idea—which was not fully realised in general relativity—was first clearly articulated by a colleague of Einstein, Hans Reissner, so we have named it "Reissner's hypothesis".
In this talk, we will revisit this overlooked idea and motivate its reconsideration by clarifying the philosophical appeal of Mach's principle and Mach's hypothesis. In particular, we discuss the distinction between two applications of the principle of relative motion: (1) in subsystems of the cosmos and (2) for the cosmos as a whole. The second of these leads to the considerations of Ernst Mach — that for the universe as a whole, the relativity principle ought to be extended to arbitrary rigid transformations. On this basis Mach sought a material explanation for the observed violation of the relativity principle in subsystems and proposed the hypothesis that the mass distributed throughout the cosmos was physically responsible conditioning inertial frames.
In combination with the equivalence principle of Einstein, the idea came to be recognised that inertial influences of distant masses might be communicated through the force of gravity; or indeed that gravity might be explained entirely as a phenomenon of relative inertia. We assess the plausibility of this idea by briefly considering various models developed throughout the 20th Century that tried to implement it in the context of classical mechanics, including those of Hans Reissner, Erwin Schrödinger, Dennis Sciama, Hans-Jürgen Treder, Julian Barbour and André Assis. We then show how a relativistic generalisation of Dennis Sciama's model can be constructed which elegantly embodies Reissner's original idea and clarifies its results, leading to an equation linking the strength of gravitational coupling to the cosmic mass distribution.
In the final part of the talk we discuss how similar expressions were considered by leading physicists such as Robert Dicke, John Wheeler and Pascal Jordan throughout the 20th Century, although these were not always directly related to Mach's principle, we then explore some of the possible cosmological implications of these ideas.

Antonio Ferreiro
Utrecht University, The Netherlands

Deflating the space-time / matter dichotomy

Abstract: One of the core debates in philosophy of space-time is concerned with what exactly space-time is, how it does or does not constraint the dynamics of matter and how these ideas can be formalised in our best modern theories, in particular, General Relativity. A key presupposition in these cases is the existence of a clear separation between what is considered to be matter and what is to be considered part of the space-time (structure). In particular, in the case of General Relativity, it is a standard assumption to consider the metric field to be part of the latter.
While the concepts of matter and space-time may well change or break down upon entering the quantum gravity regime, such conceptual problems already arise in much more familiar contexts. In this talk we focus on a new case study: scalar-

tensor theories. These are generalisations of General Relativity involving a coupling between the Ricci scalar and an additional scalar field. They have been studied extensively to successfully account for both the inflationary and the accelerated Dark Energy phase of the Universe. Within the context of the space-time / matter dichotomy, a natural question is whether this additional scalar counts a space-time, matter, both or neither. In order to provide an account for this, we introduce a list of criteria that allow us to classify relativistic fields either in the space-time or in the matter category. The main guide for these criteria will be to assume the space-time / matter dichotomy for the case of General Relativity, i.e., in the absence of the extra scalar field. We proceed to apply these criteria to a general family of scalar-tensor theories and discuss the possibility of classifying the scalar in the given categories. Furthermore, we analyse the state of affair for the dichotomy in the case of (empirical equivalent) frame transformations.
Finally, we discuss the different philosophical interpretations of these results. First, the functional account of space-time and the role of the scalar field. Second, the conventionalist thesis of the space-time / matter distinction. And lastly, decoupling the spacetime and gravity category, and the preference for retaining only the latter.

Samuel Fletcher

University of Oxford, The United Kingdom

The Definition of Spacetime Singularities, Revisited

Abstract: A “singularity” in the context of a physical theory is a location, event, or process where some representationally significant quantity or structure becomes infinite or ill-defined. In general relativity (GR), a spacetime singularity is a singularity in the metric field, g, or one of the significant fields it determines, such as the Riemann curvature. But because in the models of GR (Lorentzian manifolds) g is well-defined at every atomic event by definition, there cannot be a location or event where it or one of the structures it determines is ill-defined. Indeed, because g represents the structure of durations and lengths, such an event would have to be outside time and space.
The analysis of spacetime singularities concerns the resolution of this puzzle and the detailed account and classification of their types and significance. Aside from its intrinsic interest, it has at least two important implications. Insofar as singularities are taken to betoken some sort of “breakdown” of or “serious physical pathology” in GR’s representational capabilities, their analysis and consequent prevalence have implications for the bounds of the possibilities that GR represents. Moreover, the “resolution” of these singularities is often taken as a necessary criterion for a satisfactory theory of quantum gravity.
Earman (1995) has dubbed the notion of b-incompleteness, as formulated by Schmidt (1971), the “semi-official definition” of a spacetime being singular. Schmidt proceeded by analogizing Lorentzian manifolds with Riemannian manifolds. In the latter, all incomplete curves have a bounded parameterization, so Schmidt formulated a “generalized” parameterization that agrees with the usual definition in the Riemannian case but applies also to the Lorentzian. However, as Curiel (2021) complains, adopters of this definition never adequately explained the physical significance of this generalized parameter; the mathematical strategy for defining singularities is thus inconclusive. I make progress on this issue by proving that the b-incomplete curves are precisely those that would have a missing endpoint if they were in Minkowski spacetime. Thus b-incompleteness is more properly understood as a kind of counterfactual missing point criterion for a singular g.

Guilherme Franzmann

Nordic Institute for Theoretical Physics / Stockholm University, Sweden

Are quantum subsystems invariant?

Abstract: What is a physical subsystem? How classical physical subsystems localized in spacetime (causally independent) are identified from quantum ones?
Traditionally, classical systems have been uniquely identified with quantum systems, typically represented as factors in Hilbert space for finite-dimensional systems or associated with a local (microcausality) algebra of operators in QFT. Both representations aim to instantiate a specific prescription of subsystems' independence, that they must be statistically independent for state preparations and measurements. Despite this prescription, it is easy to show that canonical linearized quantum gravity prevents us from obtaining a gauge-invariant local algebra, thus undermining one of the conditions needed for statistical independence

of subsystems in QFT. Arguably, this precludes most of the modeling associated with early universe cosmology as well as current attempts to model gravity-induced-entanglement table-top experiments. Nonetheless, primarily it presents a major roadblock towards a theory of quantum gravity. In this talk, after reviewing the aforementioned points, I will propose that a way forward is that the unique identification between quantum and classical systems should be dropped, and instead this mapping should be dynamical, which opens the possibility for a single-world unitary quantum mechanics.

Link to a related paper:
https://arxiv.org/abs/2405.21031

Simon Friederich

University of Groningen, The Netherlands

Reproducing EPR correlations without superluminal signalling: backward conditional probabilities and Statistical Independence

Abstract: Bell's theorem states that no model respecting Local Causality and Statistical Independence can reproduce the quantum correlations predicted by entangled states. In this paper, we introduce a systematic method for constructing “realist” causal models that circumvent these constraints by employing backward-in-time probabilistic dependencies while preserving Statistical Independence as a fine-tuning condition. This approach relaxes conventional assumptions of temporal ordering --avoiding retrocausal control of past events – and yet forbids superluminal signaling. We demonstrate that our framework successfully reproduces both the EPR / Bell correlations and the GHZ predictions, offering a compelling alternative to conventional causal models in quantum theory.

Link to a related paper:
https://arxiv.org/abs/2501.11064

Stefano Furlan

Utrecht University, The Netherlands

The Partecipatory Universe and Bohr’s Smoky Dragon: John Wheeler’s 'It from Bit' in a Proper Light

Abstract: Like all famous slogans, "it from bit" has been used, misused, and transformed over the last few decades, ever since its "prophet," John Wheeler, started to spread it in the 1980s. Since we are dealing with the speculative frontiers of physics and many of the issues that were raised back then are still open, a new historical-critical look can offer key insights to orient oneself among the plethora of proposals and misunderstandings, as well as to gain a more solid philosophical understanding of the roots of such a vision. After the late-1960s crisis of the geometrodynamical worldview Wheeler had been trying to develop for the previous fifteen years, a new wave of interest in the foundations of quantum physics inaugurated a new phase of his long and versatile career. What is typically underappreciated in this turn is that Wheeler actually changed in quite a radical way not just the focus of his research, but also his cosmological views and philosophical attitude. He started to believe that the ordinary naturalistic outlook of theories in which the observer is tacitly omitted or considered irrelevant was no longer tenable—hence his famous notion of “observer-participator,” which he considered a legacy of Niels Bohr. Accordingly, at the cosmological level, Wheeler tried to develop a view of a “participatory universe” and that is the context in which he came up with the idea of the delayed-choice experiment. But by focusing exclusively on this narrative, we would not fully capture the spirit of Wheeler's relentless quest. For it is in that same period that Wheeler started to speak of the quantum as “Merlin's principle,” as elusive in its core as Merlin the shapeshifter. That meant that Wheeler, his devotion to Bohr notwithstanding, adopted a comparative approach to examine different views of quantum physics, being interested not much in what we nowadays would call “interpretation debate,” but rather in heuristic hints about a deeper level. The results of these investigations, as I will show, converged in the 1980s toward the tentative synthesis labelled “it from bit” —and, in view of the previous considerations, it will become clear how there is no way in which the proponent of the notions of “observer-participator” and “participatory universe” would just

come up with an ontology of (problematically and) objectively reified "units of information," as commonly misunderstood. In this way, we will realize that Wheeler's challenge is, in some respects at least, much more thought-provoking and intriguing than what is assumed today in "informational" perspectives on the foundations of physics.

Evan Gale

University of Queensland, Australia

The localization problem: an antinomy between measurability and causal dynamics

Abstract: The localization problem in relativistic quantum theory has persisted for more than seven decades, yet it is largely unknown and continues to perplex even those well-versed in the subject. At the heart of this problem lies a fundamental conflict between localizability and relativistic causality, which can also be construed as part of the broader dichotomy between measurement and unitary dynamics. In this talk, I briefly review the localization problem and discuss its significance more broadly within the foundations of physics, particularly as regards the antinomy between measurability and causal dynamics.

Henrique Gomes

University of Oxford, The United Kingdom

Gauge theory doesn't need gauge symmetry

Abstract: In general relativity, the strong equivalence principle is underpinned by a geometrical interpretation of fields on spacetime: all fields and bodies probe the same geometry. This geometric interpretation implies that a single affine connection dictates the parallel transport of all spacetime tensors and spinors. In this interpretation, the Lorentz group is implicitly encoded in the metric structure of each tangent space, but it also emerges explicitly as the holonomy group of the Levi-Civita connection.

No similar interpretation of gauge theories appears in the standard textbook presentation of them. There, principal bundles are used to coordinate the parallel transport of different interacting fields. Since principal bundles directly encode the symmetry group of a type of interaction, it is fair to say that, unlike the case of gravity, the standard presentation of gauge theories puts symmetry, not geometric structure, first.

Nonetheless, here I will argue that gauge theories do admit such a geometric interpretation, in close parallel with general relativity---and so completely obviating the need for principal bundles. In this interpretation, gauge symmetry can be understood as merely the automorphisms of an internal geometric structure. For instance, in the case of the standard model, this is an internal vector space isomorphic to $C^3\times C^2\times C^1$, where C^n is the n-dimensional complex plane endowed with an orientation and canonical inner product. Thus reformulated, the standard model uses a single vector bundle and its tensor products, with no principal bundles needing to be postulated. This geometric interpretation of gauge theory has a few conceptual advantages over the standard one. For lack of space, I will give two.

(1): One can present the entire content of the theory `without coordinates', in abstract index notation, and thus without gauge symmetry: the symmetry is introduced only upon the introduction of coordinates for the internal vector spaces. Indeed, this allows a very straightforward anti-haecceitist interpretation, on a par with GR, which requires gauge-related models to represent the same physical possibility, thus eliminating the threat of physical indeterminism.

(2): In order that the different irreducible representations (irreps) appearing in the standard presentation of a given gauge theory admit this geometric interpretation, they must be given a geometric reconstruction. This reconstruction uses the fundamental representation on the vector bundle to induce a representation on tensor products of the vector bundle. However, not all irreps of all groups can be reconstructed in this way: in particular, not all irreps of some of the exceptional Lie groups. Thus, one can hope that this geometric interpretation of gauge theory might constrain 'beyond the standard model' extensions.

Link to a related paper:
https://doi.org/10.1017/psa.2024.49

Márton Gömöri

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The Idol of Linear Probability Dynamics

Abstract: In recent years, there have been numerous attempts in the foundations literature to derive quantum mechanics from first principles. The primary goal of these investigations is to clarify how the Hilbert space formalism of quantum theory emerges from more natural physical assumptions. Some of these attempts have provided popular frameworks for addressing foundational issues in quantum theory. However, upon closer inspection, many of the assumptions underlying these frameworks turn out to be less plausible than they initially seem. We must resist the idols of mathematics and remember that what is "natural" or "canonical" from a mathematical perspective is not necessarily reasonable from a physical one. To illustrate this, I will examine one particular assumption that appears in various forms and plays a crucial role in multiple approaches: the claim that the temporal evolution of probabilities, under any conceivable dynamical law, must be linear (more precisely, convex combination preserving). Specifically, I will focus on two widely discussed approaches: the general probabilistic theories framework (Hardy 2008; Müller 2021) and Jacob Barandes's (2023) stochastic processes approach. I will argue that the a priori justification offered in each case for why the dynamics of probabilities must necessarily be convex combination preserving is conceptually flawed. To support this claim, I will present a simple yet physically realistic example that exhibits non-linear probability dynamics. Finally, I will point out that the temporal evolution of probabilities in quantum mechanics—as prescribed by Schrödinger's equation and Born's rule—is, in general, not linear. This contradicts the assumptions made in the above-mentioned theories and significantly limits their applicability to quantum phenomena.

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Alexei Grinbaum

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Operationalism on the march: conceptual lessons of indefinite causality

Abstract: What did we learn after almost twenty years of research on indefinite causality? I submit that the main take-away is a much clearer understanding of an unbridgeable gap between the operational approach and physical theory in spacetime. Much like the device-independent models of nonlocality in previous decades, the models of noncausality teach us a quantifiable lesson about the fundamental concepts of systems and observers. If\textemdash to celebrate the 100 years of Heisenberg's approach with a slightly refreshed formulation\textemdash one wishes for a theory founded exclusively on inputs and outputs of physical experiments, then the space-time theoretical paradigm based on a geometric conception of events becomes an obstacle to further progress.

Jordan Grujic

Ludwig-Maximilians-Universität München (LMU Munich), Germany

Quantization Anomalies as a Loss of Structure

Abstract: Quantization anomalies arise when the symmetries of a classical field theory fail to be preserved upon quantization. This occurs when the path-integral measure, rather than the Lagrangian, is not invariant under symmetry transformations, leading to empirically significant consequences. These anomalies are central to various physical phenomena, such as neutral pion decay and the behaviour of the Yang-Mills vacuum term. Despite their ubiquity in modern physics, quantization anomalies remain underexplored in the philosophy of physics, particularly regarding their implications for structural realism. This paper seeks to bridge this gap by demonstrating that anomalies have profound repercussions for key philosophical positions.

The role of quantization anomalies in this paper is twofold. First, they reveal that gauge degrees of freedom are non-eliminable components of physical theories, as their loss has measurable empirical effects. For example, in QCD, their presence necessitates the introduction of large gauge-variant theta terms in the Lagrangian, directly challenging eliminativist views, which attempt to describe physical theories exclusively in gauge-invariant terms. This demonstrates that not all gauged symmetries are mere changes in representation and suggests that (some) gauge degrees of freedom are the content of the theories. I will further address some debated weaknesses of this stance relying upon formal treatment of anomalies through the lens of non-invertible generalized symmetry operators.

Once we establish the empirical and theoretical significance of these lost symmetries, quantization anomalies pose a severe challenge to structural realism. Many structural realists hold that symmetries capture or constitute the structure of physical theories and they further adhere to realism about the structure due to its seeming persistence across theoretical transitions. However, if key symmetry structures do not persist through such a common transition as quantization, then structural realism faces a serious problem.

This paper argues that the existence of quantization anomalies forces structural realism to confront a dilemma: either redefine the notion of theoretical structure to accommodate symmetry loss, without following some eliminativist path or accept that a significant part of the structural content of physical theories does not survive theory change and move to some even weaker selective realism (or anti-realism).

Jonte Hance

Newcastle University, The United Kingdom

External quantum fluctuations select measurement contexts

Abstract: Quantum paradoxes show that the outcomes of different quantum measurements cannot be described by a single measurement-independent reality. Any theoretical description of a quantum measurement implies the selection of a specific measurement context. Here, we investigate generalised quantum measurements, in order to identify the mechanism by which this specific context is selected. We show that external quantum fluctuations, represented by the initial state of the measurement apparatus, play an essential role in the selection of the context. This has the non-trivial consequence that, when considering measurements other than just idealised projection-valued measures, different outcomes of a single measurement setup can represent different measurement contexts. We further show this result underpins recent claims that contextuality can occur in scenarios without measurement incompatibility.

Link to a related paper:
https://arxiv.org/abs/2501.04664

Ladina Hausmann

Eidgenössische Technische Hochschule Zürich (ETHZ), Switzerland

Against probability

Abstract: In quantum theory, a state is a density operator associated with a Hilbert space, which has its own structure, such as a scalar product. In contrast, according to generalised probabilistic theories (GPTs), the state space of a physical system is the set of probability distributions of all measurements but has no additional structure. To equip the state space with structure, one represents states in terms of a tomographically complete set of measurements rather than the set of all measurements. For example, if the system is composite, one may choose the set of measurements that act separately on individual subsystems. In this talk, I will show that such a representation of a system's state has a severe limitation: it is not robust. Technically, this means that sequences of states that converge in a probability representation do not necessarily converge. At first glance, the lack of robustness might appear to be merely a technical issue. However, because GPTs aim to provide a framework for studying fundamental theories, it questions the very foundations of the GPT framework. One of the basic assumptions of this framework is that the states of two systems can be independently composed. Yet, as pointed out by de Finetti, it is fundamentally impossible to experimentally verify the independence of subsystems. The independence can, however, be derived from operationally justifiable symmetry assumptions, which is known as de Finetti's theorem. One

might hope that a similar theorem could be proven for GPTs. But, unfortunately, due to the robustness issue discussed above, such a result cannot be established. As a consequence, the assumption of independent composition remains unexplained within the GPT framework. But because the framework strongly relies on the idea that systems can be composed independently, one has to question its foundations – the use of probabilities to represent states.

Guy Hetzroni

The Open University of Israel, Izrael

Invariance Heuristics, the Higgs Mechanism, and the Symmetry-to-Reality Inference

Abstract: The Higgs mechanism is typically understood in terms of spontaneous gauge symmetry breaking of gauge symmetry, placing it in tension with the fundamental status of symmetries in modern physics. Philosophers of physics have highlighted that this understanding generates conceptual difficulties, especially concerning the widely accepted understanding of gauge symmetries as mere mathematical redundancies. This latter understanding is, in turn, central to the `symmetry-to-reality inference', which maintains that only invariant quantities represent genuine physical magnitudes, a crucial interpretive principle in contemporary physics. The two foundations debates—on the Higgs mechanism and on the interpretation of gauge symmetries—have both direct relevance to Beyond Standard Model (BSM) physics (see Berghofer et al. 2023).

In this talk I propose a new perspective based on the analysis of invariance heuristics, as a theoretical-methodological practice guiding the formulation of theories. In the first part, I argue that the construction of the Higgs mechanism exemplifies invariance heuristics akin to those employed both in general relativity and in gauge theories in particle physics, understood as the introduction of a field that determines local structure that is initially non-invariant. I will demonstrate how these heuristics are at play in Higgs's (1966) invariant formulation and also in the formulation of the Higgs mechanism by Fröhlich et al (1980, 1981).

In the second part, I explore the implications of this perspective for the symmetry-to-reality inference. I argue that the persistent success of invariance heuristics in leading to empirically successful theories offers a stronger basis for the inference than arguments derived solely from symmetry properties of completed theories. By contrasting these two forms of justification, I advocate for the minimalistic, heuristics-based argument as more conceptually robust and conducive to clearer interpretation of field theories, and explore its implications on the relationship between symmetry, conjectured structural properties, and theory construction.

