



## QCS 2019 Tutorials and Talks

Wednesday 10<sup>th</sup> July

**Rob Spekkens (Perimeter Institute)**

*A survey of causal inference techniques*

**Elie Wolfe (Perimeter Institute)**

*Quantum Inflation Technique*

Review forthcoming paper describing universal quantum causal inference technique (overobserved variables). I spoke about this once before at Oxford, but now we have expanded the technique to include truly all possible causal structures, not just networks.

**Jonathan Barrett (University of Oxford)**

*Quantum causal models*

TBC

**Jacques Pienaar (IIP-UFRN, Natal, Brazil)**

*Is the arrow of causality reversible?*

In this talk I will raise the question of whether the asymmetric relation between a 'cause' and its 'effect' is an objective feature of an external process, or whether the direction of this relation might depend in some way on an observer or user of the process.

**Ravi Kunjwal (Perimeter Institute)**

*Bell Quantified: The Resource Theory of Nonclassicality of Common-Cause Boxes*

TBC

**David Schmid (Perimeter Institute)**

*Causal-Inferential Theories I*

**John Selby (Perimeter Institute)**

*Causal-Inferential Theories II*

We discuss how the omelette of epistemic and ontological concepts is problematic not only within quantum theory, but even in the simpler realm of operational and ontological theories. We then revise the traditional notion of an operational theory in a manner which separates out its inferential and its causal aspects. In an analogous way, we refine the traditional notion of an ontological theory, while extending it to apply to arbitrary acyclic causal structures. One can then define an ontological model as a structure-preserving map from an operational theory to an ontological theory. Consequently, we also refine the traditional concepts of operational equivalence and Spekkens' notion of generalised contextuality.



## QCS 2019 Tutorials and Talks

Thursday 11<sup>th</sup> July

**Paolo Perinotti (University of Pavia)**

*Causal structures induced by Cellular automata*

The notion of a cellular automaton (CA) was historically introduced in the context of classical computation, and later extended in the realm of the theory of quantum computation. In this talk, we will illustrate the generalization of this notion in the wider context of operational probabilistic theories (OPTs), providing the necessary background, which essentially consists in the notion of infinite composite systems. We will then illustrate the notion of homogeneity for CAs through a definition that avoids reference to extrinsic geometric structures such as space or space-time. We then specialize to the case of the Fermionic OPT, and show some examples of cellular automata that were studied in the time-span of the project, with particular focus on the reconstruction of free relativistic and interacting quantum field theories.

**Ognyan Oreshkov (Invited | Université Libre de Bruxelles)**

*Cyclic quantum causal models*

TBC

**Alessandro Bisio (University of Pavia)**

*Theoretical framework for HigherOrder Quantum Theory*

The most general (probabilistic) transformation of a quantum state is described by a quantum operation. Quantum operations can be axiomatically defined as the most general map which are compatible with the probabilistic structure of the theory, and produce a legitimate output when applied locally on one side of a bipartite input. These admissibility requirements characterise quantum operations as completely positive trace non increasing linear maps. What happens if we now consider maps from quantum operations to quantum operations? Can we give an axiomatic characterisation of these objects according to some generalised notion of admissibility? What happens if we recursively iterate the construction and we define a full hierarchy of higher order maps? Some special cases of higher order maps have been already studied in the literature. Causally ordered Quantum Networks, which encompass all conceivable quantum protocols, form a sub-hierarchy of maps which are endowed with a well ordered causal structure and they can be realised as quantum circuits. However, more general higher order maps may exhibit an indefinite causal structure which prevents a physical implementation as a quantum circuit. Non circuital higher order maps allow to accomplishing certain tasks that cannot be achieved by circuital maps, like the violation of causal inequalities, and can outperform circuital maps in certain quantum information processing tasks. The experimental realisation of non-circuital higher order maps has also been considered. Notwithstanding many results on the subject, a general mathematical framework is still missing. The aim of this contribution is to fill this critical gap by providing an axiomatic framework for higher order quantum theory. Higher order quantum theory is introduced axiomatically with a formulation based on the language of types of transformations. Complete



positivity of higher order maps is derived from the general admissibility conditions instead of being postulated as in previous approaches. We will see that a complete mathematical characterisation of admissible maps is possible and that the set of admissible maps of a given type is in correspondence with a convex subset of the cone of positive operators. This result encompasses the analysis existing in the literature and gives them an axiomatic operational foundation. The present axioms for higher order quantum theory have an operational nature and do not refer to the specific mathematical structure of quantum theory. Therefore, with due care, our framework can be applied to general operational probabilistic theories.

