Abstracts

Adlam, Emily

Two Roads to Retrocausality

I will discuss two distinct conceptions of retrocausality and argue that `all-at-once' retrocausality is more coherent than the alternative dynamical picture. I will then argue that since the all-at-once approach requires probabilities to be assigned to entire histories or mosaics, locality is somewhat redundant within this picture. I will consider some possible motivations for using dynamical retrocausality to rescue locality, arguing that none of these motivations is adequate, and finally I will show that accepting the existence of nonlocality and insisting on the nonexistence of preferred reference frames leads naturally to the acceptance of all-at-once retrocausality.

Argaman, Nathan

Toy models for quantum entanglement — statistical independence and the arrow of time

Bell's theorem is a no-go mathematical theorem, so one of its assumptions (at least) must be violated in any physical theory which reproduces the success of Quantum Mechanics. These assumptions are reviewed, with special attention to (no) superdeterminism and (no) retrocausality, the major topics of this workshop. In particular, Bell's locality assumption is generalized into a time-symmetric locality assumption called "Continuous Action," and toy models which fulfill this assumption are discussed. These models violate the time-asymmetric "No Future-Input Dependence" condition, i.e., the no retrocausality assumption, but still conform to the signal causality condition which is required for consistency (they are not completely time symmetric). This situation is closely analogous with the tension between signal locality and quantum nonlocality in standard descriptions of quantum entanglement.

Reference: K.B. Wharton and N. Argaman, "*Colloquium*: Bell's theorem and locally mediated reformulations of quantum mechanics," Rev. Mod. Phys. **92**, 021002 (2020).

Bradshaw, Peter

Towards an Algebraic Theory of Spin

The discovery of spin in the twentieth century is widely regarded as one of the many heralds of the quantum age in physics. It presents as an intrinsic angular momentum of a particle for which there is no classical analogue. It demonstrates the ability to couple with other forms of angular momentum, the physical consequences of which are myriad and well-known. It has also long been established that the physically allowed spins conform to (ir-)reducible representations of the universal covering group of the "homogeneous" space(-time) symmetries.

However, what has remained somewhat mysterious is how necessary quantum physics is to this story. In particular, what features of quantum theory are required for the complete description of spin as we know it? To begin to answer this question, spin as we know it must be deconstructed. We will present the established non-relativistic theory of spin and distill the essential components from the formalism. In so doing we will motivate the characterisation of spin by abstract algebraic means. This method reveals striking connections to the Clifford and Kemmer algebras, and forms the core of a new, first-principles approach to the representation theory.

Cohen, Eliahu

Superdeterminism and Retrocausality within the Two-State-Vector Formalism

The Two-State-Vector Formalism (TSVF) of quantum mechanics emerged as an attempt to symmetrize the measurement process and specifically the "reduction of the wave packet" which seems to introduce irreversibility into quantum theory. While its predictions have been identical to those of textbook quantum mechanics, the TSVF managed over the years to address not only the measurement problem [1], but also many kinematically and dynamically nonlocal phenomena, counterfactuals [2], realism and energetic causal sets [3], emergence [4] and even the black-hole information paradox [5]. I would therefore like to discuss this formalism, mostly focusing on its recent formulations [6,7]. I will make connections between the TSVF and related approaches, trying to define the unique sense in which it is "retrocausal" and "superdeterministic".

[1] Y. Aharonov, E. Cohen, T. Landsberger, "The Two-Time Interpretation and Macroscopic Time-Reversibility", Entropy 19, 111 (2017).
[2] Y. Aharonov, E. Cohen, S. Popescu, "A Dynamical Quantum Cheshire Cat effect and Implications for Counterfactual Communication", Nat. Commun. 12, 4770 (2021).
[3] E. Cohen, M. Cortes, A.C. Elitzur, L. Smolin L., "Realism and causality I: Pilot wave and retrocausal models as possible facilitators", Phys. Rev. D 102, 124027 (2020), "Realism and causality II: Retrocausality in Energetic Causal Sets", Phys. Rev. D 102, 124028 (2020).
[4] Y. Aharonov, E. Cohen, J. Tollaksen, "Completely top–down hierarchical structure in quantum mechanics", Proc. Natl. Acad. Sci. USA 115, 11730-11735 (2018).
[5] E. Cohen, M. Nowakowski, "Comment on 'Measurements without probabilities in the final state proposal'", Phys. Rev. D 97, 088501 (2018).
[6] Y. Aharonov, E. Cohen, F. Colombo, T. Landsberger, I. Sabadini, D.C. Struppa, J. Tollaksen, "Finally Making Sense of the Double-Slit Experiment", Proc. Natl. Acad. Sci. USA 114, 6480-6485 (2017).
[7] M. Waegell, E. Cohen, A.C. Elitzur, J. Tollaksen, Y. Aharonov, "Quantum reality with negative-mass particles", arXiv:2201.09510.