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Karol Horodecki

Faculty of Mathematics, Physics and Informatics, University of Gdańsk, Poland

Quantification of energy consumption of quantum entanglement distribution

Abstract: One of the main tasks of quantum information technologies is generating, manipulating, and using quantum resources. Prominent examples of such resources are quantum entanglement and key secure against quantum adversary, which are planned to be used in future quantum networks, e.g., for distributed quantum computing and secret communication, respectively. In these networks, quantum resources will be distributed via technologically advanced devices modelled with CPTP maps aka quantum channels. This process is expected to involve energy consumption both due to technological imperfections but also due to fundamental phenomena. The consumption takes place during both passing input to the channel and the distillation of imperfect resources taken from the channel's output to its almost perfect form required for coherent processing of information. For this reason, we propose estimating and minimizing this consumption as one of the important tasks on the way to resource aware quantum information processing.

We therefore establish a quantitative study of energy expenditure in producing quantum resources via quantum channels. We distinguish technological and fundamental energy costs. Technological cost depends on hardware; hence, it is not a fixed quantity. We then focus mostly on the fundamental one. We establish a paradigm for quantifying the minimal, i.e., unavoidable fundamental energy consumption in creating a maximally resourceful state expressed in units of Jule per

Rbit (energy invested while distributing a unit of resource). We explore this paradigm in the case of quantum entanglement. We derive a lower bound on the fundamental energetic cost of the standard entanglement distribution procedures (taking maximally entangled states as input to the channels). Hence, under the contemporary design, we provide a quantitative estimate (a lower bound) of the inevitable energy consumption in future quantum networks.
We also compare energy performance of the first three entanglement distillation protocols in the case of distribution of quantum entanglement encoded in the polarization of photons. Fundamentally these protocols require energy by many orders of magnitude higher than the proposed lower bound on energy consumption, stemming from entanglement irreversibility.

Sebastian Horvat

University of Vienna, Austria

Reflections on a future quantum event-ontology

Abstract: The aim of this talk is to systematically reflect on the question: "Which events (can plausibly be said to) occur in quantum phenomena?" That such a reflection is needed in a sense in which a parallel such reflection that would concern more ordinary phenomena – say, coin tosses – is not needed, can be very easily illustrated on the by-now paradigmatic electronic double slit experiment. The double slit experiment features statistical regularities of the detection of electrons at various locations on a screen, which coincide with the empirical predictions of an appropriate use of quantum theory. There is accordingly an uncontroversial consensus that in each execution of the said experiment there are events that correspond to the detection or non-detection of the electron at some location on the screen. There is however no analogous consensus on which events, if any, occur in the void that is allegedly traversed by the electron before impinging on the screen. More generally, there is a lack of clarity on which events take place in quantum phenomena, besides those few events that quantum mechanical models are already concerned with – and that are most often referred to using the arguably physical-ontologically problematic language of 'measurements', 'operations', 'outcomes' and so forth. In other words, there is no agreement on which “event-ontology” is adequate for quantum phenomena, paralleling the lack of consensus on which, if any, “object-property-ontology” would be so adequate.
The plan of the talk is to first discuss statistical phenomena in general, keeping in mind ordinary examples such as coin tosses, and analyzing the adequacy of certain mathematical models as descriptions of such phenomena. Then we will apply this general discussion to quantum phenomena, attempting to treat them as ordinarily as possible, suppressing our quantum-mechanically trained prejudices on how to interpret them. The reflection will not lead here to any definite verdict on which, if any, event-ontology is adequate of the vast plurality of phenomena that are studied with the aid of quantum-mechanical techniques. It will instead prepare the ground for a possible such future verdict and bring to the fore some peculiarities that concern a possible event-ontology of a subclass of non-relativistic quantum phenomena – the said peculiarities being arguably interpretable as manifestations of certain forms of ""complementarity"" and (spatial or temporal) ""holism"".

Link to a related paper:
https://arxiv.org/abs/2502.08823

Karthik Hosapete Seshadri

International Centre for Theory of Quantum Technologies (ICTQT), University of Gdańsk, Poland

Coherence leveraged quantum metrology

Abstract: Quantum metrology concerns improving the estimation of an unknown parameter using optimal measurement scheme on the quantum system. More optimal the measurement, the better will be the improvement in sensing the value of the unknown parameter. Pertaining to the case of a two level system (qubit) undergoing rotation, the metrological task concerns the estimation of the angle of rotation given the information about the axis of rotation (θ, ϕ). The method for garnering much information about the angle of rotation, is by maximizing the Fisher information which is the figure of merit. In the absence of information about the axis parameters, the optimality of the task reduces drastically. We overcome this limitation by initializing the system in a state of coherent superposition. The system and the probe then interact through an entangling unitary. The system is measured in the same coherent state as initialized. The measurement of the probe

now results in the enhanced Fisher information about the rotation angle than could be gathered from the probe alone. Notably, this strategy doesn't involve any entangled probe states nor entangled measurements yet accounts for maximum Fisher information about the rotation parameter.

Michael Huber

University of Bristol, The United Kingdom

Defending Psi-Ontic interpretations via case-discrimination

Abstract: In this work, an alternative attempt to motivate psi-ontic interpretations (POI) of QM is undertaken. The usual way of arguing for POIs mostly revolves around how they might solve the measurement problem in a more straightforward and concise manner than rival interpretations. However, here an effort is made to defend POIs in an indirect manner, namely via repeated case discrimination and a process of 'conceptual elimination'. That is, it will be argued that its anti-realist rivals, with QBism being among the most noteworthy ones, either face conceptual incoherence or ultimately conceptually collapse into a variant of POI.

Link to a related paper:
https://www.mdpi.com/2624-960X/5/2/23 (This talk will be based on sec. 3.1 in my MDPI article linked below)

Nick Huggett*[1], Mike Schneider[2]

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The Highs and Lows of Particle Physics

Abstract: Recent work on the philosophy of high energy physics experiments has considerably advanced our understanding of their epistemology, for instance concerning measurements by the ATLAS collaboration at the large hadron collider (Beauchemin 2017). In this talk we aim to highlight and analyze complementary low energy 'tabletop' experiments in particle (and other kinds of fundamental) physics. In particular, we contrast ATLAS measurements with high precision measurements of the electron magnetic moment. We find, for instance, that the simplicity of the latter experiment allows for uncertainties to be minimized materially, in the very construction of the apparatus; it promises to probe new 'regimes' of physics found in 'increased significant figures' rather than higher energies. We finally suggest that a better appreciation of the capacities of such comparatively 'frugal' experiments broadens our conception of 'cutting edge' physics, and ultimately helps to inform value judgments about possible research programs in the field.

Jack Johnson

The University of Western Ontario, Canada

Equilibration in Quantum Systems at Non-random Times

Abstract: Equilibration is a fundamental concept for thermodynamics and statistical physics, describing how physical systems approach a stable state of equilibrium over time. Progress in the last decade in the foundations of physics has rigorously shown that isolated quantum systems on large Hilbert spaces equilibrate under quite general conditions. However, a key question remains whether the equilibration so described (and perhaps thereby explained) happens on realistic timescales—neither too long to be observable nor too short to be physically meaningful. This too has received much attention and progress.

A key class of recent results prove what is known as Equilibration on Average of generic quantum systems. This states that, when their evolution is averaged over sufficiently long finite periods, realistic quantum states exhibit the same expectation values over observables as a fixed equilibrium state. Such results entail that when a system is measured at a random time

within the period in question, one should expect the same results as if the system were in equilibrium. Yet, further explanation is required to bring these findings into contact with experiments in which observation times are not selected at random. My talk will demonstrate this connection. Specifically, I exhibit a general method for translating Equilibration on Average results into Equilibration at a Time results. These are of the kind: if coffee is prepared at 12:00 and left in a cold room, it and the room will have equilibrated at 13:00 (but not at 12:30). Rather than incorporating uncertainty over the time of measurement, the method utilises uncertainty in the Hamiltonian of the system, arising from limitations on preparation control at the outset of the experiment. The specific form of this uncertainty is different from other approaches seeking to show equilibration that utilise random Hamiltonians. I then argue that on minimal posits about this uncertainty, one can derive realistic bounds on quantum equilibration times. This updated equilibration result extends existing theorems by permitting them to entail results about their intended target: the length of time that it in-practise takes systems to transition from states of non-equilibrium to those of equilibrium. Furthermore, it permits greater understanding of the root cause of such equilibration (and the time required for it to occur) in terms of variances of initial conditions brought about by the preparation procedure.

Caroline Jones

Institute for Quantum Optics and Quantum Information (IQOQI-Vienna), Austria

Theory-independent monitoring of the decoherence of a superconducting qubit with generalized contextuality

Abstract: Characterizing the nonclassicality of quantum systems under minimal assumptions is an important challenge for quantum foundations and technology. Here we introduce a theory-independent method of process tomography and perform it on a superconducting qubit. We demonstrate its decoherence without assuming quantum theory or trusting the devices by modelling the system as a general probabilistic theory. We show that the superconducting system is initially well-described as a quantum bit, but that its realized state space contracts over time, which in quantum terminology indicates its loss of coherence. The system is initially nonclassical in the sense of generalized contextuality: it does not admit of a hidden-variable model where statistically indistinguishable preparations are represented by identical hidden-variable distributions. In finite time, the system becomes noncontextual and hence loses its nonclassicality. Moreover, we demonstrate in a theory-independent way that the system undergoes non-Markovian evolution at late times. Our results extend theory-independent tomography to time-evolving systems, and show how important dynamical physical phenomena can be experimentally monitored without assuming quantum theory.

Link to a related paper:
https://arxiv.org/abs/2411.13421

Som Kanjilal

International Iberian Nanotechnology Laboratory (INL), Portugal

Unbounded Sequential Extraction of Nonlocality using Local Randomness Assisted Projective Measurements

Abstract: The notion of sequential extraction of a resource for indepdendently distributed copies have numerous applications. Operationally, measurement of each copy extracts only a small amount of resource in such a way that the post-measurement state is still resourceful. By using unsharp measurements for the copies, it has been shown that unbounded sequential extraction of Bell nonlocality can be achieved. We demonstrated a local randomness assisted projective measurement scheme for the same. More over, we gave an answer to what type of measurements can extract nonlocality in such a way that the post-measurement state is still nonlocal.

Link to a related paper:
https://arxiv.org/abs/2311.07977

Shashaank Khanna
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Which Causal Scenarios can support non-classical correlations

Abstract: The classical causal relations between a set of variables, some observed and some latent, can induce both equality constraints (typically conditional independences) as well as inequality constraints (Instrumental and Bell inequalities being prototypical examples) on their compatible distribution over the observed variables. Enumerating a causal structure's implied inequality constraints is generally far more difficult than enumerating its equalities. Furthermore, only inequality constraints ever admit violation by quantum correlations. For both those reasons, it is important to classify causal scenarios into those which impose inequality constraints versus those which do not. Here we develop methods for detecting such scenarios by appealing to d-separation, e-separation, and incompatible supports. Many (perhaps all?) scenarios with exclusively equality constraints can be detected via a condition articulated by Henson, Lal and Pusey (HLP). Considering all scenarios with up to 4 observed variables, which number in the thousands, we are able to resolve all but three causal scenarios, providing evidence that the HLP condition is, in fact, exhaustive.

Link to a related paper:
https://arxiv.org/abs/2308.02380

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Topos-theoretic approach to vacuum algebraic quantum field theory over curved space-times

Abstract: A topos-theoretic approach to the foundations of quantum theory, developed by Chris Isham and his collaborators, has emerged from the consideration of some foundational problems in quantum gravity and quantum cosmology. However, it does not include any notion of space-time and has so far only dealt with the foundations of quantum mechanics. Our aim is to bring it back to the quantum / gravity interface, by extending the spectral presheaf formalism to vacuum algebraic quantum field theory over curved space-times. We do this by replacing the base category of abelian von Neumann subalgebras, used in the original approach, by two orthocomplemented (not necessarily orthomodular) lattices: of causally closed regions of (not necessarily globally hyperbolic) time-oriented lorentzian space-time, and of (mostly nonabelian) factor subalgebras of an arbitrary von Neumann algebra. The (various variants of) relativistic nonsignalling, as well as the commutant of subfactors, are represented by the paraconsistent negation operators in the respective spectral presheaves. Furthermore, the presence of closed time-like (or vertex) curves corresponds to nontrivial bi-Heyting modal operators. By introducing a natural category-theoretic generalisation of Haag's "tentative postulate", we construct a representation of the vacuum a.q.f.t. as a suitable functor between the above presheaves. This allows to study the context-dependent quantitative properties of the vacuum sector of an underlying theory (as reflected in the structure of von Neumann subfactors), while allowing for the wide structural variability of causal structures (e.g., time-like vs time-and-null-like signalling, presence of closed time-like curves, discretisation of the space-time, etc.).

Ved Kunte
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Theories without local tomography need entanglement0

Abstract: Physical theories that are described by generalized probabilistic theories (GPTs) often make the assumption of 'local tomography', according to which the global statistics of a multipartite system can be determined completely by looking at the measurement statistics of local subsystems. Quantum theory, classical theory, and even certain post-quantum theories follow this principle. However, there is no reason to assume that all GPTs must follow this principle. Certain physical theories are known to violate local tomography, most notably fermionic quantum theory and real Hilbert space quantum theory. Recently, it was shown that a classical theory can be made to include entangled states by simply abandoning local tomography. In this work, we prove a stronger result. We claim that any physical theory that violates local tomography must necessarily contain not just entangled states but also entangled effects, and non-entanglement breaking channels. We do this by considering the process theoretic description of a physical theory. If two processes are not operationally equivalent, then there must exist an element of its dual space, called a tester, that will give different probability distributions for both of them. We first show that all such testers must themselves be operationally equivalent to a process consisting of a state s, an effect e, and a process w between two ancillary systems E and E'. We show that if a theory is non-local tomographic, then there must exist two processes that can only be distinguished using a tester where both s, e are entangled, E and E' are non-trivial systems, and w is not a discard and prepare process. We show that condition is equivalent to saying that the process must necessarily contain a non-empty set of entangled states, entangled effects, and non-entanglement-breaking channels. Thereby establishing a relation between non-local tomography and entanglement that must hold for all physical theories.

Marek Kuś
Center for Theoretical Physics, Polish Academy of Sciences, Poland

Everett intepretation, Lewis, modal realism, and Kripke's semantics

Abstract: Ideas for the application of non-classical logics to quantum mechanical problems emerged as early as the 1930s. Chronologically, the first trend was based on attempts to apply three-valued logic, which had been invented shortly before by Łukasiewicz (Zawirski, Zwicky, Destouches-Février), and was continued, among others, by Reichenbach and Putnam in the 1950s. The second trend is, of course, the two-valued but non-Boolean "quantum logic" of Birkhoff and von Neumann, which seems to have won the race against its three-valued and multi-value competitors in the logical analysis of quantum mechanical statements. Here we would like to propose another application of non-classical logics in quantum mechanics, namely the analysis of Everett's interpretation in terms of modal logic. In particular, we show how the concept of "many worlds" in Everett's interpretation can be interpreted in terms of Lewis's "possible worlds". The resulting modal aspects of Everett's interpretation can be treated on a somewhat more formal ground. Everett's "worlds" can constitute a domain of appropriate modal semantics in the sense of Kripke. By Kripke semantics we mean here the ordered triple <W,R,V>, where W is the set of possible worlds, R – a relation on W×W that determines which possible worlds are mutually accessible, and P – a mapping from Z×W to the two-element set {0,1}, where Z is a set of sentences about objects in the set of possible worlds (quantum-mechanical statements), whose image is 1 if in world W the sentence z is true and 0 otherwise. The analysis of the relation R allows for the identification of the type of modal logic suitable for the interpretation of Everett. Depending on additional assumptions, this logic turns out to be the B or S5 type of modal logic. One can also give such an analysis a temporal meaning, i.e. consider problems of the type: which worlds will be possible in the future if the present world is currently described by the Everettian "universal" wave function ψ. Here, the Kb logic of Rescher and Urquhart turns out to be an adequate temporal logic.

Ohkyung Kwon
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Quantum foundations are incomplete without holography in the background space-time: Probing the ground state of gravitational entanglement

Abstract: The foundations of quantum mechanics have been tested with exceptional levels of rigor, mathematically and experimentally. However, the theoretical framework in which the mathematical formalism is constructed presumes a classical, definite space-time as its background. As the causal structure of space-time is dynamically coupled to mass-energy in general relativity, a complete study of quantum foundations necessitates a probe of entanglement in the background space-time itself, arising from couplings to quantum superpositions of mass-energy. It is widely assumed that detecting such gravitational entanglement will involve large coherent states of quantum matter for measurable superpositions of geometry. This talk will make the case that in holographic models of quantum gravity, even the quantum states of the vacuum may result in measurably large irreducible correlations in the background space-time. Unlike in the standard theory

where vacuum fluctuations lead to incoherent Planck scale jitters, a dimensional reduction in the total degrees of freedom contained in a finite causal volume of space-time may lead to a large degree of coherence on the scale of the causal boundaries, allowing the gravitational memory effect to accumulate the fluctuations like a Planck random walk. We present the latest updates in our research program to empirically probe such correlations of quantum space-time, connecting signatures in the CMB arising from primordial space-times to experimental data from state-of-the-art laser interferometers enhanced with novel quantum metrology under commissioning at Cardiff University.

Collaborators on the work:
Nikitha Kuntimaddi and Abhinav Patra (Cardiff Univ.)
Lorenzo Aiello (Univ. of Rome Tor Vergata)
Craig J Hogan (Univ. of Chicago)
Karim P Y Thébault (Univ. of Bristol)
Alasdair L James and Sander M Vermeulen (Caltech)
Aldo Ejlli (Max Planck Institute for Gravitational Physics)
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The Contextual Heisenberg Microscope

Abstract: The Heisenberg microscope provides a powerful mental image of the measurement process of quantum mechanics (QM), explaining the uncertainty relation through an uncontrollable back-action from the measurement device. However, the back-action uses features that are not present in the QM description of the world, and according to Bohr not present in the world. Therefore, Bohr argues, the mental image proposed by Heisenberg should be avoided. In this presentation we will re-examine the measurement process within a restriction of QM known as stabilizer QM, that contains many of the specifically quantum properties studied in the foundations of QM and more recently in the foundations of quantum information, for example, Greenberger-Horne-Zeilinger nonlocality and Kochen-Specker (Peres-Mermin) contextuality. Notably, there exists a recent extension of stabilizer quantum mechanics called the Contextual Ontological Model (COM) which is complete in the EPR sense but still reproduces the quantum predictions, including all of the mentioned phenomena. A consequence of the existence of this model is that the mental image that Heisenberg proposed becomes consistent, and even useful. This gives a modified interpretation of the uncertainty relation in particular, as well as several other concepts in quantum foundations, including the Heisenberg microscope.

Thijs Latten
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Visualising the Quantum World in Quantum Technology: On Realism, Pragmatism and Quantum Interpretations

Abstract: No consensus exists on how quantum mechanics should be interpreted (e.g., Laloë, 2019), yet physicists and engineers in quantum technologies are finding innovative ways to create, manipulate and exploit quantum behaviour. This paper explores a connection between the interpretations of quantum mechanics and quantum technology. I argue there is a tension between the interpretational framework researchers and engineers in quantum technology embrace (i.e., orthodox quantum mechanics) and the visualisations they utilise to explain quantum mechanics (of quantum phenomena beyond measurement outcomes).
Presentations of quantum mechanics in engineering contexts, typically characterised as orthodox or standard quantum mechanics (e.g., Griffiths & Schroeter, 2018; Nielsen & Chuang, 2010), traditionally sidestep ontological questions about the reality of quantum phenomena beyond measurement outcomes. However, in research and engineering practices

in quantum technology, physicists and engineers often use tools for visualising quantum phenomena outside measurement outcomes, where definite properties are ascribed to quantum systems – such as sketches of tunnelling processes (e.g., Kalinin & Gruverman, 2011) or visualising the trapping of electrons in quantum dots (Vandersypen, 2024). In this paper, I address how this leads to a tension between the framework engineers and researchers in quantum technology typically embrace (i.e. orthodox quantum mechanics that restricts its domain to measurement outcomes) and the visualisations they utilise to explain quantum mechanics (visualising quantum phenomena beyond measurement outcomes). I outline some possible resolutions to the tension from both realist and pragmatist perspectives and elaborate on the challenges for each response. On the one hand, neglecting engineering sketches in light of their instrumental nature challenges the pragmatist to explain how to reconcile the utility of the sketches (i.e., that which informs truth for the pragmatist) with the typical emphasis on orthodox quantum mechanics in engineering practices. On the other hand, taking the engineering sketches seriously in a realist fashion, reminiscent of Hacking (1983) for example, challenges philosophers of physics to adjust interpretational commitments to fit the practice, placing conditions on quantum interpretations (Vermaas, 2005). I explore what such adjusted interpretational commitments can look like.