Gisin, Nicolas

Indeterminism is physical

Deterministic chaos requires that the initial condition contains all the random information about the chaotic future evolution of the dynamical system. Accordingly:

- The initial conditions contain infinite information,
- God played all dice at the big-bang and coded all outcomes in the initial conditions.

Admittedly, events that just come out of the blue is not an appealing alternative.

Here, we assume some degree of indeterminacy: states of classical systems are not fully determined. Equivalently, real numbers are never fully determined: at each time, only computable approximations exist. As time passes, new information gets created which reduces the indeterminacy and improves the real number approximations as in intuitionistic mathematics. Accordingly, if the dynamical system is chaotic, its evolution is indeterministic.

Hance, Jonte

Supermeasured: Violating Statistical Independence without violating statistical independence

Bell's theorem is often said to imply that quantum mechanics violates local causality, and that local causality cannot be restored with a hidden-variables theory. This however is only correct if the hidden-variables theory fulfils an assumption called Statistical Independence. Violations of Statistical Independence are commonly interpreted as correlations between the measurement settings and the hidden variables (which determine the measurement outcomes). Such correlations have been discarded as "fine-tuning" or a "conspiracy". We here point out that the common interpretation is at best physically ambiguous and at worst incorrect. The problem with the common interpretation is that Statistical Independence might be violated because of a non-trivial measure in state space, a possibility we propose to call "supermeasured". We use Invariant Set Theory as an example of a supermeasured theory that violates the Statistical Independence assumption in Bell's theorem without requiring correlations between hidden variables and measurement settings.

Kastner, Ruth

What is Retrocausation in the Transactional Interpretation?

In this talk I discuss the latest incarnation of the Transactional Interpretation. The fully relativistic form that I have developed in recent years, known as "RTI", has two distinct types of evolution—one unitary (reversible) and the other non-unitary (irreversible). The latter non-unitary process constitutes 'measurement' in the quantum context. I consider in what sense the term 'retrocausation' applies to each of these processes, and propose an ontological picture in which spacetime can be viewed as an emergent construct.

Kent, Adrian

Quantum Reality from Asymptotic Measurements: possibilities and problems

I review the idea [Phys. Rev. A 96, 062121 (2017)] of understanding quantum reality via a postulated hypothetical asymptotic measurement of the electromagnetic field and related proposals, and discuss more recent developments.

Kinney, David

Corroboration Conditions for Cyclic Bayesian Networks

Since the 1980s, Bayesian Network models have been used torepresent the causal structure of systems. Verma and Pearl (1988) provethat in an acyclic Bayesian Network, there is a one-to-onecorrespondence between sets of variables that stand in the d-separationrelation to one another in a graphical structure and sets of variablesthat are conditionally independent of each other in a probabilitydistribution that is Markov to that structure. This result providesclear corroboration conditions for acyclic Bayesian Network models.However, Neal (2000) shows that the same result does not hold for cyclicBayesian Networks. This poses difficulties for the corroboration oftheories that posit causal loops. Expanding on work by Clarke et al.(2014), I show that cyclic Bayesian Networks can be re-written asacyclic, Dynamic Bayesian Networks that are infinitely long in twodirections. These models allow us to use to Verma and Pearl's result tostate probabilistic corroboration conditions for theories with causalloops. I discuss the implications of these results for superdeterminism.

Palmer, Tim

Discretisation of the Bloch Sphere, Fractal Invariant Sets and Bell's Theorem

Max Planck famously introduced the notion of discretised packets of energy, quanta, thus kickstarting the development of our most successful theory of physics, replacing classical theories in which energy varies continuously. Despite its success, however, the concepts of reality and local causality are deeply problematic in quantum mechanics. Such problems may lie at the heart of why it has been so difficult to synthesise quantum and gravitational physics.

Motivated by these issues, we apply Planck's discretisation insight again, but this time to the continuum of quantum mechanics' state space – complex Hilbert Space. A particular discretisation is discussed – one which draws on number theoretic properties of trigonometric functions. This leads to a model of quantum physics which is necessarily superdeterministic in character, that is to say violates the Statistical Independence assumption in Bell's Theorem. Because of this, the model does not need to invoke concepts of indefinite reality or nonlocality to explain the violation of Bell's inequality.

Price, Huw

Can two zigs make a zig-zag? Causal engineering on the Parisian model

Costa de Beauregard (1953) discovered the Parisian zig-zag. He pointed out, initially as an objection to the EPR argument's Locality assumption, that retrocausality might allow spacelike causality in an EPR experiment, without action at a distance. Given retrocausality, a causal influence might follow a zig-zag path, via the past lightcones of the two particles involved. But how would the zig-zag actually work? On the face of it, retrocausality only gets us half way, in either direction. It gives us two zigs – two retrocausal arrows, meeting at the source event in the past. How do we get from z*ig-zig* to z*ig-zag?* This talk, based on joint work with Ken Wharton, proposes an answer. In causal modelling terms, the two zigs give us a *collider* at the source. It is well known that colliders often produce causal artifacts; this is the problem of 'collider bias'. But in special circumstances a collider can transmit genuine causal influence, and this may be the key to building a zig-zag.

Reilly, Michele (presenter) and Lloyd, Seth

Closed timelike curves, game theory, and quantum foundations

This talk discusses the implications of projective closed timelike curves (P-CTCs) for decision making. We show that P-CTCs solve the social dilemma problem in multiparty games: no sub-optimal Nash equilibria can occur if all players know each others' future actions. We show that this advantage persists for experimentally realizable P-CTCs. We discuss the consequences of closed timelike curves for quantum foundations.

Sutherland, Roderick

Marriage of Convenience

In considering the subtleties associated with the possible existence of retrocausality, it will likely be helpful to have viable examples of retrocausal models on hand in order to gain some insight into the good and not-so-good features that can typically arise. A sample model will be presented here which hopefully can serve this role. It is formed by a convenient merging of two well-known models, namely the de Broglie-Bohm approach and the weak value
formalism, in order to incorporate the better features of each. In particular the resulting model is local, time-symmetric and Lorentz covariant, with no need for a preferred frame. Coming from the weak value side, the model encompasses all observables (i.e., it is not just a toy model for e.g., spin) with the ontology all residing in three dimensions (rather than configuration space) and with all conservation laws satisfied. From the de Broglie-Bohm side, the model provides a resolution of the measurement problem and also provides the same derivation of the Born rule as originally formulated by Bohm. The merger of the two models
is achieved by deriving it all from a single Lagrangian. The intention is for this framework to draw out the more unfamiliar characteristics likely to be encountered with retrocausal schemes and make them more evident.

Vervoort, Louis

Probability Theory as a Physical Theory Points to Superdeterminism.

We try to make superdeterminism more intuitive, notably by simulating a deterministic model system, a billiard game. In this system an initial ‘bang’ correlates all events, just as in the superdeterministic universe. We introduce the notions of ‘strong’ and ‘soft’ superdeterminism, in order to clarify debates in the literature. Based on the analogy with billiards, we show that superdeterministic correlations may exist as a matter of principle, but be undetectable for all practical purposes. This allows us to counter classical objections to superdeterminism, such as the claim that it would be at odds with the construction of new theories. Our main argument in favor of superdeterminism comes from probability theory. Probability theory as a physical theory is, in a sense, the most general physics theory available, more encompassing than relativity theory and quantum mechanics, which comply with probability theory. We show that superdeterminism has a greater explanatory power than its competitors: it can coherently answer three questions from probability theory for which other positions remain powerless (cf. L. Vervoort, *Entropy* **2019**, *21*(9), 848).

Weinstein, Steven

PR boxes as a limiting case of the Boltzmann Machine model

A conditional restricted Boltzmann machine (cRBM) is a type of machine learning model which can be taught to “learn” the EPR correlations, and more generally the correlations associated with any discrete quantum system, with arbitrary initial state and final measurement. This provides the archetype for a hidden variable theory in which the “hidden” units in the Boltzmann machine are the “hidden variables”. Boltzmann machines have their inspiration in classical statistical physics, and have a free parameter which corresponds to kT in an Ising-like model. Letting this parameter go to infinity gives rise to completely random behavior in the model, while letting it go to zero gives rise to extreme nonlocality, including PR boxes. In this brief talk I will show how this works, and consider what this might be telling us about the physics behind the cRBM model.

Wharton, Ken

All Useful Superdeterminstic Models are Retrocausal

Using the causal model framework popularized by Judea Pearl, one can mathematically distinguish superdeterministic models from retrocausal models. (See arXiv:1208.4119, 1906.04313.) To be useful, all superdeterminstic models must be supplemented with future inputs (measurement settings), which transforms them into retrocausal models (i.e. models with future-input-dependence). Attempting a "past-inputs-only" analysis on such models is shown to not only lose all meaningful aspects of causation, but also makes them incapable of prediction. These conclusions will be supported using analogous classical scenarios, such as retarded/advanced potentials in electromagnetism. The implication is that superdeterminists must not be averse to retrocausal models.