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Matthew Leifer
Chapman University, The United States

Contextuality of the Quantum Zeno Effect

Abstract: I will show that the quantum probability of freezing a state in the quantum Zeno effect cannot be reproduced in a (Spekkens) noncontextual ontological model. This has implications interaction free measurement based on boosting the probability of success of the Elitzur-Vaidman bomb tester using the Zeno effect. In quantum mechanics, this can be done perfectly in the asymptotic limit. In a noncontextual theory, if we demand no false positives then it is not possible to reduce the probability of false negatives or of the bomb blowing up to zero via the Zeno effect.

Joanna Luc, Tomasz Placek
Jagiellonian University in Cracow, Poland

On randomness arguments against deterministic hidden variable programs

Abstract: Landsman (Found. Phys. (2020) 50, p. 78) advanced the argument that "[t]ruly deterministic hidden variable theories [...] compatible with the Born rule do not exist", where such theories are assumed (1) to have determined outcomes given the initial (hidden) state and (2) do not appeal to irreducibly random samplings from the set of such states. Claim (2) forms the backbone of the argument: Born's rule applied to infinite outcome sequences of flips of a fair quantum

coin yields the result that typically, wrt Born's measure, such sequences are random. According to Landsman, to recover this result, hidden variable theories have to posit a source of irreducible randomness. We argue that the required randomness comes (almost) for free.

Landsman exploits the mathematical relation between the single-case probability measure m_1 (assumed to satisfy m_1(1) = m _1(0) = 1/2) and the measure m on the infinite product space, derived from m_1. With respect to m, a typical infinite sequence is random. Significantly, this measure is the same as the measure m_B, obtained by applying Born's measure to projectors representing infinite sequences of results. This identity of measures implies that for a fair quantum coin, typically (wrt Born's measure) an infinite outcome sequence is random.

The standard concept of randomness is given by three equivalent definitions. Martin-Löf's definition is based on the measure m specified above. A sequence is random iff it does not belong to the intersection of any uniformly effective open sequence of nested sets such that the measure m of the n-th set is less than 1/2^n. It can be proved that a typical (wrt m) infinite sequence is random.

Consider finally a physical process generating binary outcomes. Assume we know that the true probability measure for its outcomes is a "fair" single-case measure m_1. The assumption that this probability measure applies to every outcome of the process implies that consecutive outcomes are independent. Thus, the measure for infinite sequences of outcomes is the product measure – i.e., m. Accordingly, once we know that m_1 is the right single-case measure for a given process, we can apply all mathematical results concerning m to infinite sequences of outcomes of that process. It follows that typical infinite sequences of outcomes are random. To establish this result for an empirical phenomenon, it is enough to justify that the probability measure for that phenomenon is equal to m_1. This is the only empirical input to our reasoning. Thus, positing a source of randomness is not a substantial constraint. Positing a measure on hidden states that delivers the same measure for hidden states determining each outcome is enough.

Jorge Alberto Manero Orozco

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On the detectability of arrival times as rest mass residues in the non-relativistic limit

Abstract: There are physical situations where the limiting case of a successor theory becomes the corresponding predecessor theory plus additional elements whose empirical significance has remained controversial.

One illustrative example is the status of the rest mass appearing in the quantum, non-relativistic limit of relativity theory. As argued by (Bohm and Hiley, 1993, sec 10.4), if one calculates the non-relativistic limit of the Dirac equation for a one ½-spin Dirac particle, one obtains the Pauli equation plus an extra constant term given by the rest mass of the particle — interpreted, from the Bohmian perspective, as a circulating factor associated with spin angular momentum. Although this extra term contributes to the Hamiltonian in a way that cannot be dropped in this limit, many scholars, such as (Tumulka, 2022, 357), believe that it has no empirical consequences due to the fact that the generalized equation that includes this term makes exactly the same empirical predictions to the standard Pauli equation (as it corresponds to an extra term in the current that has null divergence). As a result, they argue that the question of whether this additional term exists in nature is empirically undecidable and, therefore, should be eliminated for sake of simplicity —as normally done for any gauge term.

However, there is a recent contribution that objects the supposed undetectability of the rest mass term. As argued by (Dass and Dürr, 2019), there is an actual detectable deviation to the quantum-mechanical distribution associated with arrival time distributions. This deviation occurs in the context of an extended ideal-arrival-time-experiment applied to a Bohmian ½-spin particle in a state of equal superposition of spin-up and spin-down wave functions. It is shown that the corresponding deviation is associated with the nonzero contribution of the additional rest mass term of the particle appearing in the Pauli equation and, furthermore, that this term takes the form of a "spin current" in a generalized guiding equation within the Bohmian theory. This objection, however, has not been unchallenged and a recent critique has been made to it (Goldstein et al., 2023), followed by a reply due to (Dass and Aristarhov, 2023).

Given this, the aim of my talk is to defend the thesis that deviations of arrival times quantum-mechanical distributions can actually be detected as a consequence of the natural detectability of the rest mass term in the non-relativistic limit. In so doing, I shall appeal to an alternative case study introduced by (Greenberger, 2001) and (Hernandez, 2012) to argue that, from the perspective of the symmetry groups underlying quantum theory and relativistic theory, the detectability of

deviations of arrival times quantum-mechanical distributions arises from the fact that the rest mass term not only produces physical effects that naturally occur in the relativistic domain but also leaves detectable residues in the non-relativistic limit. Indeed, it should be noted that the non-relativistic limit of the Poincaré group is the standard Galilean group plus an extra group element associated with the rest mass generator. The resulting group is the extended Galilean group, which can consistently account for certain quantum states impossible to be described by the standard one, such as superpositions of different mass under certain type of transformations (i.e., Bargmann transformations), but also equal superpositions of spin-up and spin-down in the context of extended ideal-arrival-time-experiments.
Considering this, I shall conclude that the relativistic, detectable property of rest mass enters into the non-relativistic limit generating deviations of arrival times quantum mechanical distributions, in the same way that it generates proper time differences between moving frames —which in turn produce a physically meaningful phase shift due to the variation of superpositions of different mass under Bargmann transformations.

Eleanor March

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Minimal coupling, the strong equivalence principle, and the adaptation of matter to spacetime geometry

Abstract: I provide a systematic exploration of one set of precise technical conditions under which matter fields might be said to be "adapted" to a relativistic spacetime geometry – namely, that the equations governing those matter fields be minimally coupled, quasilinear, and symmetric hyperbolic. I discuss the implications of this for the role and status of the "strong equivalence principle" and the geometry-dynamics debate. (This talk is related to the talk proposed by James Owen Weatherall.)

Enrico Maresca

University of Pisa, University of Florence, Italy

Noncommutative Geometry and the Problem of Chronogeometry in Quantum Gravity

Abstract: Noncommutative approaches to spacetime physics have emerged as a significant area of research in quantum gravity (QG) over the past few decades. These approaches employ the mathematical framework of noncommutative geometry (NCG) to explore fundamental physics in the quantum gravitational regime. The central hypothesis is that spacetime exhibits a noncommutative structure beyond a certain energy scale, typically near the Planck energy, where the symmetries of general and special relativity are replaced by deformations, known as quantum groups. This leads to an algebraic description of the noncommutative structure that postulates a minimal length scale and deforms relativistic (commutative) physics.
The ""algebra-first"" approach, combined with the violation of Gelfand duality due to noncommutativization, raises questions about whether noncommutative theories retain spatiotemporal content. If not, these theories would only be mathematically well-defined, with no direct physical relevance. At a minimum, an argument for spatiotemporality would require showing that the noncommutative structure can be interpreted as chronogeometrically meaningful. This means the structure must either provide representations of distances, angles, and durations (representational chronogeometricity) or allow for the development of measurement protocols for these quantities (operational chronogeometricity). However, satisfying these chronogeometric principles is far from trivial within an algebraic framework. In fact, several major treatments of NCG in the philosophical literature on QG suggest that noncommutative structures may lack spatiotemporal meaning.
In contrast, I argue that noncommutative approaches can indeed fulfill an appropriate definition of chronogeometricity, thus becoming physically significant within QG. To demonstrate this, I first introduce the noncommutative approach to QG, emphasizing the relationship between the algebraic structure and spatiotemporal concepts, mediated by quantum symmetries. I then illustrate how this algebraic structure connects to spatiotemporal significance. I argue that physical relevance arises from specifying two crucial elements: a representation of the noncommutative algebra and a set of suitable observers. I use the

example of k-Minkowski spacetime to show how these elements complete the algebra-first approach. In this framework, the algebra can be interpreted as encoding localization procedures for events in noncommutative spacetime, relative to a ""noncommutative reference frame,"" with frame transformations governed by the quantum group structure. By enriching the algebra-first approach, NCG can satisfy the necessary representational principles, achieving representational chronogeometricity.

Marcin Markiewicz

International Centre for Theory of Quantum Technologies (ICTQT), University of Gdańsk, Poland

Quantum (Ir)reversibility: extended Wigner's Friends, relationalism and unitary quantum mechanics

Abstract: In this talk a summary on recent disputes on extended Wigner's Friends paradoxes, relational approach to quantum measurements and unitary quantum mechanics will be presented. It will be shown that the common assumption behind all these recently very popular approaches to the quantum measurement problem is the assumption of in principle fundamental reversibility of arbitrary unitary interactions, which leads to abandonment of the idea of objectivity of measurement outcomes. Arguments will be presented that any physically reasonable and logically consistent application of the quantum theory involves fundamentally irreversible processes, which guarantee unique and objective perception of physical reality.

Link to a related paper:
https://arxiv.org/abs/2409.17061

Niels Martens

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Dark Energy & the Spacetime-Matter-Constant Trichotomy

Abstract: The titular Lambda in our standard model of cosmology, LambdaCDM, parametrises the accelerated expansion of our universe. Although the standard model treats it simply as a cosmological constant, the definitive physical nature underlying this `dark energy' remains unclear, with theorists and experimentalists considering a large variety of dynamical matter alternatives as well as modified gravity / spacetime alternatives to a cosmological constant. This talk will consider this situation in the context of the orthodox conceptual dichotomy between spacetime and matter (i.e. everything in our universe is either an aspect of spacetime structure, or a form of matter, never both, never neither), extending it by adding a third category: constants of nature. It will be argued that a strict conceptual distinction between these three ontological categories is no longer tenable in the context of dark energy. This analysis will be further connected to three philosophical themes: conventionalism, the substantivalism vs relationalism debate, and the semantic component of scientific realism.
Two arguments will be provided that suggest a breakdown of, or at least a blurring of, the distinction between at least two of the ontological / conceptual categories in the context of dark energy. Firstly, it will be discussed to what extent a cosmological constant is equivalent to a specific modified matter model (a perfect fluid with equation of state w = -1). The two main interpretational options of this formal equivalence are functionalism and conventionalism. The second argument critically assesses David Baker's (2005) claim that a cosmological constant, assumed to be part of the spacetime structure, vindicates substantivalism about spacetime. An alternative analysis---focusing on the Raychaudhuri equation---of the explanation of the accelerated expansion of the universe in terms of a cosmological constant suggests that this is at the same time a matter-like and a geometrical / gravitational explanation. Rather than vindicating substantivalism over relationalism, this analysis suggests that this is a false and outdated dichotomy. Finally, both these arguments together suggest that the semantic component of scientific realism about dark energy---is this concept rich enough for it to be clear what it means to be a realist about it?---is not yet satisfied.

Lucy Mason

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Can Measurement be Entirely Quantum?

Abstract: I will look at Bohr's doctrine of classical concepts – the claim that measurement requires classical concepts to be understood – and connect it to the work done in measurement theory regarding the representation of measurable properties by a metric scale. This is a central aspect of measurement and is prominent from the inception of measurement theory up until recent model-based accounts of measurement in metrology. I argue that representing a property with a metric scale, which marks a shift from the empirical process of measurement to the informational output, introduces the inherently classical assumption of definite states and precise values, hence fulfilling Bohr's doctrine. This assumption – although sometimes treated as a mathematical idealisation in the measurement process – has played an important role in debates about measurement realism, as well as in assessments of measurement quality and the success of research programmes. It is ineliminable from measurement and is further reinforced by how we break down and quantify uncertainties in measurement.

Furthermore, I will discuss how the implications of this vary depending on what stance is taken towards measurement realism and argue that Bohr's doctrine should be understood primarily as an epistemological point. The assumption of precise values can be tempered by acknowledging the operational and conventional elements of how we treat uncertainties and calibration in measurement. These aspects are increasingly prevalent in recent model-based approaches to measurement, which have largely superseded the traditional representational theory of measurement. However, ontological implications remain possible.

Connecting Bohr's doctrine to the philosophy of measurement not only translates Bohr's ideas into a new context but also shows how debates about measurement realism are directly relevant to quantum mechanics. Whether Bohr's doctrine is seen as epistemological or ontological, however, this discussion makes it clear that measurement cannot be entirely quantum, and approaches such as the decoherence picture explain at most the empirical aspect of measurement and not its informational output.

Nicolás Medina Sánchez

University of Vienna, Austria

Geometric reconstruction of quantum theory: projectivity and unitarity

Abstract: We address the question about why the state space of quantum theory in finite dimensions admits a representation as the family of probability measures on the complex-projective space, i.e., of mixtures of pure states. Starting from two assumptions, namely, a) a physical state is an element of a 2n-dimensional smooth manifold such that there is a well-behaved projection to a probability space and, b) transformations between states correspond to transitive actions of a connected Lie group on the state space by hamiltonian symplectomorphisms, we prove that this is enough to conclude that the state space is isomorphic as a manifold to the complex-projective space and that the transformation group is isomorphic to the unitary group. This two postulates admit direct operational interpretations that can be discussed, showing a minimal reconstruction for quantum theory.

Manuel Mekonnen

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Invariance under quantum permutations rules out parastatistics

Abstract: Quantum systems invariant under particle exchange are either Bosons or Fermions, even though quantum theory could in principle admit further types of behavior under permutations. But why do we not observe such "paraparticles" in nature? The analysis of this question was previously limited primarily to specific quantum field theory models. Here we give two independent arguments that rule out parastatistics universally, originating in quantum information theory and recent research on internal quantum reference frames. First, we introduce a notion of complete invariance: quantum systems should not only preserve their local state under permutations, but also the quantum information that they carry about other systems, in analogy to the notion of complete positivity in quantum information theory. Second, we demand that quantum systems are invariant

under quantum permutations, i.e. permutations that are conditioned on the values of permutation-invariant observables. For both, we show that the respective principle is fulfilled if and only if the particle is a Boson or Fermion.
Moreover, we argue that quantum permutations should be understood as quantum reference frame transformations, which allows us to introduce a reference frame formalism for the permutation symmetry of indistinguishable particles. Not only does this clarify conceptually what we mean by indistinguishability of particles, but it also lets us establish a connection with existing quantum covariance principles in the literature, stating that physical laws are preserved under quantum coordinate transformations. While we are able to make use of this in our second argument to essentially single out Bosons and Fermions, we find that applying some quantum permutations for a given physical scenario does lead to observable consequences. We argue that this has important implications for the quantum reference frame research program and suggest a modification for the postulate of quantum covariance.
Our results thus show how quantum reference frames can shed light on a longstanding problem of quantum physics, they underline the crucial role played by the compositional structure of quantum information, and they demonstrate the explanatory power but also subtle limitations of recently proposed quantum covariance principles.

Link to a related paper:
https://arxiv.org/abs/2502.17576

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Quantum Speed Limits for Change of Basis

Abstract: Quantum speed limits provide ultimate bounds on the time required to transform one quantum state into another. Here, we introduce a novel notion of quantum speed limits for transformation of a collection of quantum states, investigating the time interval for converting a basis of states into an unbiased one as well as basis permutation. Establishing a mutually unbiased basis, we provide tight bounds for the systems of dimension smaller than 5, and general bounds for multi-qubit systems and the systems living in the Hilbert spaces of the dimension d. Especially, an observation is that it is possible to establish an unbiased basis of n qubits within a universal time which is independent of the number of qubits. For two-qubit systems, we show that the fastest transformation implements two Hadamards and a swap of the qubits simultaneously. Our study unravels that for qutrit systems, the minimal evolution time depends on the particular type of the unbiased basis, which indicates a counterintuitive assymetry in the Hilbert space of the dimension 3. Moreover, an exact analytic expression is obtained for the time to permute a basis of dimension d. We also investigate speed limits for the coherence generation, providing the minimal time to establish a certain amount of quantum coherence by a unitary evolution.

Link to a related paper:
https://arxiv.org/abs/2212.12352

Alyssa Ney

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Why Did Wheeler Reject the Everett Interpretation?

Abstract: 100 years after the invention of quantum mechanics, we still face a fundamental disagreement regarding the ontological lessons we should draw from the paradigm, especially concerning the status of observers. Many argue that the Copenhagen interpretation and textbook versions of quantum mechanics have a measurement problem, and that the ontological implications of quantum mechanics can only be properly assessed when we arrive at interpretations that excise reference to measurements or observers. However, many others disagree, and argue that to properly understand the metaphysical lessons of quantum mechanics, the fundamental postulates must keep the observer in view. I propose to make progress resolving this disagreement by looking to the past. The contemporary disagreement shares many features in common with the famous Bohr / Einstein dialogue of the 1920s and 1930s. However, in this talk, I will seek insight in a later historical episode: Wheeler's reaction to the proposal of his PhD student Everett, which evolved from the time Everett was writing his dissertation in the 1950s to the 1970s when Wheeler developed his participatory universe idea to

eventually the 1990s. Wheeler initially supported Everett's interpretation, more frequently referred to today as the many worlds interpretation. Wheeler encouraged Everett to go to Copenhagen and "[fight] out the issues of interpretations one by one with Bohr" (Barrett and Byrne 2012). When Everett published his dissertation in Reviews in Modern Physics in 1957, his article was accompanied by a piece by Wheeler, who aimed to make the proposal more accessible to the physics community. However, despite this initial enthusiasm, Wheeler eventually adopted a view about the ontological implications of quantum mechanics that looked a lot more like that of his mentor Bohr and the Copenhagen interpretation. This is often called the participatory universe view, which Wheeler sometimes referred to as the idea of "it from bit" (Wheeler 1989). The main question this paper asks is what made Wheeler, someone who saw the value of adopting an interpretation of quantum mechanics in which observers did not play a fundamental role, ultimately reject the Everett interpretation and reinstate the observer to a central place in the interpretation of quantum mechanics. Through discussion of Wheeler's published and unpublished papers, correspondence, and archival interview transcripts, I will introduce several hypotheses that answer this question. Ultimately, my claim will be that Wheeler never completely rejected the Everett interpretation, but rather saw the two views – Everett and Copenhagen – as compatible. In the final part of the paper, I seek to develop how Wheeler may have thought the two positions could be reconciled, which perhaps makes a step forward in reconciling the stalemate in the interpretation of quantum mechanics we face today.

Alexander Niederklapfer

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Localisation of Particles in Quantum Field Theory

Abstract: The consensus in philosophy of physics is that quantum field theories (QFTs) are, on the fundamental level, not about particles. The vast majority of empirical data concerning QFTs, however, is gathered from particle experiments. It is an important task, hence, to reconcile the particle phenomenology with the theoretical framework. A key aspect of this challenge is the issue of localisability: there are several no-go theorems that show that there cannot be localised states in QFTs, and there are as many attempts that try to align these theoretical facts with the appearances of localised particles detected in experiments.

I present and defend Haag's ""detector patterns"" approach, first introduced in Araki and Haag (1967) and elaborated in Haag (1992), along with its generalisation to ""particle weights"", advanced by Buchholz et al (1991). The framework offers a method to extract the asymptotic particle content (that is, the particles present in the infinite positive and negative time limits) of an arbitrary state of the quantum field and has, thus far, received less attention in the philosophy literature. I compare this approach to the more widely known proposal by Wallace (2006) and show in what ways there are similarities in the mathematical constructions, as claimed by Wallace himself. I propose that the key differences in the conceptions can be attributed to the different ways measurement devices and procedures are represented in the theory.

While Wallace advocates for a solution in which the observer is considered part of the internal dynamics of the quantum system, described in the same terms as the system under investigation, Haag's approach builds on an operational interpretation of quantum field theory. I argue that Haag's framework is metaphysically more neutral, which, I claim, should be preferred, since there is no consensus yet on how to exactly model measurements or interpret the detection and extraction of empirical outcomes in quantum field theories. Furthermore, I suggest that Haag's approach closely mirrors the practices of particle physics, embracing the practical impossibility of directly associating physical particle detectors with specific observables of a theory. Overall, I propose that Haag's approach succeeds in providing – in the words of Arageorgis and Stergiou (2014) – ""a particle phenomenology without a particle ontology"".

Toru Ohira

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Separated out of Entangled

Abstract: The determination of whether a quantum system is separable or entangled has been a subject of active research. This question becomes particularly challenging when the quantum state is mixed rather than pure, making the identification of separability conditions for density matrices a central focus of ongoing studies. The Werner density matrix was introduced

to describe mixed quantum systems and serves as the simplest example of a bipartite 2 x 2 system in a mixed state. Despite its simplicity, it provides valuable insights into various aspects of quantum mechanics and has been extensively studied, including experimental realizations.
The standard Werner matrix consists of an independent, unbiased classical component and a quantum entangled singlet state. These components are linearly combined using a control parameter, ξ. The mixture ratio of the independent classical component and the entangled quantum component is given by 1−ξ and ξ, respectively. By applying the Peres-Horodecki separability criterion, we find a critical value of $\xi_c = 1/3$. When the independent classical component constitutes more than two-thirds of the total mixture, the state remains separable. However, if the entangled quantum component exceeds one-third, the overall state becomes entangled.
Here, we extend the Werner matrix to incorporate a classically dependent component, allowing both the classical and quantum parts to exhibit entanglement. Interestingly, we find that a suitable mixture can still yield a separable state. Furthermore, the critical control value increases to $\xi_c = 1/2$, indicating an enhanced degree of separability, even when the quantum entanglement fraction exceeds 1/3. Thus, we demonstrate the creation of a separable mixed state from components that are both classically and quantum-mechanically entangled. Related discussions from the opposite perspective of entanglement enhancement (arXiv:2409.18495) will also be presented.

Link to a related paper:
https://arxiv.org/abs/2409.18495

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An interpretation of quantum theory based on quantum causal structure

Abstract: I will introduce an interpretation of quantum theory in which causal structure plays a fundamental role. Causation is not defined as a relation between events, variables, state spaces, or the like. Instead, causation is defined as the noncommutativity interactions (a definition that turns out to be equivalent to the notion, familiar from quantum causal models, of the noncommutativity of operators in the Heisenberg picture). Events are held to emerge from the causal structure.
The sense of “interpretation” here is not of a story put on top of the standard quantum formalism; but rather of a reformulation of quantum theory with a precise mathematical formalism that articulates its conceptual claims. In the formalism, reality is modelled using a unitary circuit alone (no state is put into the bottom of the circuit). This unitary circuit has a causal structure. An “Event Theorem” is proven, showing the effect that the operators on a given system that stand in a particular causal relation (called “causal balance”) to a set of systems (called a “bubble”) are always those generated by a unique PVM (thus defining an event space). A “Probability Theorem” is proven, showing that the event spaces pertaining to a particular bubble always form a consistent set of histories, and thus admit a natural probability rule. The interpretation — called the Theory of Causal Balance — posits that one such history happens relative to any bubble.
The Theory of Causal Balance can thus be seen as a refinement of consistent histories in which consistency of a set of histories is derived from causal structure rather than simply assumed. One consequence of the requirement that the consistent set is derived from the causal structure is that there is a unique consistent set for each bubble, arguably resolving issues with consistent histories pointed out by Dowker and Kent (1996).
All predictions of the Copenhagen interpretation are reproduced by the interpretation. The interpretation successfully models scenarios in which the Copenhagen interpretation becomes ambiguous, such as (extended) Wigner’s friend scenarios. As the details of the models flesh out, the idea at the core of the theory — that events are not things that influence each other, but rather things that emerge from influences — explains various conceptually challenging quantum phenomena, including Bell inequality violations, PBR inequality violations, and Wigner’s friend scenarios.
In short, this talk proposes that the key conceptual shift needed to make sense of quantum theory is an inversion of the concept of causation and events, according to which events (and the related concepts of variables and states) are not the relata of causal relations, but rather things that emerge from causal relations.

Link to a related paper:
Based on joint work with Jon Barrett (https://arxiv.org/pdf/2401.18005) and my forthcoming PhD thesis.

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Geometric monotones of violations of quantum realism

Abstract: We explore geometric quantifiers for violations of quantum realism (VQR), extending the entropic framework proposed by Bilobran and Angelo [EPL 112, 40005 (2015)]. Quantum realism declares that projective measurements establish well-defined properties (elements of reality) in quantum systems, with VQR (also called irrealism) quantifying deviations from this classical-like behavior. We introduce geometric distances---trace, Hilbert-Schmidt, Bures, and Hellinger---as potential monotones of VQR, guided by a realism-information relation that links measurement-induced realism to conditional information encoded in the environment. These distances are evaluated against axioms for bona fide monotones, including non-negativity, contractivity under measurements, and invariance under uncorrelated subsystems. Key results reveal that trace distance fails due to violations of measurement monotonicity, while Hilbert-Schmidt distance improperly responds to uncorrelated states. In contrast, Bures and Hellinger distances satisfy all axioms, emerging as valid geometric monotones. These distances are shown to relate to symmetric instances of Rényi and sandwiched Rényi divergences, bridging geometric and entropic approaches. Analytical and numerical examples, such as Werner states and bipartite entangled systems, demonstrate their robustness. Notably, geometric quantifiers exhibit dimension-dependent maxima distinct from entropic measures, raising questions about normalization in higher dimensions. Our study underscores the necessity of aligning geometric measures with informational principles to capture quantum realism. It highlights the unique advantages of Bures and Hellinger distances, while identifying limitations in other metrics. Open questions include exploring non-commutativity effects, generalizing to broader distance classes, and rescaling geometric monotones for consistency across dimensions. This work advances the quantification of VQR of observables, offering tools for foundational studies and applications in quantum information science.

Link to a related paper:
https://arxiv.org/abs/2412.11633 (accepted in Phys. Rev. A)

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Solve to sort: a new classification of spacetime singularities

Abstract: Spacetime singularities raise important questions within the foundations of general relativity (GR). One such question concerns their classification. While physicists and philosophers of physics agree that there are different types of singularities, they do not agree on how to classify them. The currently canonical classification by Ellis and Schmidt (1977) is based on mathematical differences. An important as much as overlooked concern is that this categorization lacks physical significance because it fails to distinguish physically different and significant types of singular structures (Curiel, 1999; Taub, 1979). After pointing out the shortcomings of Ellis and Schmidt's classification, I propose a new classification of spacetime singularities based on how they can (or cannot) be solved.
There is a growing body of evidence in research programs in quantum gravity (QG) that suggests spacetime singularities may be eliminated (e.g. Bojowald 2001; Mathur 2005). This supports the expectation that spacetime singularities disappear in a theory more fundamental than GR. However, not all of them need or can be solved merely by quantum gravitational effects (Horowitz and Myers, 1995; Natsuume, 2001; Singh, 2009). After presenting the main mechanisms implemented to get rid of singularities, I argue that we should use singularity resolution as a criterion for classifying spacetime singularities. I provide an example of such a classification based on the idea that different types of singularities are associated with different ways in which they can be solved.
The last section of the paper outlines the advantages of this proposal. In particular, the new classification offers a straightforward and physically relevant understanding of the differences between the various types of singularities. In this respect, my suggestion overcomes the shortcomings of the extant canonical classification. Moreover, this work engages with the debates on the nature of spacetime singularities and their fate in QG. More specifically, it demarcates a clearcut distinction between spacetime singularities that are solved only by resorting to QG and other types of singularities by highlighting how only a few features are relevant for singularity resolution in QG. I conclude by defending the suggestive idea that the key to enhancing our understanding of spacetime singularities may lie in the physics beyond GR.

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Modal interpretations, hidden-variables and completeness

Abstract: The putative completeness of quantum theory is a central question in the study of its foundations. On the one hand, multiple no-go theorems restricted the possibility of hidden-variables theories (HVTs). On the other hand, proposing a minimal definition for HVTs in the framework of quantum logic, Gudder [1] proved an existence theorem for these completions. Modal interpretations (see [2]) also avoid the conclusions of these no-go theorems. However, there was no consensus within the modal framework as to whether its interpretations were examples of HVTs. Bacciagaluppi argued that they were best understood as stochastic non-contextual HVTs [3], whereas Healey (and more recently Lombardi) views them as a reinterpretation of quantum states [4,5]. Relying on Gudder's minimal definition, I show that these divergent conceptions stem from two different views of completeness for a theory. The first, and more demanding one, views completeness as requiring two normative criteria, regarding (i) a theory's self-sufficiency in the explanation of its own predictions, and (ii) its diachronic self-consistency. The second conception requires only criterion (i). Bacciagaluppi argues in effect for adopting the first conception, while Healey and Lombardi argue for the second. Modal interpretations, as mere reinterpretations, can still be considered complete, although they fail to meet criterion (ii), by endowing possibility with a primitive role. I further show that this conceptual distinction can be applied to investigate proposals other than modal ones, and I claim that some 'orthodox' interpretations also fail to meet criterion (ii). They can still be considered complete by granting a primitive status, not to possibility, but to an external cause, outside the quantum-mechanical model.

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Is String Field Theory Background Independent?

Abstract: The question of whether string theory is a `background independent' theory---that is, whether it is a theory which is not committed to fixed, non-dynamical elements in its ontology, has continued to be a pertinent one for philosophers working on the foundations of quantum gravity since (at least) the challenges raised by \citet{Smolin} on this very topic. This issue was more recently taken up by \citet{ReadBI} in the context of perturbative string theory (PST); Read argues that it is not possible to provide an answer to this question without having fixed antecedently (a) the notion of `background independence' in play, and (b) the exact way in which one is understanding PST (i.e.,\ as a spacetime theory versus as a worldsheet conformal field theory). All of these discussions of the background independence of string theory, however, play out only at the level of PST; non-perturbative versions of string theory remain to be assessed. One such approach to string theory is 'string field theory' (SFT), which is the string-theoretic analogue of quantum field theory: one posits a `string field' over spacetime, and studies excited states of this string field (rather than studying only one such string in an ambient spacetime, as in PST). One would like, then, to study the background independence of SFT; this, indeed, will be my focus in this talk.

Physicists have already spoken on the background independence of SFT. Notably, \citet{Witten} and \citet{Sen2018} have both argued that one can construct background independent open / closed (respectively) SFTs. In this talk, I will interrogate this claim. Drawing on an analogy with the case of spin-2 gravity, where one can set general relativistic physics on various different fixed spacetime backgrounds and moreover where one can `deform' between these theories, I will argue that something very similar occurs in the case of SFT: one has various different SFTs each set of different – fixed! – spacetime backgrounds, but one can likewise `deform' (via so called `marginal deformations') between them.

As such, when applying the various different definitions of background independence collated by \citet{ReadBI} to the case of SFT, what one finds is that while (i) any \emph{individual} SFT still has background structure, nevertheless, at the level of the \emph{space of SFTs}---i.e.,\ at one higher level of abstraction---the claims of the background independence of SFT hold up. All in all, this work not only (a) sheds conceptual clarity on claims regarding background independence in an important sub-field of string theory, but also (b) draws attention to the importance of discussions both of spaces of solutions, and of spaces of theories, in the philosophy of quantum gravity (a point also stressed recently by \citet{DHButterfield}).

Albert Rico

Universitat Autonoma de Barcelona, Spain

Quantum advantage in high-dimensional communication from correlations

Abstract: The benefits of quantum communication over classical communication can be seen in terms of enhanced security and the scalability of the carrier system. In this talk, we will focus on the latter: we present a communication protocol between Alice and Bob where correlated events occur with zero probability, while anticorrelated events occur with maximal probability. We will demonstrate that this protocol can be realized using a quantum system of operational dimension d, whereas a classical implementation would require at least dimension 2d. This research is hybrid in nature: the classical dimension can be bounded through polynomial optimization, while the quantum dimension is determined by an explicit setup that is currently under experimental preparation. Additionally, we will discuss our observations on the protocol's robustness against noise.

Tom Rivlin

Technische Universität Wien (TU Wien), Austria

Wigner's Friend Scenarios in the Presence of a Environment

Abstract: The Wigner's Friend thought experiment describes paradoxical disagreements between agents about the outcomes of measurements of a quantum system [1]. Variants of the problem have shown that, under "Bell-like", natural-seeming assumptions, it can be impossible for two agents to simultaneously reason about probability distributions that physically exist [2].

Whilst Wigner's Friend effects have been shown in experiments, the setups have tended to model the agents as single qubits, or at best small quantum circuits [3]. This is far from the ideal of an agent being a quantum system that is still able to perform a 'measurement' in the conventional sense [2]. Additionally, with few exceptions [4], no work has theoretically analysed the role a decohering environment might play in any Wigner's Friend scenario.

In this talk, I will present theoretical investigations [5] of both a standard and extended Wigner's Friend setup that treats the 'Friend' agent as part of a wider environment inside the lab, and allows said Friend to be a large, generic collection of qubits. The Friend's measurement is modelled as a dynamical equilibration process [6,7] where information is broadcast from the system into its surroundings (as in the Quantum Darwinism framework [8]), and where decoherence is modelled in a fully unitary, closed-system setting.

Using this model, I will show how to distinguish a true Wigner's Friend effect from classical ignorance, and also what is required to maximise disagreements between agents (including numerical results for small N). In the extended case, I will also demonstrate how both the environment and different system-environment interaction Hamiltonians affect one's ability to observe CHSH-like violations of Local Friendliness.

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Bryan Roberts
London School of Economics and Political Science (LSE), The United Kingdom

The reduction of thermodynamics to statistical mechanics

Abstract: This paper introduces a novel reduction of thermodynamics to dynamical systems—whether classical or quantum—that sidesteps statistical methods and addresses many longstanding challenges in reduction.
We begin by proposing a central postulate for thermodynamics, which says what makes a given dynamical system thermal: namely, that its energy naturally divides into contributions that are measurable and extractable through some specified procedures (identified as 'thermodynamic work') and contributions that are not (identified as 'heat'). For instance, a gas cylinder contains energy contributions of the form PdV, which can be determined via conventional volume and pressure measurements, but also contributions from molecular interactions that cannot be extracted through those procedures. Similarly, the total energy (or ADM mass) of a black hole comprises terms like ΩdJ—accessible through mechanisms like the Penrose process—as well as others linked to horizon area and surface gravity that cannot be measured in that way.
Our strategy is to exhibit a reduction procedure, akin to symplectic reduction, which maps any dynamical system satisfying our postulate onto the full contact geometry of thermodynamic phase space. We demonstrate that the foundational proposals of Wayne Myrvold and David Wallace emerge as special cases of this method, including the interpretation of heat as arising from microscopic degrees of freedom; indeed, our approach generalises these ideas.
Although the notion of equilibrium is not presupposed in our analysis, we identify a particular set of critical points exhibiting a stability property that may be construed as equilibrium, and we show how a version of the second law naturally arises at these points. This fresh perspective invites a re-examination of classic problems—ranging from Maxwell's demon and the origins of fluctuations away from equilibrium to the arrow of time—while preserving more of the intrinsic structure of thermodynamics than other well-known approaches, such as Robertson's functional approach or Callender's cautious stance. The result is a charming new lens through which to view the foundations of thermodynamics, of potential interest to both philosophers of science and physicists.

Link to a related paper:
https://arxiv.org/abs/2503.08753

Pascal Rodríguez-Warnier
Western University & The Rotman Institute, Canada

Fluctuation theorems and (ir)reversibility in statistical thermodynamics

Abstract: In this paper, I propose that the fluctuation theorems illuminate the link between equilibrium and non-equilibrium thermodynamics by offering a new conceptual apparatus for establishing equations of state via processes that do not even come close to thermodynamic reversibility.
The thermodynamic state of a system is characterised by a small number of parameters, known as state functions (e.g., total energy, temperature, pressure, and entropy), which are well-defined only in equilibrium. Finding the so-called equations of state, which relate state functions, provides thermal physics with predictive power. Deriving these equations necessitates equalities between thermal quantities, which typically hold only for the special case of thermodynamically reversible processes.
At the macroscopic level, the posit of thermodynamically reversible processes is a harmless approximation since there is no principled reason preventing a process from being driven arbitrarily close to equilibrium at all times. This justifies considering reversible processes as limiting cases of sets of irreversible processes. For any non-limiting process, thermodynamics provides only inequalities. The extent to which reversible processes are unproblematic in a regime where thermal fluctuations cannot be neglected has raised controversy in the philosophy of physics community (Ladyman and Robertson 2014, Norton 2017, Myrvold and Norton 2023).
After briefly examining the controversy, I show that the fluctuation theorems are a family of results that enable the derivation of equalities for the probabilities of thermodynamic quantities that hold irrespectively of the nature of the process (i.e., whether it is arbitrarily close to equilibrium or arbitrarily far away from it). In particular, I propose that implicit in Jarzynski's equality --a fluctuation theorem equating the expectation value of the exponentiated work with the exponential of the free energy difference between initial and final equilibrium states – there is a method for deriving

equations of state dispensing of reversibility (Jarzynski 1997, 2011). For this, I outline additional steps that allow for obtaining not only the free energy difference and the partition function values for a specific pair of Hamiltonians, their fixed external parameters, and a particular temperature (as in Jarzynski's work), but the free energy and partition function as state functions, encapsulating all the thermal properties one may need.

I conclude by discussing some insights that the proposal offers into both practical and foundational issues in statistical thermodynamics and by highlighting the general takeaway—namely, that the philosophy literature sometimes exaggerates the distance between equilibrium and non-equilibrium thermodynamics.

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Davide Rolino
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On Complementarity and Incompatibility

Abstract: The development of quantum theory began in the early 20th century in response to a series of experimental results that challenged our understanding of the physical world. The black body radiation, the photoelectric effect, and Compton's effect, just to cite a few, were inexplicable using the physical theories that had been developed till that moment. However, the development of the new formalism of quantum mechanics came with a lot of interpretative challenges. A proposal to overcome some of these interpretative issues was made by Bohr through the concept of complementarity. In his view, the corpuscular and wave-like nature of matter are just two complementary aspects of reality. Only by considering both descriptions simultaneously is it possible to achieve a complete description of a phenomenon. Following Bohr's idea a lot of research has been conducted on the duality of nature. However, if we move in the field of quantum information and look to the extensions of the definition of complementarity to refer to any quantities that can be measured of a quantum system, then less is understood. In our paper we address this by showing that complementarity, defined as the impossibility of making simultaneous statements about properties of a physical systems, is equivalent to the incompatibility of the operators associated to the measurements of that properties. Furthermore, we show how this result can be extended to hold for generic theories of information processes. However, in the latter case, the relationship can be shown to hold only in one direction, i.e., complementary operations are incompatible. We were not able to prove nor disprove the converse implication.

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Is Black Hole Evaporation Prediction Friendly?

Abstract: Manchak and Weatherall (2018) articulate a precise formulation of the black hole information paradox based upon the failure of predictability in black hole evaporation spacetimes. This failure is a consequence of the breakdown of global hyperbolicity. In this paper I offer a resolution to this paradox. I first introduce two novel spacetime properties: prediction and retrodiction friendliness, before arguing that an information paradox based upon predictability, such as that articulated by Manchak and Weatherall, requires a failure of either prediction or retrodiction friendliness, not just a failure of global hyperbolicity. Manchak and Weatherall do not establish that black hole evaporation spacetimes fail to be prediction or retrodiction friendly, and indeed they need not be. Deidealized models of black hole evaporation plausibly do not have event horizons and so are both prediction and retrodiction friendly. Moreover, whether or not our best models of black hole

evaporation have event horizons depends upon open questions in quantum gravity of which we are ignorant. Thus we have no positive argument for a failure of prediction or retrodiction friendliness, and so no paradox arises due to a failure of predictability.

Matthias Salzger

International Centre for Theory of Quantum Technologies (ICTQT), University of Gdańsk, Poland

A decompositional framework for process theories in spacetime

Abstract: There has been a recent surge of interest within the field of quantum foundations regarding incorporating ideas from general relativity and quantum gravity. Many of the tools that are used in quantum foundations and information, however, remain completely agnostic as to the underlying spacetime in which the quantum systems live. For example, when we draw a quantum circuit the effective spacetime imposed by the connectivity of the physical qubits which will realize this circuit is not taken into account. In this work, we aim to address this limitation. In particular, we show how to extend the formalism of process theories (a framework to study both quantum and post-quantum theories) to incorporate a background causal structure arising from a fixed spacetime. We discuss when processes are embeddable in spacetime under certain constraints. To this end, we introduce the concept of an implementation of a process, which is simply an arbitrary decomposition of the process. A process is then embeddable if and only if one of its implementations can be embedded in such a way that all the component processes are localized and all wires follow time-like paths. Whilst this is conceptually simple, it turns out that testing for embeddability is, in general, computationally intractable. We therefore work towards simplifying this problem as much as possible, showing that there is a canonical subset of implementations which tell us everything we need to know, both about the other implementations and the embeddability of the process. Additionally, we can view this canonical subset as those causal structures which can be distinguished in arbitrary process theories. This leads us to the question of which causal structures can be distinguished by and are hence relevant for specific process theories, for example, quantum and classical theory. In particular, we find that already for processes with two inputs and outputs there exist countably infinite canonical causal structures, which we call zigzag causal structures due to their shape, beyond the causal structures usually considered in the literature. We show that while these zigzags can be ignored in classical theory, they cannot be discounted in quantum theory as the quantum CNOT gate has an implementation for each one of them but not a more useful ``standard'' causal structure. These zigzags may hence be important for a fully quantum account of causal modelling and in the search for interesting quantum resources.

Link to a related paper:
https://arxiv.org/abs/2411.08266

David Schmid

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Shadows and subsystems of generalized probabilistic theories: when tomographic incompleteness is not a loophole for contextuality proofs

Abstract: It is commonly believed that failures of tomographic completeness undermine assessments of nonclassicality in noncontextuality experiments. In this work, we study how such failures can indeed lead to mistaken assessments of nonclassicality. We then show that proofs of the failure of noncontextuality are robust to a very broad class of failures of tomographic completeness, including the kinds of failures that are likely to occur in real experiments. We do so by showing that such proofs actually rely on a much weaker assumption that we term relative tomographic completeness: namely, that one's experimental procedures are tomographic for each other. Thus, the failure of noncontextuality can be established even with coarse-grained, effective, emergent, or virtual degrees of freedom. This also implies that the existence of a deeper theory of nature (beyond that being probed in one's experiment) does not in and of itself pose any challenge to proofs of nonclassicality. To prove these results, we first introduce a number of useful new concepts within the framework of generalized probabilistic theories (GPTs). Most notably, we introduce the notion of a GPT subsystem, generalizing a range of preexisting notions of subsystems (including those arising from tensor products, direct sums, decoherence processes, virtual encodings, and more). We also introduce the notion of a shadow of a GPT fragment, which captures the information lost when one's states and effects are unknowingly not tomographic for one another.

Link to a related paper:
https://arxiv.org/pdf/2409.13024

Charles Sebens
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Relativistic Locality from Electromagnetism to Quantum Field Theory

Abstract: Electromagnetism is the paradigm case of a theory that satisfies relativistic locality. This can be proven by demonstrating that, once the theory's laws are imposed, what is happening within a region fixes what will happen in the contracting light-cone with that region as its base. The Klein-Gordon and Dirac equations meet the same standard. We show that this standard can also be applied to quantum field theory (without collapse), examining two different ways of assigning reduced density matrix states to regions of space. Our preferred method begins from field wave functionals and judges quantum field theory to be local. Another method begins from particle wave functions (states in Fock space) and leads to either non-locality or an inability to assign states to regions, depending on the choice of creation operators. We take this analysis of quantum field theory (without collapse) to show that the many-worlds interpretation of quantum physics is local at the fundamental level. We argue that this fundamental locality is compatible with either local or global accounts of the non-fundamental branching of worlds, countering an objection that has been raised to the Sebens-Carroll derivation of the Born Rule from self-locating uncertainty.

Link to a related paper:
https://arxiv.org/abs/2412.11532

John Selby
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Generalised Process Theories

Abstract: Process theories have been widely applied, from the foundations of physics through to computational linguistics. They are conceptually based on the idea that we can describe all of these things in terms of systems which interact and evolve via processes, and that we can explore their behaviour by considering how these systems and processes compose. On a formal level, they are based on the mathematics of symmetric monoidal categories which is known to be broadly applicable within many branches of mathematics. There are, however, situations where the formal notion of a process theory does not seem applicable, but where the conceptual idea of a process theory still does. That is, where we still have systems, processes, and their composition, but those which neatly fit the mould of a symmetric monoidal category.

In this work we discuss whether the conceptual idea of a process theory might in fact be better formally understood in terms of operad algebras. In particular, this view hinges on the works of Patterson et al. [2021], Yau [2018] in which the authors demonstrate a close connection between symmetric monoidal categories (along with some of their variants) and certain kinds of operad algebras. We build on these previous works by identifying an adaptation needed to recover those symmetric monoidal categories which are causal, and demonstrate the utility of the operad algebra perspective by showing how it can be easily adapted to subsume alternative kinds of process theories such as those which are time-neutral, enriched, or higher-order.

We present all of this using a convenient string-diagrammatic notation, such that this paper should be readily accessible to anyone who has some familiarity with string diagrams in other contexts. That is, we use string diagrams both for the new kinds of process theories that we introduce, as well as for the operads and operad algebras underpinning them.

Link to a related paper:
https://arxiv.org/abs/2502.10368

Amrapali Sen
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Superluminal Quantum Reference Frames

Abstract: The theory of relativity is generally assumed to provide us with a speed limit for all interactions. Particles cannot travel faster than the speed of light, nor can information. A standard argument for the impossibility of superluminal particles, also known as tachyons, and superluminal observers says that they would allow for backwards-in-time signalling, thus causing causality paradoxes. Nevertheless, over the years, this assumption has been frequently questioned and the idea of breaking this speed limit has popped up from time to time in an attempt to explain various phenomena.
Most recently, [1] have argued that in a world with superluminal observers local determinism is impossible linking the two pillars of physics — quantum theory and relativity — suggesting that the latter serves as the foundation for the former. In this work, we extend the framework of quantum reference frames to incorporate superluminal Lorentz transformations and ensure consistency with a few fundamental laws of Physics. We examine an apparent paradox where particles acquire negative energies after undergoing a superluminal Lorentz boost and propose a resolution within this framework that draws inspiration from previous studies. We consider a number of proposals for how thermodynamic quantities evolve under (subluminal) Lorentz boost and argue that their extensions to superluminal transformations is consistent with the second law of thermodynamics.
Finally, we discuss Bell experiments under superluminal quantum reference frame transformations, where we find that probabilities are (still) conserved. These insights not only challenge conventional assumptions about superluminal theories but also represent the first work to integrate superluminal transformations within the framework of quantum reference frames. This approach opens new avenues for rethinking the interplay between quantum theory and relativity.

Kuntal Sengupta
Institut Néel, CNRS, Grenoble, France

Achieving Maximal Causal Indefiniteness in a Maximally Nonlocal Theory

Abstract: A second version of the paper (on arXiv) is in preparation with clarifications on certain concepts and further details of higher order operations in the Hex-Square theory.
Quantum theory allows for the superposition of causal orders between operations, i.e., for an indefinite causal order; an implication of the principle of quantum superposition. Since a higher theory might also admit this feature, an understanding of superposition and indefinite causal order in a generalised probabilistic framework is needed. We present a possible notion of superposition for such a framework and show that in maximal theories, respecting non-signalling relations, single system state-spaces do not admit superposition; however, composite systems do. Additionally, we show that superposition does not imply entanglement. Next, we provide a concrete example of a maximally Bell-nonlocal theory, which not only admits the presented notion of superposition, but also allows for post-quantum violations of theory-independent inequalities that certify indefinite causal order; even up to an algebraic bound. These findings might point towards potential connections between a theory's ability to admit indefinite causal order, Bell-nonlocal correlations and the structure of its state spaces.

Link to a related paper:
https://arxiv.org/abs/2411.04201

Sina Soltani
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Noncontextual ontological models of operational probabilistic theories

Abstract: An experiment or theory is classically explainable if it can be reproduced by some noncontextual ontological model. In this work, we adapt the notion of ontological models and generalized noncontextuality so it applies to the framework of operational probabilistic theories (OPTs). A defining feature of quotiented OPTs, which sets them apart from the closely related framework of generalized probabilistic theories (GPTs), is their explicit specification of the structure of instruments, these being generalizations of quantum instruments (including nondestructive measurements); in particular, one needs to explicitly declare which collections of transformations constitute a valid instrument. We are particularly interested in strongly causal OPTs, in which the choice of a future instrument can be conditioned on a past measurement outcome. This instrument structure might seem to permit the possibility of a contextual kind of ontological representation, where the representation of a given transformation depends on which instrument it is considered a part of. However, we prove that this is not possible by showing that for strongly causal quotiented OPTs the structure of instruments does not allow for such a contextual ontological representation. It follows that ontological representations of strongly causal quotiented OPTs are entirely determined by their action on individual transformations, with no dependence on the structure of instruments.

Link to a related paper:
https://arxiv.org/abs/2502.11842

Antoine Soulas

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An interpretation-independent formulation of the measurement problem

Abstract: In this presentation, we do not try to solve the measurement problem of quantum mechanics (QM), but rather to properly formulate it. One of the reasons why it still lacks a precise, agreed definition is that the problem may take very different forms depending on the interpretation of QM embraced. We propose to identify the common root of the puzzle in an interpretation-independent way (i.e. as a property of the probabilities only) and derive its ontological consequences. The key point is that the violation of the total probability formula in QM does not allow to construct an objective ontology, independent from epistemology. This enables us to:

(i) shed light on the ubiquitous presence of the total probability formula in the quantum foundations literature (definition of hidden variables, historical and modern formulation of Bell's theorem, absoluteness of observed events in the local friendliness theorem, macrorealism à la Leggett-Garg, ontological models à la Spekkens...);

(ii) study how the problem manifests itself in five famous interpretations of QM (Copenhagen, collapse-models, Bohmian mechanics, many-worlds and relational QM) : how they propose to solve it and which new difficulties arise. This provides a fresh look on the different interpretations, and allows to better compare them.

Jer Steeger

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Complementarity as infringement

Abstract: Werner Heisenberg's 1927 paper introducing his uncertainty principle contains an unusual postscript. It flags apparent shortcomings in the work, particularly concerning a thought experiment with a gamma-ray microscope, that were pointed out to Heisenberg by his supervisor and mentor, Niels Bohr. Does this postscript truly reflect a mistake in Heisenberg's reasoning, or does it mask a philosophical disagreement with Bohr? Historians such as Max Jammer and Mara Beller have tended to endorse Bohr's claim that Heisenberg's reasoning about the gamma-ray microscope contains a mistake: a failure to account for the finite aperture of the lens of the supposed microscope. Conversely, we argue that the postscript reflects a disagreement about whether the gamma-ray microscope should emphasize wave-particle duality—i.e., roughly, complementarity—or particles with properties created through observation.

Our argument is twofold. First, we reconstruct Heisenberg's original version of his gamma-ray microscope from letters he sent to Pauli and Dirac, showing that it contains no lens or imaging screen at all; rather, it is designed to roughly operationalize the paths of light in the Geiger-Bothe and Compton-Simon cloud chamber experiments from just a few years earlier. Second, we argue that Heisenberg was influenced to frame the difference as an error via psychological abuse from

Bohr. The sort of abuse in play is what feminist philosopher Lauren Laydon-Hardy calls epistemic infringement, an abuser's systematic subversion of the healthy social and epistemic norms governing their relationship with their target. We demonstrate how a model of this systematic subversion maps neatly onto Bohr and Heisenberg's relationship from their first meeting in 1922 to the submission of the postscript in 1927. This case provides a striking example of how paying attention to the psychology of theory building can help us better understand past physics.

Ward Struyve

KU Leuven, Belgium

The action principle as a guide to substantial general invariance?

Abstract: Einstein was led to the formulation of general relativity by demanding the theory to be invariant under space-time diffeomorphisms. However, as shown by Kretschmann, any theory can be formulated in a diffeomorphism invariant manner. This raises the question whether there is a way of distinguishing artificial diffeomorphism invariance (which would be at play in Kretschmannian reformulations), from substantial diffeomorphism invariance (which would be at play in general relativity). This has led to an extensive debate, without any clear consensus. It has been suggested that the general invariance can only be substantial if the theory can be derived from an action principle. The actions of Rosen and Sorkin, which describe a Kretschmannian formulation of theories in flat space-time, seem to be counterexamples. However, these actions introduce an extra field, which has a non-trivial dynamics. Because of this non-trivial field, it can be argued that the theory described by the action is actually different from the Kretschmannian one. Our aim is to show that there are other actions for Kretschmannian formulations of flat space-time theories, which still involve auxiliary fields, but so that these fields are completely trivial. That is, the dynamics is such that the auxiliary fields are either gauge variables or they are completely determined in terms of the other fields. As such, the actions arguably describe just the Kretschmannian reformulations and not different theories. This way of formulating an action principle can actually be used for any theory whose dynamical equations can be expressed in terms of differential equations. In particular, an action can always be found by turning the theory into a gauge theory. While this work shows that the possibility of formulating an action principle does not seem to offer a guide to distinguish substantial invariance from artificial invariance, we will speculate how this could perhaps still be achieved.

Nicetu Tibau Vidal

University of Hong Kong, Hong Kong

BMV experiment without observable spacetime superpositions

Abstract: The interplay between quantum mechanics and general relativity remains one of the most profound challenges in modern physics. The BMV experiment has a promising effect on exploring the quantum nature of gravity by testing whether gravitational interactions can generate entanglement between quantum systems.

In this work, we challenge the standard assumption of local tomography, which posits that global quantum states can always be reconstructed from local measurements. We show that entanglement can be generated through locally classical gravitational mediators without requiring spacetime superpositions or quantum spacetime degrees of freedom in non-locally tomographic couplings. We showcase how entanglement can be generated using three distinct toy models that display non-locally tomographic couplings between quantum matter and a locally classical gravitational mediator. These models include (i) fermionic systems with the parity superselection rule, (ii) non-Abelian anyonic systems, and (iii) a novel bit anti-bit model.

Our results suggest that even without intrinsic quantum properties of spacetime, such as superpositions or gravitons, gravitational interactions may still exhibit quantum effects via non-local coupling mechanisms. This work underscores the importance of relaxing local tomography in exploring the quantum-gravitational interface. It provides a novel perspective on the role of spacetime degrees of freedom in entanglement generation through system-local interactions.

Antoine Tilloy

Mines Paris – PSL, France

The general structure of quantum-classical theories: for gravity and more

Abstract: It is possible to couple quantum and classical variables consistently (i.e. without paradoxes like faster than light signalling) provided one accepts a certain amount of stochasticity. This is useful, for example, if one wants to entertain the possibility that spacetime is fundamentally classical. These hybrid dynamics are not trivial (like meanfield) but they are nothing fancy either, and one way to construct them is via “measurement and feedback”. I will explain how this is concretely done, and how the construction gives some intuition about the type of physics one can expect. I’ll also try to mention some of the challenges in applying this formalism to gravity.

Link to a related paper:
https://arxiv.org/abs/2403.19748

David Trillo

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The Diósi-Penrose model of classical gravity predicts gravitationally induced entanglement

Abstract: The Diósi-Penrose (DP) model was originally introduced as a collapse model to try to explain the quantum to classical transition via an essential decoherence due to gravity. Originally heuristic, it is now understood as a semiclassical theory of classical gravity sourced by quantum systems (in a Newtonian limit and with non-relativistic quantum matter). We show that the dynamics of the DP model can entangle the mechanical degrees of freedom of two separate particles. For standard proposed table-top experiments of gravitationally induced entanglement (GIE), we find that entanglement can be generated iff the particles are separated by a distance smaller than some limiting value, which is proportional to the only free parameter of the DP model. Greater distances can be achieved through new experimental configurations, where the initial wave-functions of the particles are allowed to spread perpendicularly to the separation axis. Although the DP dynamics asymptotically drives the system to a separable state, we observe that, for reasonable experimental parameters, GIE can survive for more than a day. Our results therefore imply that GIE detection is not enough to validate quantum gravity, as opposed to what is widely believed. Experimental tests of GIE dynamics have nonetheless the potential to falsify the DP model.

Link to a related paper:
https://arxiv.org/abs/2411.02287

Mritunjay Tyagi

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Kochen-Specker non-contextuality in the light of quantization: Rethinking value assignments in quantum theory

Abstract: Quantization is traditionally viewed as a method for transitioning from classical to quantum theory, mapping phase space functions to self-adjoint operators on Hilbert space. While not usually linked to the measurement problem, this talk examines whether refining our understanding of quantization could help vindicate single-world realism about quantum theory. We propose reconceptualizing quantization as a mapping within quantum theory, connecting phase space functions—dynamical variables with sharp values—to their corresponding self-adjoint operators. This perspective circumvents the Kochen-Specker non-contextuality condition which prohibits assigning sharp values to all quantum observables while preserving algebraic relations among commuting operators. We critically examine this assumption and argue that the promising general quantization schemes violate this condition leaving it implausible as they systematically alter algebraic relations between dynamical variables. We focus on two prominent schemes of quantization – Weyl quantization and coherent state (Anti-Wick) quantization and show how the algebraic property such as the product of variables is not faithfully mapped to their operator counterparts. This failure

holds not only for operators corresponding to polynomial dynamical variables but also to the projection operators where the corresponding phase space functions are not idempotent undermining the assumption that their values must be 0 or 1.
Considering the guiding principle for choosing the appropriate quantization scheme to be that the quantum expectation value of an operator corresponds to a weighted integral of its associated phase space function with a suitable probability distribution, reveals that coherent state (Anti-Wick) quantization uniquely satisfies this interpretation. Here the Husimi Q-function serves as the natural choice for the probability distribution, thus bypassing the negativity issue of other quasi-probability distributions. We highlight that violations of KS non-contextuality conditions are expected in quantized theories and advocate that the KS non-contextuality condition should not deter one from trying to develop models which assign sharp values to all dynamical variables. Further research, beyond the ontological models framework, is needed to explore the empirical and theoretical implications.

Link to a related paper:
https://arxiv.org/pdf/2409.13071

Lev Vaidman
Tel Aviv University, Izrael

Quantum nonlocality

Abstract: We are celebrating 100 years of quantum mechanics, but we are not closer to the consensus about understanding of nonlocality in quantum theory than we were when Einstein introduced a gedanken boxes experiment questioning completeness of quantum mechanics. First aspect of nonlocality of quantum mechanics is nonseparability: a set of complete descriptions of all space-time points is not a complete description of the Universe. For two separate entangled spin half particles the combination of complete local descriptions of each spin is not enough to specify the state of the two particles. The second aspect of nonlocality of quantum mechanics is action at a distance. It enters quantum theory in the process of quantum measurement through the collapse of the quantum wave. The measurement can be man-made when a single-photon detector is placed after a beam splitter on an optical table, or nature-made when a quantum phenomenon triggers a supernova explosion. Apparently the third aspect of nonlocality is the Aharonov-Bohm effect. A localized wave packet of an electron splits into two wave packets which interfere such that all parts move in the field-free region. The result of the interference, however, depends on the magnetic field elsewhere. There is no action at a distance in the sense described above. The nonlocality here is that there is no local explanation of how it happens. The magnetic field has no local observable effect in any point of the path of the electron.
One purpose of my talk is to describe clearly the problem of nonlocality in quantum theory. But I also propose the way to analyse it. First, I claim that the nonlocality of the Aharonov-Bohm effect is not of a new type, but it is the nonlocality of entanglement. If one considers the source of the magnetic field, the solenoid, as a quantum object, the effect can be explained by local action of the field of the electron on the solenoid and entanglement. Second, since action at a distance is completely foreign to all physics we know, I accept existence of parallel words, which is apparently the only way to avoid action at a distance when the whole universe is considered. It is still present in the history of our world – every time we open one of Einstein's boxes, the local description of the other is changed for us. In the universe, which includes all the worlds, the local description of the second Einstein's box is a density matrix which is not affected by the interaction with the first Einstein's box. Finally, the nonseparability which is the consequence of entanglement (demonstrated in experiments acknowledged by the 2022 Nobel prize) is the nonlocality we have to accept.

Link to a related paper:
https://philsci-archive.pitt.edu/24659/

Francisca Vasconcelos
University of California (UC Berkeley), The United States

Rethinking Quantum Advantage via the Quantum Singular Value Transform

Abstract: The central aim of quantum computation is to demonstrate quantum advantage—the ability to solve important computational problems substantially faster with quantum computers than with classical ones. Yet, despite decades of effort,

quantum computer scientists have discovered only a handful of algorithms offering large provable speedups over their classical counterparts. While there is compelling evidence for quantum advantage (Preskill, 2018), no formal proof exists that the class of problems efficiently solvable by quantum computers exceeds that of classical computation. A precise characterization of the source(s) of quantum speedup could not only enable such a proof but also provide a general framework for the systematic design of efficient quantum algorithms.

A major recent breakthrough in quantum algorithm design was the development of the Quantum Singular Value Transformation (QSVT)—a powerful algorithmic framework enabling polynomial transformations of the singular values of matrices block-encoded into unitary operators. Remarkably, QSVT has been described as the ""grand unification of quantum algorithms"" (Martyn et al., 2021), subsuming and generalizing the major paradigms of quantum computation: search, simulation, and factoring. In this work, I argue that QSVT should play a central role in the pursuit of a philosophical theory for the source(s) of quantum advantage. To support this claim, I revisit a lesser-known philosophical theory of quantum advantage: Bub's Disjunctive View (BDV). In 2010, Jeffrey Bub argued that the power of quantum computation arises from the fundamentally different role of the disjunction operation in quantum versus classical logic. Specifically, Bub demonstrated how information processing in hidden-subgroup (HSP) type problems – i.e. Deutsch (1985), Simon (1997), and Shor (1994)'s algorithms – exploit the non-Boolean logic represented by their Hilbert spaces' projective geometry and subspace structure. However, BDV faces two major challenges: its analytical complexity (even simple algorithms, such as Deutsch's, require non-trivial analysis under BDV) and its failure to generalize beyond the HSP algorithmic family—limiting its potential as a unifying theory of quantum advantage.

In this work, I demonstrate how any algorithm implementable by the QSVT can be directly mapped into BDV. Thus, the QSVT is a tractable algorithmic framework, capable of generalizing BDV to all known quantum algorithms. Furthermore, while most QSVT parameterizations do not result in efficient quantum algorithms, all efficient quantum algorithms are parameterized by the QSVT. Thus, a deeper philosophical understanding of quantum speedup via the QSVT could enable systematic discovery of novel efficient quantum algorithms – a holy grail for quantum computation.

Sanne Vergouwen

Utrecht University, The Netherlands

Black Holes as Massive Spacetime

Abstract: That an astronomical black hole has mass is uncontroversial. However, the claim that an idealized Schwarzschild black hole spacetime possesses mass does not have an uncontroversial interpretation. This talk will focus on two tentative interpretations of the mass of a Schwarzschild black hole: a local, special relativistic notion and a global, general relativistic notion. As mass is often considered to be a key criterion for identifying something as matter, the idea that a vacuum black hole spacetime has mass can be interpreted as suggesting that spacetime has matter properties. This challenges the traditional conceptual dichotomy between spacetime and matter. I will explore the extent to which a global notion of mass, in particular the Arnowitt-Deser-Misner mass, can be considered a matter criterion for spacetime. Furthermore, I will evaluate whether the two mass interpretations support a (super)substantivalist interpretation of Schwarzschild spacetime and consider the implications of that on the dichotomy between spacetime and matter.

Quentin Vigneron

Nicolas Copernicus University in Toruń, Poland

Modifying general relativity on the basis of topological considerations from the Newtonian limit

Abstract: Cosmic topology is the study of the shape and global curvature of our Universe. While general relativity is defined for any possible topology for or Universe, classical Newtonian gravitation is only well-defined for a universe with a Euclidean topology. This leads to the following question: can we generalise Newtonian gravitation to any topology? I will show that the answer is YES and basically unique, which leads to a second question: is general relativity compatible with Newtonian gravitation in any topology possible for our Universe? I will show that the answer is NO. I will argue that this incompatibility asks for a modification of general relativity in order to admit a Newtonian limit in any topology. I will present such

a modification in which a non-dynamical term depending on the topology is added in the Einstein equation. The modification is parameter-free. Consequences for cosmology, and future prospects will be briefly presented.

Link to related papers:
https://arxiv.org/abs/2204.13980
https://arxiv.org/abs/2212.00675

James Weatherall

University of California, Irvine, The United States

Some Results on Natural Theories

Abstract: We will introduce the formalism of Natural Theories, which are systems of partial differential equations that are functorial over the category of n-manifolds, and argue that this formalism provides a useful explication of the long-vexed notion of "generally covariant field theory". We will then show how this formalism can clarify different senses in which a theory may be said to have symmetries and how it provides a context for defining "minimal coupling". We will also state a fundamental result about the well-posedness properties of natural theories. If time permits, we will present other recent results, including that minimal coupling is unique, up to natural isomorphism, and that under certain circumstances, minimally coupled hyperbolic natural theories are associated with a symmetric rank 2 tensor field satisfying by the dominant energy condition and, for solutions, is divergence free.

Christopher Weaver

University of Illinois at Urbana-Champaign, The United States

On Feynman Diagrams and Causal Models

Abstract: In the spirit of what I maintain was Richard Feynman's original intent behind the invention of Feynman diagrams for quantum electrodynamics (QED) in the late 1940s, I argue that at least some Feynman diagrams in the practice of QED, quantum chromodynamics (QCD), quantum flavordynamics (QFD), and electroweak theory (EWT) are used by quantum field theorists, not merely as bookkeeping devices or calculational helps, but as ways of graphically depicting certain scattering / interaction processes. I show that (a) the interactive phenomena in question are undoubtedly causal, that (b) these diagrams include explicit representations of such causal interactions, that (c) Feynman diagrams bear a remarkable similarity to directed graphs in the causal modeling literature, that (d) the associated mathematical formalism that is very precisely encoded by Feynman diagrams bears an uncanny resemblance to the structural equations of causal models, and (e) that (given some qualifications) that formalism can be plausibly understood as mathematical machinery that causally models in the way discussed by Pearl (2009) and many others. One crucial upshot of my reasoning is that the epistemology of our best quantum field theory is in important ways a causal epistemology.

Nanxin Wei

University of Birmingham, The United Kingdom

Reduction and Reductive Explanation: from Statistical Mechanics to Statistical Physics

Abstract: In the philosophy of physics, statistical mechanics is largely conceived as a reduction project for thermodynamics with two main approaches: Boltzmannian Statistical Mechanics and Gibbsian Statistical Mechanics (Frigg & Werndl, 2023). It has been acknowledged that the Boltzmannian approach enjoys more popularity in the philosophy or foundation of statistical mechanics literature, while the toolkits of practicing physicists often lean towards the Gibbsian approach. The standard account for this is that the former provides a clearer ontological picture thus favored for reduction (and consequently more fundamental) and the latter boasts computational expediency hence practically more useful.

For the first part of the standard account, different ways of conceptualizing reduction might challenge the fundamentality of the Boltzmannian approach (Guo, 2024). Moreover, if modern thermodynamics should be understood statistically (Wallace, 2024), the Gibbsian approach would be indispensable to provide a proper reduction base. Nonetheless, there is more that philosophical analysis of the Gibbsian approach can offer, since in practice statistical mechanics (or more broadly statistical physics) is primarily not about metaphysical or theory reduction, but aims for reductive explanations of phenomena engaging many degrees of freedom (thermodynamical phenomena being special cases), more specifically, structural mechanisms at some lower level that account for the target phenomena. The Gibbsian approach provides a powerful framework to produce such reductive explanations via a mode of reasoning referred to as Abduction to Characterization. On this view, statistical physics is not just mechanics with a condiment of probability as most studies in the philosophy or foundation of statistical mechanics would have it, but often a modeling practice of constructing generative mechanisms under physical constraints for some salient statistical characterization of the phenomena.
Various case studies will be presented to demonstrate the above account of the practice of statistical physics, which explains 1) the ubiquity of the Gibbsian approach beyond mere computational expediency, 2) the pervasive interdisciplinary applications of statistical physics (complexity sciences), 3) the essential roles of minimal models (Batterman & Rice, 2014) and mesoscale modeling in statistical physics (Batterman, 2021). It also resonates with recent discussions in the metaphysics of mechanisms (Jiang, 2024) and structural realism (Wallace, 2022).

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Joppe Widstam
Max Planck Institute for the Physics of Complex Systems, Germany

Inference and Fine-Tuning in Causal Explanations of Bell-Inequality Violations

Abstract: A quantum experiment involves an atemporal dependency between the probability of the outcome of the preparation and the probability of the outcome of the measurement. A quantum experiment also involves an experimenter's subjective probability of the outcome of the measurement given the outcome of the preparation.
In this work, we make use of some extensions to the operational theory of quantum mechanics that make evident a correspondence between a prepare-and-measure experiment and a Bell-type experiment [1-3]. This correspondence entails that there is an atemporal, or retrocausal, dependency between the two measurements in the Bell-type experiment. Being isolated from the environment, nothing that has an entropy defined for it is influencing the system, making the retrocausal nature of the dependency seem less strange.
Having understood the nature of the dependency between measurement outcomes in the Bell-type experiment, we turn to understanding how the outcome and the measurement basis on opposite legs of the experiment are statistically independent, despite there being causal dependence between them. In our analysis, the dependency is absent in the statistics if the experimenter is completely ignorant about some relevant variable of the experiment. The dependency is revealed if the experimenter is less than completely ignorant about the relevant variable, unless also completely ignorant about some other relevant variable. It's clear that the relevant variable in this case is the outcome at the opposite leg. This resolves the issue about unnatural fine-tuning raised by [4]. The correlations in a Bell-type experiment are fine-tuned, but naturally so, by the experimenter being completely ignorant about the outcome at the opposite leg, and when conditioning on the measurement basis on the opposite leg, there are no other relevant variables of the experiment that they are completely ignorant about.

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Yìlè Yīng

Perimeter Institute for Theoretical Physics, Canada

A review and analysis of extended Wigner's friend arguments

Abstract: The Wigner's friend thought experiment was intended to illustrate the difficulty one has in describing an agent as a quantum system when that agent performs a measurement. While it does pose a challenge to the orthodox interpretation of quantum theory, most modern interpretations have no trouble in resolving the difficulty. Recently, a number of extensions of Wigner's ideas have been proposed. We provide a gentle introduction to six such arguments, modifying the specifics of many of them so that they are as simple and unified as possible. In particular, we show that all of the arguments hinge on assumptions about correlations between measurement outcomes that are not accessible to any observer, even in principle. We then provide a critical analysis of each argument, focusing especially on how well one can motivate the required assumptions regarding these inaccessible correlations. Although we argue that some of these assumptions are not entirely well-motivated, all of the arguments do shed light on the nature of quantum theory, especially when concerning the description of agents and their measurements.

Link to a related paper:
https://arxiv.org/abs/2308.16220

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Poster Presenters' Abstracts

Antoni Antoszek

Jagiellonian University in Cracow, Poland

Why Defining Determinism of Axiomatic Physical Theories Fails and How to Correct It

Abstract: This talk aims to demonstrate how a rigorous definition of determinism can be formulated and applied to a formal axiomatization of a physical theory. Examining an example of Newtonian classical particle mechanics (CPM) formalized in set-theoretical axioms by Patrick Suppes (2002), it will be shown how to construct a formally correct and philosophically adequate definition of determinism based on temporal developments of physical systems represented as models of the theory. Then, it will be argued that to deliver a meaningful verdict, such a definition of determinism cannot be applied to the whole framework of CPM itself, but rather to its particular theories: sentences defining different physical systems that incorporate an equation of motion. Therefore, the verdict of determinism or indeterminism usually depends on the uniqueness (or non-uniqueness) of solutions to the differential equations governing the system's behavior. The talk will conclude with a demonstration of how a correct definition of determinism can be used to deliver a verdict of indeterminism of the theory of Norton's (2008) domes that is stated within the framework of CPM. Although the exemplar definition concerns pre-relativistic Newtonian mechanics, the crucial philosophical distinction between frameworks and theories reaches beyond them and suggests that examining determinism of any physical theory requires special caution to properly distinguish it from its framework.

Bryan Cheng

University of Oxford, The United Kingdom

Approximate Symmetries, Groups, and Heuristics: Analysing the Eightfold Way

Abstract: Approximate symmetries played a significant role in the development of particle physics during the mid-twentieth century. The quantum numbers of isospin, strangeness, and hypercharge provided a way to categorise newly discovered particles; because these quantum numbers were approximately conserved in strong interactions, theories with terms invariant to transformations in the internal spaces of quantum numbers were proposed. This approach relied on group-theoretic notions, inspired by models of intrinsic spin and Yang-Mills theory. The results were schemes such as SU(2) isospin and SU(3) flavour symmetry, providing a theoretically fruitful approach that would inform the development of quantum chromodynamics and the Standard Model.

This talk will analyse the case of SU(3) flavour symmetry, also known as the Eightfold Way. Developed independently by Murray Gell-Mann and Yuval Ne'eman, the theory is usually presented as a mere stepping stone towards quantum chromodynamics, due to its approximate nature. Nevertheless, I will argue that there are aspects of the theory that are philosophically significant. I will focus on three features: its application of group theory, the use of heuristic models, and the issue of broken symmetries.

Firstly, the function of group-theoretic notions in the theory. Contrary to claims made by Borrelli (2021), I will argue that both Gell-Mann and Ne'eman were dependent by group theory in developing the Eightfold Way, with core features of the theory reliant on group-theoretic notions. Group theory facilitated the development of formal analogies that justified the transfer of key ideas from the theory of isospin, and resulted in novel empirical predictions such as the properties of the omega baryon. Heuristic models were crucial to the development of the theory, particularly for Gell-Mann, whose original paper proposed several composite models of baryons and mesons to which he attributed no physical significance. It is notable that these models are strictly speaking wrong, but possessed correct symmetry properties that enabled the classification of particles. I will claim that, while this is clearly a case of reasoning from false models, the underlying mathematical framework made the success of the theory possible.

Finally, I will analyse the role of symmetry breaking. The fact that SU(3) flavour symmetry was approximate and violated by interactions other than the strong force was emphasised by both authors. Yet it was precisely this incompleteness that sparked further theoretical developments, inspiring more fundamental explanations that would lead to the quark model and beyond. Thus, I will argue that the approximate nature of the Eightfold Way contributed rather than detracted from its scientific worth.

Daniele Colosi
Universidad Nacional Autónoma de México, Mexico

An invitation to the General Boundary Formulation of quantum theory

Abstract: The quantization of fields in a neighbourhood of arbitrary spacetime hypersurfaces, including those that are not Cauchy surfaces, is central to the General Boundary Formulation (GBF) of quantum theory. This formulation offers a novel perspective on quantum dynamics and enables the treatment of problems that are challenging within the standard framework. This poster provides a concise overview of the GBF, highlighting recent developments such as the encoding of dynamics within Lagrangian subspaces of the solution space of the equations of motion, a proposal for a time operator in quantum field theory, and the quantization of evanescent modes (classical modes with energies below the field's mass).

Niccolò Covoni
University of Urbino – University of Italian Switzerland (USI), Switzerland

Progress Crucial Realism

Abstract: This talk introduces Progress Crucial Realism (PCR) and applies to the Quantum Electrodynamics (QED). PCR is a framework that balances the empirical focus of Progress Realism (PR) (Saatsi, 2020) with the ontological commitments of Truth-Content Realism (T-CR). The core idea of PCR is the concept of crucial objects: the indispensable mathematical structures required for a theory's formulation and empirical success. This approach addresses critiques of PR (Egg, 2021), which avoids metaphysical commitments entirely, and T-CR, which adopts commitments often deemed excessive. This definition allows us to retain a realist stance without delving into speculative metaphysics (wavefunction realism). In particular, PCR proposes the following method for establishing minimal metaphysical commitments: beginning with a well-established theory, identifying its crucial objects, providing an empirical interpretation, and limiting metaphysical commitments to this minimal set. This approach respects Saatsi's call for reducing unnecessary metaphysical commitments while addressing the concerns raised by critics of PR, who argue that some level of metaphysical grounding is essential for a coherent realist account.
To illustrate the application of PCR, the case of spin realism in QED is examined. We Identify spin as a crucial object because of its indispensable role in the classification of particles and, thus, the formulation of fundamental equations like the Dirac equation. Indeed, spin, as described by Wigner's theorem, is mathematically a Casimir operator used to classify irreducible representations of the Poincaré group indispensable for the theory's formulation. Moreover, we argue that spin is not only a crucial object in QED but also has an empirical interpretation, understood by apparatus such as the Stern-Gerlach experiment. According to PCR, spin is classified as a real and fundamental property of the physical world since it is a crucial object in our definition.
PCR provides a framework that can address the pessimistic meta-induction argument. By grounding ontological commitments to the crucial objects of empirically successful theories, PCR provides as a way to avoid this scepticism, even in situation in which scientific theories evolve. PCR contributes to debates on scale-dependent ontologies versus fundamentality. As a consequence, the concept of crucial objects provides a framework for navigating the layered ontologies of physical theories across different scales.

Anita Dąbrowska
Faculty of Mathematics, Physics and Informatics, University of Gdańsk, Poland

Perfect excitation of a three-level atom by a propagating two-photon field

Abstract: I would like to present the results of a study conducted in collaboration with Karolina Słowik, Gniewomir Sarbicki, and Masood Valipour from Nicolaus Copernicus University in Toruń. We considered the problem of optimal excitation of a three-level atom of ladder configuration by propagating light in the two-photon state. The applied atom-light interaction model is based on the Wigner-Weisskopf approximation. Thus, the model is formulated within the following assumptions: a flat coupling constant, rotating wave approximation, and the extension of the lower limit of integration over frequency to minus infinity. We analyze the probability of two-photon absorption by the atom using the analytical formula determined in [1] by making use of quantum trajectories.

We comprehensively characterized the properties of the optimal two-photon state that excites an atom perfectly, i.e. with probability equal to one. We consider two scenarios. In the first one, the three-level system has transitions excited by photons with two distinct central frequencies. In the second scenario, the transitions are closely spaced and are excited by indistinguishable photons. In the considered cases, we obtain two different states that optimally excite the system. Their characteristics are determined by the properties of the atom: the values of atomic transitions and the lifetimes of the excited states due to spontaneous emission associated with the given modes. Interestingly, in both cases, we are dealing with entangled states of photons. The degree of photonic entanglement is determined by the relation between the lifetimes of the excited states of the atom. In consequence, two distinct interaction regimes can be identified in which the entanglement of the input state of light has a qualitatively different impact. We show that photon entanglement plays a fundamental role in the optimal excitation of a system by two-photon light and show how destructive and constructive light interference affects the excitation of the atom. Part of the obtained results has already been published and presented in [1] and [2].

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Link to a related paper:
https://arxiv.org/pdf/2411.13274

Emilien de Bank
Inria Qinfo, France

Operational localisation limits in linearised quantum gravity with quantum clocks

Abstract: Many indirect arguments in quantum gravity point toward the existence of a minimal length that can be interpreted as the smallest resolvable unit of spacetime. However, most approaches to quantum gravity do not offer a measurement model that would clarify how such a length scale can be obtained more concretely. An operational definition of this minimal length has not been derived even in the weak field regime, where there is a solid formulation of gravity in the quantum regime, i.e. linearised quantum gravity. This thesis aims to fill this gap and justify the Planck length's role as the minimal precision on proper time measurements. Intuitively, if gravity is a quantum field, the uncertainty on the recorded proper time is limited by the quantum vacuum fluctuations of gravity. In the presented situation, this effect constitutes a fundamental and unavoidable limit. Ideal clocks following classical trajectories in linearised quantum gravity are considered. Then, quantum clocks are used to infer the localisation limit using interferometry. Different clock models have been considered to probe how quantum clocks directly hinder the resolvability of the localisation limit.

Arthur Dutra
State University of Campinas (UNICAMP), Brazil

Extended Scenarios in Quantum Networks Yield Improved Nonclassical Correlations

Abstract: Quantum networks promise a wide range of applications, particularly in communication tasks. In such networks, multiple independent sources produce and distribute entangled states among observers, who then perform measurements and collect experimental statistics. Recent discoveries have shown that these networks also generate remarkable correlations that showcase unprecedented non-classical behaviors. In this project, we are exploring extended scenarios, where we try to simultaneously observe Bell-nonlocality and Kochen-Specker contextuality. Previous studies in simpler quantum systems have shown that these extended scenarios yield improved inequalities with lower violation thresholds and can even activate nonclassical behavior in states once deemed classical. Here, we extend these findings to quantum networks, demonstrating that these scenarios provide a powerful tool for leveraging quantum advantage in this emerging paradigm.

Benjamin Engel
Independent researcher

Topos-theoretic approach to vacuum algebraic quantum field theory over curved space-times

Abstract: A topos-theoretic approach to the foundations of quantum theory, developed by Chris Isham and his collaborators, has emerged from the consideration of some foundational problems in quantum gravity and quantum cosmology. However, it does not include any notion of space-time and has so far only dealt with the foundations of quantum mechanics. Our aim is to bring it back to the quantum / gravity interface, by extending the spectral presheaf formalism to vacuum algebraic quantum field theory over curved space-times. We do this by replacing the base category of abelian von Neumann subalgebras, used in the original approach, by two orthocomplemented (not necessarily orthomodular) lattices: of causally closed regions of (not necessarily globally hyperbolic) time-oriented lorentzian space-time, and of (mostly nonabelian) factor subalgebras of an arbitrary von Neumann algebra. The (various variants of) relativistic nonsignalling, as well as the commutant of subfactors, are represented by the paraconsistent negation operators in the respective spectral presheaves. Furthermore, the presence of closed time-like (or vertex) curves corresponds to nontrivial bi-Heyting modal operators. By introducing a natural category-theoretic generalisation of Haag's "tentative postulate", we construct a representation of the vacuum a.q.f.t. as a suitable functor between the above presheaves. This allows to study the context-dependent quantitative properties of the vacuum sector of an underlying theory (as reflected in the structure of von Neumann subfactors), while allowing for the wide structural variability of causal structures (e.g., time-like vs time-andnull-like signalling, presence of closed time-like curves, discretisation of the space-time, etc.).

Ulaş Eyüpoğlu
Eberhard Karls Universität Tübingen, Germany

A Case for Ontology: A Bohmian Perspective on Weak Values

Abstract: Since their inception, weak values have exhibited highly counterintuitive and seemingly paradoxical results. Notable examples include anomalous weak values that go beyond the usual spectrum of the operator that the weak value is associated with (Aharonov-Albert-Vaidman) and the apparent paradox of a particle occupying two places at once. However, a careful analysis using Bohmian Mechanics shows that these anomalous weak values can be explained without any paradoxes. In particular, we revisit the seminal AAV setup and show that, in a Bohmian framework, the anomalous values are an artifact of inferring the spin value of an electron using its positional degrees of freedom. Our results, in turn, suggest that Quantum Formalism should not be interpreted literally, and show the need for a coherent ontology to explain such phenomena.

Jan Głowacki
Institute for Quantum Optics and Quantum Information (IQOQI-Vienna), Austria

In the search for relational and operation foundations for relativistic quantum physics

Abstract: I will present recent advances in developing a relational foundation for Quantum Field Theory (QFT), extending the operational approach to Quantum Reference Frames into the relativistic domain. By systematically incorporating relational principles into the Poincaré-covariant setting, we arrive at a formalism that strikingly parallels Wightman axiomatics for QFT, yet is derived from a distinct conceptual and mathematical foundation. This framework offers novel insights into longstanding foundational challenges in QFT, particularly concerning the role of symmetry, the structure of local observables, and causality constraints. I will elaborate on how relational principles are embedded into the construction, how certain no-go theorems that typically constrain relativistic quantum theories can be circumvented, and how minimal coherence assumptions on quantum frames naturally enforce macrocausality for relationally defined local field observables.
If time permits, I will outline potential extensions of this approach, including its implications for gauge theories, QFT in curved spacetime, and without predetermined space-time structure. This perspective not only deepens our understanding of QFT foundations but also suggests new directions for reconciling quantum information and field-theoretic principles.

Link to a related paper:
https://arxiv.org/abs/2405.15455

George Hobart
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Action without Reaction: A Critique of the Action-Reaction Principle and Implications for de Broglie-Bohm Theories

Abstract: In this talk, I explore how--contrary to what is often believed--de Broglie-Bohm Theories can indeed be reformulated to satisfy or obviate the Action-Reaction Principle (ARP), so that they can now be reassessed on a more equal footing with rival ARP-satisfying theories. The Action-Reaction Principle has been used to assess whether physical theories are dynamically complete; its proponents argue that theories whose proposed entities do not each pairwise both act and react on each other should be rejected. In this talk, I briefly analyse the definition of the ARP in a new light, precisifying it to its most general and weakest form, before showing that even this is too strong a requirement, in that it does not follow from the intuitive historical notions of substances' interactions; further reasoning is needed to derive this principle as a requirement. Lacking this justification, the principle should instead be used as a desideratum at best. I then discuss the ontologies of a variety of de Broglie-Bohm Theories, specifically the Quantum-Hamilton Jacobi interpretation, Holland's Quantum Force interpretation, and Bohmian Mechanics, investigating how the ARP can be obviated, or satisfied by introducing / reinterpreting a back-action from the particles on their wavefunction(s).

Niyusha Hosseini
Technische Universität Wien (TU Wien), Austria

The time of arrival problem in the Page and Wootters formalism

Abstract: The concept of time in quantum mechanics presents unique challenges, as time is not an observable in the conventional sense. This paper explores the construction of a time of arrival observable within the framework of the Page-Wooters formalism, which treats time as an additional degree of freedom in a larger Hilbert space. By conditioning on a clock subsystem, we derive a time of arrival observable and investigate the resulting time of arrival probability distribution. We examine the necessary structure for the conditional Hilbert space and discuss the limitations of using single factor observables in deriving accurate probability distributions. Through comparative analysis with similar approaches, we evaluate the validity and applicability of the derived distribution. This study provides insights into the boundaries and potential applications of the Page-Wooters formalism in quantum mechanics, offering a deeper understanding of the nature of time and its measurement at the quantum level.

Caspar Jacobs
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Conspiratorial Quantum Mechanics

Abstract: The relational interpretation of quantum mechanics (RQM) proposes that quantum states describe relations between systems. Adlam (2022) and others have objected that RQM makes science solipsistic, because there is no guarantee that different perspectives are aligned. Adlam and Rovelli (2023) have therefore proposed to add to the postulates of RQM a 'cross-perspective link' (CPL), which roughly says that observers' perspectives are in tune with each other. If, from Alice's perspective, a system S has been measured to have particular property P, then from Bob's perspective Alice has measured S to have P. Therefore, Alice and Bob won't 'talk past each other'.
But can CPL really function as a fundamental postulate of RQM? The principle that Fundamentality Entails Modal Freedom (Wang 2016), which follows from Hume's dictum, says that the fundamental facts are modally free: such facts cannot constrain each other. Any combination of the fundamental facts is possible. In RQM, the fundamental facts are perspectival: they are facts about which property a system S has with respect to an observer O. CPL, on the other hand, asserts that those fundamental facts are highly coordinated. If S has P with respect to Alice, then this constrains the state of Alice herself with respect to Bob. If there is an absolute reality that underlies those perspectival facts, then this is not a problem. But if the perspectival facts themselves are fundamental, then those mutual constraints seem counter to FEMF.

This is made precise by Ismael and Schaffer's (2016) 'common ground inference', which says that if two facts are modally connected then they must have a common ground. If there is no common ground, such modal connections are 'cosmic conspiracies'. Jacobs (2024) shows that any relational theory (under some reasonable conditions) has to postulate cosmic conspiracies. For example, relationalism about mass has to postulate that mass ratios are well-behaved, i.e. reflexive, symmetric and transitive (Martens 2022). We propose to analyse CPL as another cosmic conspiracy. This extends Jacobs' earlier results, which were all classical, to the quantum case.
If CPL is a cosmic conspiracy, then this indicates that perspectival facts possess a common ground. This would constitute an absolute reality, contra the other main postulates of RQM. We believe that this absolute reality just is the many-worlds universe posulated by Everettian QM. Thus, we pose a dilemma for RQM: either CPL is a cosmic conspiracy, or RQM's perspectivalism is merely effective. This would also affect Adlam's (2024) claim that RQM+CPL is inherently perspectival.

Vishal Johnson
Max Planck Institute of Astrophysics, Germany

Measurement in a Unitary World

Abstract: “Wavefunction collapse” is usually taken as one of the axioms of the quantum mechanics framework. In this work we explore how quantum measurement can be understood in the context of a universe evolving according to unitary (reversible) quantum dynamics. We describe a unitary measurement procedure consistent with the non-measurement axioms of quantum mechanics — the system being measured and the observer of that system become correlated. We argue that for this to work, a certain physical resource, which we call correlation capacity, necessarily has to be transferred from some other system. We show that the correlation can be provided by a GHZ-like state before or after the interaction with the measured system. We also argue that a network of such measurements establishes a stable objective classical reality — the agreement of several independent systems about the state of the measured quantum system. Finally, we investigate the dependence of the achieved objective reality on the initial state of the observer — observer network states with a high amount of correlation gives rise to high fidelity measurement results. We verify our hypotheses through simulations in python.

Link to a related paper:
https://arxiv.org/abs/2212.03829v2 (partial results)

Miguel Jorquera Riera
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Uncertainty Relations Relative to Phase Space Quantum Reference Frames

Abstract: Heisenberg's uncertainty relations give a minimum uncertainty trade-off when observing a quantum system with incompatible observables. Our results show that the minimum uncertainty is larger when the reference system is also quantum. We use the operational formalism of quantum mechanics to construct a quantum reference frame (QRF), describe a joint position and momentum observable relative to it, and calculate the variances of its margins. In the classical limit of the QRF, the standard uncertainty relations are recovered.

Link to a related paper:
https://arxiv.org/abs/2411.08589

Branko Kovac
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Critique of the principle of equivalence

Abstract: There are two forces associated with mass: static and dynamic force, or, by other names, the weight and inertial force. The mass, the source of these forces, is defined once by Newton’s law of gravitation for static force and the second time by the equation of motion F=ma for dynamic force. It is assumed that the masses in these two cases are equivalent.

Einstein extended this equivalence and assumed that the gravitational field and acceleration are equivalent. I will argue that the gravitational field and acceleration are not equivalent. The force caused by the gravitational field has a reaction force on another mass. Assigning inertial property to the mass and explaining inertial force by inertial mass that resists acceleration in space violates the principle of action and reaction. All our experience with mass dynamics is based on observations and experiments on or near the Earth and satisfies the principle of action and reaction. Discussed is the explanation of the inertial force by the field theory that satisfies the principle of action and reaction. The most serious criticism of the field concept of inertial force is that such a field may not exist as no one has detected it. A laboratory experiment that can detect a dynamic gravitational field or invalidate the force field concept of inertial force is proposed to address that criticism. The experiment is designed to test if the principle of action and reaction is valid for mass dynamics or if acceleration and gravitational field are equivalent.

Link to a related paper:
https://www.scirp.org/journal/paperinformation?paperid=132406

Charlène Laffond
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A Generalized Approach to Quantum and Classical Probabilities via Frequentist Interpretation

Abstract: Several extensions to classical probability theory have been proposed to recover quantum probabilities, particularly to address Bell-type no-go theorems and in the context of the path integral formulation of quantum mechanics. However, beyond mathematical artifacts that share similarities with Kolmogorovian probabilities, justifying those extensions to recover actual probabilities and measurement outcomes remains challenging. We argue that a generalized probability theory, accommodating both quantum and classical probabilities, should retain linearity and give rise to valid relative frequencies of measurable events. Linearity is a fundamental feature of quantum theory, and quantum mechanics is consistent with a frequentist interpretation of probabilities, where relative frequencies are the only directly measurable probabilities in experiments. We explore generalizations of probability theory that extend beyond real numbers between 0 and 1, examining the convergence of relative frequencies. In our first example, involving complex-valued measures, two types of non-trivial convergence of relative frequencies emerge, leading to behavior of frequencies akin to classical probabilities or frameworks similar to lower and upper probabilities theory. For more general measures, we investigate conditions under which relative frequencies converge under a weak law of large numbers-inspired requirement, and conditions for them to behave as classical probabilities.

Anastasiia Lazutkina
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Evidence in Cosmology: How Galaxies Became Complicated

Abstract: It is a widely accepted view in the philosophy of science that what counts as evidence for a theory depends on the theory itself. However, the question of how a theory selects its evidential base remains largely underexplored. This paper addresses this gap by analyzing a case study from cosmology: the evolving role of galaxies as evidence for cosmological models, particularly those involving dark matter, from the 1970s to the present. Initially central to testing and developing cosmological models, galaxies have gradually lost their status as decisive sources of evidence. I ask: Why and how did this happen? What criteria determine whether galaxies count as evidence for particular phenomena and our theories of them?
I trace the historical role of galaxies, showing how phenomena like galactic tidal tails and galaxy morphology provided critical data for evaluating cosmological scenarios of structure formation in the 1970s–1980s. Since then, advances in the precision, depth, and scope of galaxy observations have been remarkable, but the current model, Lambda Cold Dark Matter (ΛCDM), struggles to account for them (so-called small scales problems).
Despite this, the cosmological community largely does not interpret galactic discrepancies as evidence against ΛCDM [1]. Instead, galaxies are considered "too complicated" to provide clean tests of the model. This attitude marks a shift: galaxies, once crucial, are now often dismissed as unreliable sources of evidence.

To understand this shift, I employ Curiel's [2, 3] idea of epistemic control—a theory's capacity to meaningfully connect with empirical data within its regime of applicability. I argue that galaxies became ""epistemically untrustworthy"" because ΛCDM lost epistemic control at galactic scales, primarily due to the complex and multiscale nature of baryonic physics. My main argument is that the selection of evidence by a theory is governed by the level of epistemic control over the phenomena in question.

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Forming Concepts and Conceiving Forms: Physiology and Epistemology of Light in Bohr's Quantum Mechanics

Abstract: What can light teach us about knowledge? Five years after Niels Bohr introduced complementarity in his 1927 Como Lecture, he presented 'Light and Life' at the 1932 International Congress on Light Therapy, noting that "light is our principal tool for observation." I argue that this quote contains an overlooked key concept in human observation and epistemology: light. By doing so, I show how the reason behind Bohr's interest in the life sciences remains underexplored, and that an interdisciplinary perspective on light can illuminate foundational concepts in quantum mechanics.
I combine a historical survey with a philosophical analysis, and suggest a conceptual pivot to light by revealing an understudied dimension of Bohr's scientific interests concerning physiology. Philosophers and historians of science, such as David Favrholdt and Gunther S. Stent, have previously placed the lectures mentioned above on a continuum. Yet focusing on light raises new questions: what was Bohr's connection to light therapy? Why was ophthalmology brought up in 'Light and Life'? How does light connect physics, chemistry, physiology and philosophy? And what can an interdisciplinary treatment of light teach us about observation, the subject-object distinction, and formation of foundational quantum concepts?
Such questions led me to research Danish dermatology and ophthalmology during the early 20th century. New materials from the Niels Bohr Archive reveal a previously neglected milieu of dermatologists, chemists, and ophthalmologists who worked with Bohr in the vicinity of the Niels Bohr Institute between 1919-1935. Discussions between Bohr and these actors concerning the nature of light, such as its direction in time, have been overlooked, yet likely influenced foundational concepts in quantum mechanics. A historical resetting enlightens Bohr's thoughts on open and closed systems, clarifies his distinction from the generally termed Copenhagen Interpretation, and elucidates complementarity's latent epistemological lesson, which has remained obscured to this very day. Centralizing light as a transdisciplinary notion in Bohr's thought also aims to better grasp his unique views on prevailing debates, such as organicism vs. vitalism, the psycho-physical distinction, and the subject-object distinction in observation. Finally, it offers physical as well as metaphorical links between quantum and classical descriptions that further inform our contemporary conceptual foundations and tools.

André Malavazi
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Two-time weak measurement protocol for ergotropy protection in open quantum batteries

Abstract: Quantum batteries are emerging as highly efficient energy storage devices that can exceed classical performance limits. Although there have been significant advancements in controlling these systems, challenges remain in stabilizing stored energy and minimizing losses due to inevitable environmental interaction. In this paper, we propose a protocol that employs selective weak measurements to protect quantum states from such influence and mitigate battery discharging, that is feasible in state-of-the-art technologies. We establish thermodynamic constraints that allow this method to be implemented without disrupting the overall energy and ergotropy balance of the system, i.e., no extra net recharging. Our findings demonstrate that appropriately chosen measurement intensity can reduce unwanted discharging effects, thereby preserving ergotropy and improving the stability of quantum batteries. We illustrate the protocol with single and two-qubit systems and establish the generalization for N-cell batteries. Additionally, we explore how weak measurements influence the coherent and incoherent components of ergotropy, providing new insights into the practical application of quantum coherence in energy storage technologies.

Link to a related paper:
https://arxiv.org/abs/2411.16633

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Coherent Charging of Quantum Batteries by an Incoherent Source

Abstract: We propose a setup for extraction and energy processing in the nano- and microscale, relying on the interaction of a compound of quantum batteries with a common mode of a thermal bath. The setup can be implemented in the current state-of-the-art quantum photonic systems or microwave superconducting circuits. We also explore the setup's role in preparing entanglement and coherence in the stationary limit of the dissipative evolution.
The transfer of energy from a coherent source (e.g. a laser) to a quantum battery is of significant technological importance. However, a bounded transfer of energy from an incoherent source (e.g. a thermal bath) to a quantum battery, and its storage in a coherent form (active states) is also possible. In this study, we propose a novel approach for using thermal reservoirs for battery charging. Our method involves utilizing a system of non-interacting two-level fermions as the fundamental units of the quantum battery, interacting collectively with a shared reservoir. We provide analytic formulas for a stationary state of the system of N fermions that interact with a shared reservoir of a given temperature. The nonergodicity of the evolution plays a crucial role in enforcing the second law of thermodynamics, limiting maximal ergotropy one can extract from a single bath. Furthermore, we observe that, with increasing the number of cells in the battery, a linear increase in the extracted ergotropy can be observed, with a fixed gap between the ergotropy and the energy. Our analysis reveals that the charging power of the battery experiences an enhancement with an increase in the temperature of the reservoir. Exploring evolution dependence on the initial state, we show that for the most experimentally friendly initializations of fermions in a product of Gibbs states, the ergotropy extracted per battery cell is a monotonic function of temperature difference between local baths preparing the state and the shared reservoir, and that for finite temperatures it achieves its maximum at a specific size N of the system. Finally, we analyze the stability of stationary entanglement against local noise.

Noah Migoski
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Geodesic Motion in General Relativity

Abstract: In general relativity, one of the foundational statements is the hypothesis that freely-falling test particles follow geodesics. At first glance, this geodesic hypothesis seems to be independent of the central equation of general relativity, the Einstein field equation. However, since point-like test particles are an idealization used to approximate sufficiently small extended bodies, their motion should correspond to the motion of such bodies, i.e. it should be determined by Einstein's equation coupled to the conservation law it imposes on the corresponding energy-momentum tensor. In this poster I explore the proof given by Gralla and Wald and compare it with the proof of Ehlers and Geroch, (with clarifications by Bezares et al.) both of which show that geodesic motion is indeed a consequence of Einstein's equation that arises when considering special cases of energy-momentum tensors that can be localized to arbitrarily small neighborhoods of a curve in space-time. By considering the subtleties of these proofs, we gain insight into the notion of test particles in general relativity, and investigate whether geodesic motion is a fundamental aspect of the theory.

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Consistency between Local Realism and the Free Choice Assumption:
A Consideration Based on Causal Statistical Inference

Abstract: Quantum correlations that violate a Bell inequality are widely regarded as incompatible with local realism, assuming the validity of the free choice (or free will) assumption [1][2]. Mathematically, it is true that the Bell inequality is satisfied by any (deterministic / stochastic) hidden variable theory that satisfies Bell locality—more precisely, the factorizability condition, which is equivalent to the conjunction of parameter independence, outcome independence, as well as measurement independence. Given that "reality"" is naturally associated with determinism, interpreting measurement independence as the free choice assumption (or the existence of ""free will"") leads to the above conclusion. However, it should be emphasized that measurement independence merely refers to the statistical independence between hidden variables and measurement settings, and does not necessarily imply the existence of free will. Therefore, the above conclusion cannot be definitively asserted.
In this presentation, we demonstrate that local realism and the free choice assumption can, in fact, be consistent with the violation of a Bell inequality, by explicitly constructing such examples [5]. In addition, we discuss this result within the framework of causal inference [3][4], and show that our model cannot be described by this framework, as the observed correlations cannot be accounted for by either direct or common causes [5].

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Unexpected consequences of postquantum theories
in the graph-theoretical approach to correlations

Abstract: This work explores the implications of the exclusivity principle (EP) in the context of quantum and postquantum correlations. We first establish a key technical result demonstrating that given any set of correlations for a complementary experiment, the EP restricts the maximum set of correlations for the original experiment to its antiblocking set. Based on it, we can prove our central result: Assuming that the EP holds and that postquantum behaviors are accessible in at least one experiment, it follows that certain genuinely quantum behaviors become forbidden in a related yet completely independent experiment. Since this contradicts a premise we firmly uphold (that every quantum behavior is, in principle, realizable in Nature), it is plausible to argue that one of the other two assumptions (that the EP holds and that some experiment might be described by a postquantum behavior) must be false.

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Rigorous Schrödinger Quantum Mechanics of Infinitely Many Particles

Abstract: So far, approaches to Schrödinger quantum mechanics (QM) over infinite dimensional configuration spaces Q (representing, for instance, infinitely many particles or field configurations) have been elusive to mathematical rigorization,

mainly due to the fact that there is no infinite dimensional version of the Lebesgue measure to distinguish some ``wavefunctional'''' space ``$L^2(Q,d^\infty x)$''''. Instead, such theories are either presented merely heuristically (Struyve, 2010), in terms of sequences of finite dimensional truncated theories (Wallace, 2006) or at best, using a serious but arbitrary wavefunctional space following an unmotivated choice of a particular measure ---e.g., a Gaussian measure (Corichi et al., 2004). In order to avoid this arbitrariness, historically, the mathematical QFT community centred its efforts on an algebraic approach (Baez, 2014), the abstraction of which has clearly hindered foundational work on the philosophy of QFT: an explicit configuration space appears quintessential, among others, in a debate on ontology.

Following von Neumann's work on infinite tensor products and Kakutani's study of infinite measures, we claim to have found the mathematically rigorous limit $N\rightarrow |\mathbb{N}|$ of Schrödinger QM over $L^2(\mathbb{R}^N, d^Nx)$ with equivariant trajectory ontology. In closer inspection, the Lebesgue measure's issue is solved by realizing its role as a mere ``background'''' measure, playing no true role on the probabilistic predictions nor the equivariant trajectories of the theory. Strikingly, the obtained theory has some features that were unforeseeable within heuristic or truncation approaches. For instance, even for the description of ``scalar particles'''', a tuple of infinitely many wavefunctions over $\R^\infty$ is required. All this opens doors to many foundational questions.

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Cameron Peters

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A no signalling theorem in the context of the Absorbing Boundary Rule model of particle detection

Abstract: A clear explanation of causality and the details of non-local correlations in quantum mechanics is wanting, even a century after the advent of quantum mechanics. In the latter pursuit, the question of whether agents can use entanglement to send superluminal signals has been answered in the negative using many different lines of reasoning. Some include the interaction between the measurement instrument and the entangled subsystem, and some do not. In the present work, we consider a particularly natural effective model of particle detection: the Absorbing Boundary Rule (ABR) applied to Dirac particles (ABCD) [arXiv:1601.04571 [quant-ph]], and prove that an operational no-signalling theorem holds. ABR was motivated from but inequivalent to Werner's example of a time of arrival (TOA) distribution which involves imposing a boundary condition in addition to the free Schroedinger equation [R. Werner, Annales de l'Institute Henri Poincaré, section A 47: 429–449 (1987)]. Significant extensions and key results of ABR such as: (i) moving detectors, (ii) ABR in curved spacetime, (iii) existence and uniqueness for non-relativistic ABR, and (iv) ABR as a limiting case of Allcock's imaginary potential model. There being also proposed TOA experiments with claims of distinguishing between arrival time distributions predicted by different quantum theories and phenomenological models, we find it pertinent to address the question of superluminal signalling in ABCD. The proof currently handles N non-interacting entangled Dirac particles in 3+1 dimensions, and assumes what we call "ideal detectors". Work is on-going to extend the proof to the case of moving detectors and "semi-ideal detectors" where the wave-number sensitivity, encoded in the boundary condition, can vary along the world sheets of the detectors.

Francisco Pipa
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An Indeterminacy-based Ontology for Quantum Theory

Abstract: I present and defend a new ontology for quantum theories (or ``interpretations'' of quantum theory) called Generative Quantum Theory (GQT). GQT postulates different sets of features, and the combination of these different features can help generate different quantum theories. Furthermore, this ontology makes quantum indeterminacy and determinacy play an important explanatory role in accounting for when quantum systems whose values of their properties are indeterminate become determinate. The process via which determinate values arise varies between the different quantum theories. Moreover, quantum states represent quantum properties and structures that give rise to determinacy, and each quantum theory specifies a structure with certain features. I will focus on the following quantum theories: GRW, the Many-Worlds Interpretation, single-world relationalist theories such as Relational Quantum Mechanics, Bohmian Mechanics, hybrid Classical-Quantum theories, and Environmental Determinacy-based (EnD) Quantum Theory. I will argue that GQT should be taken seriously because it provides a series of important benefits that current widely discussed ontologies lack, namely, wave function realism and primitive ontology, without some of their costs. For instance, it helps generate quantum theories that are compatible with relativistic causality, such as EnD Quantum Theory. Also, GQT has the benefit of providing new ways to compare and evaluate quantum theories, which may lead to philosophical and scientific progress.

Link to a related paper:
https://arxiv.org/abs/2404.07197

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A finite form of de Finetti's theorem in generalized probabilistic theories

Abstract: In its classical formulation, De Finetti's theorem states that the joint probability of any elements from an infinite sequence of exchangeable random variables can be expressed as a convex mixture of distributions of independent and identically distributed random variables. In both classical and quantum cases, finite-sequence versions of the theorem are known to exist, something which has not been yet verified when extending the theorem to other probabilistic theories (GPTs). In this work, we aim to understand whether or not a finite form of the theorem holds in arbitrary GPTs.

Maria Rubio
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From physics to mind: philosophical foundations of the Many Worlds and Many Minds Interpretations of Quantum Mechanics

Abstract: The Everett's "Relative State Formulation" of Quantum Mechanics (QM) (1957), in its different variants, postulates that, each time a decoherence process occurs, the system splits into as many branches as there are possible experimental results, thus applying the Schrödinger equation to the whole of reality. While the Many Worlds Interpretation (MWI) interprets Everett's "branches" as Worlds or Universes, the Many Minds Interpretation (MMI) interprets them as Minds. This is not the first time that the mind makes its appearance in the interpretations of the QM, since, in the early years of the theory, von Neumann (1932/2018) tried to combine formalism with experience and arrived at the human mind with the so-called "von Neumann chain", on the basis of which we have to take into account all the systems involved in the measurement process, including the internal structure of the conscious observer who observes the system and his "inner intellectual life" (von Neumann, 1932/2018, p. 418).
Since the aim of Everett and the proponents of the MWI is to avoid appealing to the subject to solve the problem of measurement, the defenders of this interpretation consider the observer as an automaton with memory; that is to say,

it is a way of removing the mind from the equation. However, this appeal to the mental seems unavoidable when the MWI has to address the incoherence problem, which consists in making sense of the question of how it is possible to speak of probability in a deterministic universe. At this point, its advocates adopt a subjectivist interpretation of probability, an approach based on the subject's state of knowledge / uncertainty and on his degrees of belief and expected utility. Thus, the mind inevitably reappears in the theory, and the MMI is nothing more than a way of making explicit the need to problematize the ontological status of the mental.

It therefore seems that the new interpretations of QM will have to face the problem of the mental, as von Neumann predicted, in an increasingly close and irremediable way. The question is: Do the interpretations necessarily have to go to the end of the "chain" to be able to explain "more things" and in greater depth, in order to obtain a genuine "theory of reality"?

Based on the thesis of the "von Neumann chain" and the consequences that arise from it (von Neuman, 1932/2018, pp. 418-421), we will assume the idea that any interpretation of QM that pretends to become a genuine theory will have to face the problem about the ontological status of the mental, for which we will take as a case study the MWI and its derivation in the MMI.

Amine Rusi El Hassani

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Heisenberg's transition from a spatiotemporal to a spectral probing of physical phenomena

Abstract: Heisenberg's matrix mechanics fundamentally challenged the spatiotemporal descriptions of physical phenomena in atomic scales. By excluding unobservable (spatiotemporal) quantities, such as electron trajectories, from the description of the hydrogen atom, and constructing a new kinematical quantity using only spectra of radiated light, Heisenberg necessitated a radical departure from a spatial description of kinematics in the quantum realm. This paper examines Heisenberg's transition from spatiotemporal kinematical elements to what we term "spectral kinematical elements" and argues that interpreting this transition merely as a "reinterpretation of kinematic and mechanical relations" significantly underestimates its importance, and instead emphasizes its deeper philosophical and methodological implications for the foundations of quantum mechanics. The methodological and philosophical implication is that reality is no longer probed spatiotemporally, as in the case of classical physics, but spectrally. This shift had profound consequences in the development of quantum mechanics post-Heisenberg's paper and raises unexamined questions, such as its impact on the probing of geometry at quantum scales. While classical theories probed geometry through spatiotemporal measurements, if reality at quantum scales is probed spectrally rather than spatially, the foundations of geometry itself must be reconsidered. We will briefly introduce spectral geometry as a conceptual framework that may replace the spatiotemporal view of geometry at quantum scales and discuss how Heisenberg's work can be seen as an early motivation toward this general shift in probing reality spectrally rather than spatiotemporally.

Ana Belen Sainz

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Activation of post-quantum steering

Abstract: Quantum theory has challenged the way we view nature, and has extremely succeeded at explaining our experimental observations in its limit of applicability. Nonetheless, quantum theory is still at odds with general relativity, and the door is open for some superseding theory to one day come and replace them both. This motivates the questions of ""in which other ways can nature be"" and ""what could be sensible to expect once quantum theory breaks down"". Along these lines, the study of how phenomena may look beyond their quantum manifestation (e.g., in a post-quantum theory) is placed. This poster submission discusses the phenomenon of Einstein, Podolsky, and Rosen (EPR) steering, and its relation to Bell nonclassicality. It focuses on the so-called non-signalling resources (those that could in principle be achieved in non-signalling theories satisfying special relativity) in both Bell and EPR experiments, in particular those which cannot be realised with a quantum setup (called post-quantum). The study of post-quantum EPR steering is more intricate than that of post-quantum Bell correlations, but it has been shown that it does not always imply post-quantum non-locality in a conventional Bell test. That is, previous work shows how EPR scenarios allow for post-quantum resources which, from the viewpoint of the associated Bell scenario, generate only correlations compatible with quantum theory. In this submission we will see how one can activate

the post-quantumness of such EPR resources by placing them in a larger Bell-like network, so that the observed correlations may violate a Bell inequality beyond what's possible in a quantum (gedanken) experiment. That is, we will show how to activate post-quantum steering so that it can now be witnessed as post-quantum correlations in a Bell scenario.

Link to a related paper:
https://arxiv.org/abs/2406.10570

Shubhayan Sarkar
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Operationally independent events can influence each other in quantum theory

Abstract: In any known description of nature, two physical systems are considered independent of each other if any action on one of the systems does not change the other system. From our classical intuitions about the world, we further conclude that these two systems are not affecting each other in any possible way, and thus these two systems are causally disconnected or they do not influence each other. Building on this idea, we show that in quantum theory such a notion of classical independence is not satisfied, that is, two quantum systems can still influence each other even if any operation on one of the systems does not create an observable effect on the other. For our purpose, we consider the framework of quantum networks and construct a linear witness utilizing the Clauser-Horne-Shimony-Holt inequality. We also discuss one of the interesting applications resulting from the maximal violation of classical independence towards device-independent certification of quantum states and measurements. For more details, refer to Phys. Rev. A 109, L040202 (2024).

Link to a related paper:
https://arxiv.org/abs/2309.06488

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On physicality of electromagnetic potential from causal structure of flux quantization

Abstract: Recent work by Vaidman [Phys. Rev. A 86,040101 (2012)] showed that the Aharonov-Bohm effect can be explained in terms of local fields. This effectively restated a long-debated problem of the physicality of potentials. In our work, we discuss the fundamental difference between the flux quantization setup and the Aharonov-Bohm experiment. This enables us to propose an argument for the physicality of electromagnetic potential (upon the assumption of locality) based on the causal structure in the flux quantization setup that avoids Vaidman's loophole.

Link to a related paper:
https://arxiv.org/abs/2503.15410

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Quantum state tomography of pure three-qubit states from its parts

Abstract: We present a scheme for reconstructing an arbitrary three-qubit state by employing 17 measurements in contrast to 63 Pauli measurements required for a full quantum state tomography. Additionally, a pure three-qubit state could be reconstructed from two of its two-qubit reduced density matrices. We employ a tomographic scheme involving 7 measurements for two-qubit reduced states of a pure three-qubit state. Experimental implementation of both the schemes on a 127-qubit IBM open access quantum processor is demonstrated for reconstruction of the three-qubit W state. It is seen that the fidelity of the three-qubit W state reconstructed from quantum tomography of its reduced two-qubit states is considerably better as compared to employing the three-qubit tomographic construction itself.

Rupert Smith
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Scientific Representation and the Hole Argument: Insights from a Structuralist Approach

Abstract: Recent trends in this literature can be broadly characterised by the way they begin either from the mathematics or the metaphysics. I take Weatherall (2018) as the primary example of the mathematical approach, in which he argues that if one is only to reflect on the correct use of the mathematics, one can block or undermine the hole argument. For the metaphysical approach, I focus on a line of argument I identify in Pooley and Read (2021) in which they claim that arguments from mathematical practice fail to eliminate the relevant space of metaphysical possibilities. Specifically, they maintain that the hole diffeomorphic manifolds can represent haecceitistically different spacetimes. In response to these trends, the primary aims of this research are twofold: first, I articulate a structuralist account of scientific representation, building on Van Fraassen's structuralist empiricism (2008), that answers the demarcation problems posed by Frigg and Nguyen (2022); second, I aim to use this account to diagnose the reasons for, and provide solutions to, the recent impasse in the voluminous literature on the hole argument. While I am sympathetic to the arguments from mathematical practice, I argue that without a structuralist account of scientific representation Pooley and Read's counterargument cannot be defused. While I am conceding this point, however, I am doing so in a minimal way: no such representation can meet the criteria of being a scientific representation. Further, if the points p and p' in the hole argument are to represent different events in spacetime, it is merely by means of stipulation. If, as I argue, scientific representation is to be understood structurally, for a manifold to be considered a model of a spacetime, it needs to include a representation relation, understood as some variety of structural mapping. Moreover, an isomorphism acting on a model would also need to have a corresponding transformation on the representation relation, which is at least sensitive to the strongest notion of structure in the manifold being considered. I conclude that, while mathematical practice alone fails to exclude the possibility of the hole diffeomorphic models representing haecceitistic differences, a structuralist account of scientific representation excludes the possibility of these classifying as scientific representations.

Mark Stander
Independent Researcher

Can we derive measurement collapse using regularisation

Abstract: In this talk, we explore how zeta function regularisation can be applied to a physical model of quantum measurement, offering a novel resolution to the problem of wavefunction collapse. We introduce a realistic measurement dynamics framework in which a particle transitions from isolation to interaction, leading to the derivation of an outcome function via the principle of maximum entropy. By regularising an information-theoretic quantity associated with this outcome function, we demonstrate how the apparent collapse of the wavefunction emerges naturally. The fundamental physical principles and key assumptions underlying this approach will be discussed, along with potential experimental pathways for validation.

Link to a related paper:
https://iopscience.iop.org/article/10.1088/2399-6528/ad6a4c

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Composition of local observables in quantum field theory: Towards

Abstract: Relativistic quantum information is the attempt to formulate quantum information protocols for quantum field theory. An important prerequisite to achieve this is a consistent theory of measurements in quantum field theory which we still lack. The standard treatment is based on the S-matrix paradigm which is restrictive in many ways as for instance that it can describe consistently only single time measurements. However, to formulate a complete theory of measurements we need to be able to describe equential in time measurements or more generally the composition of local spacetime

measurements. This can be achieved in a local and covariant framework of quantum field theory inspired by histories-based frameworks. In this talk, I describe some steps towards a local and compositional theory of measurements and I shortly discuss how this formalism can generalise the S-matrix paradigm.

Tao Zhou

New Jersey Institute of Technology, The United States

A non-relativistic theory of quantum mechanics and gravity with local modulus symmetry

Abstract: We have constructed a non-relativistic theory of quantum mechanics and gravity based on local modulus symmetry. The resulting connection in the covariant derivative is identified as the escape velocity of the gravitational field. A new real and positive function called the quantum metric function is attached to the complex conjugate of the wave function to satisfy the local modulus symmetry requirement. In an expanding universe, these theoretical features produce new effects that deviate from predictions of conventional quantum mechanics and Newtonian gravity. The quantum metric function yields negligible change for microscopic objects but produces quantum pointer states for macroscopic objects, thus providing a solution to the quantum measurement problem. The time-reversal symmetry is broken in the new quantum kinematics, which has implications for the second law of thermodynamics. The modification of Newtonian gravity is negligible in smaller bound systems but can become significant at the galactic scales. Its potential association with the mass discrepancy problem in the galactic systems is discussed.

Link to a related paper:
https://arxiv.org/abs/2008.07749