**Robin Lorenz (University of Oxford)**

*The dot-formalism – causally faithful graphical representations of unitaries*

Circuit diagrams as representations of the compositional structure of channels are not an expressive enough language to allow for causally faithful graphical representations of all unitary channels, that is such that there is a causal relation between an input and an output of the unitary channel if and only if these are connected by a path in the graphical representation. The question hence is whether a formalism can be developed that allows causally faithful representations for all unitary channels. We present some first results employing a new graphical formalism, the dot-formalism, which allows to find such representations in many cases. This formalism comes down to the expressibility of a particular interplay between direct sums and direct products, which can be seen to lie at the heart of understanding quantum causal structure. We further point to a first application in the context of quantum causal models.

**Christodoulou Marios (University of Hong Kong)**

*Superposition of geometries in the lab and the possibility to probe Planck time*

Detection of gravity mediated entanglement growth witnesses the quantum nature of the gravitational field. Described in general relativistic language the effect is seen to arise from spacetime being set in a superposition, and the corresponding relative time dilation. Remarkably, this proper time difference is extraordinarily small, about twenty orders of magnitude below the precision of the best atomic clocks. This opens the possibility that such interference experiments can probe the structure of time at the Planck scale.

**Alessandro Tosini (University of Pavia)**

*Information and disturbance in a physical theory*

Any measurement is intended to provide information on a system, namely knowledge about its state. However, we learn from quantum theory that it is generally impossible to extract information without disturbing the state of the system or its correlations with other systems. In this paper we address the issue of the interplay between information and disturbance for a general operational probabilistic theory. The traditional notion of disturbance considers the fate of the system state after the measurement. However, the fact that the system state is left untouched ensures that also correlations are preserved only in the presence of local discriminability. Here we provide the definition of disturbance that is appropriate for a general theory. We then prove an equivalent condition for no-information without disturbance—atomicity of the identity—namely the impossibility of achieving the trivial



evolution—the identity—as the coarse-graining of a set of non trivial ones. We will prove a general theorem showing that information that can be retrieved without disturbance corresponds to perfectly repeatable and discriminating tests. As a consequence we proved a structure theorem for operational probabilistic theories, showing that the set of states of any system decomposes as a direct sum of perfectly discriminable sets, and such decomposition is preserved under system composition. Besides proving that no-information without disturbance is implied by the purification postulate, we show via concrete examples that the converse is not true. Finally we show that no-information without disturbance and local discriminability are independent.

**Marco Erba (University of Pavia)**

*Classical theories with entanglement*

We present the framework of Operational Probabilistic Theories (OPTs), where the probabilistic structure hinges upon braided strict monoidal categories. We then focus on simplicial theories, namely those theories where the set of states are simplexes (a particular and relevant case of this family is given by classical theories). We show that, in general, a classical theory may admit entangled states, i.e. states which cannot be prepared with local operations and classical communication. This feature is found to be equivalent to the failure of local discriminability or, equivalently in the classical case, of atomicity of state-composition. On the one hand, we find that any simplicial theory must be causal; on the other hand, entanglement is found to be a ubiquitous feature for any simplicial theory which is not standard classical theory. We then construct an explicit example—complete with the set of operations—of such a theory. Finally, we characterise the possible general composition rules for the systems of a simplicial theory.



## QCS 2019 Talks

Friday 12<sup>th</sup> July

**Stefano Gogioso (University of Oxford)**

*TBC*

**Aleks Kissinger (Invited | Radboud University)**

*Teaching a new dog old tricks: causal inference by string diagram surgery*

String diagrams are a simple kind of diagram involving boxes connected by wires, which give a convenient tool for visualising and reasoning about composed processes in many contexts. In the context of probabilistic processes (i.e. stochastic matrices / conditional probability distributions), string diagrams of a certain form can be used to define and manipulate Bayesian networks. I will talk about the string-diagrammatic representation of Bayesian networks and also define an operation corresponding to a Pearl-style "do" intervention in terms of "string-diagram surgery". As in the classical approach to causal identification, if a string diagram satisfies certain conditions, the resulting interventional distribution can be computed from purely observational data via (the string diagram analogue to) "back-door adjustment". I will show a simple criterion that can be stated purely in terms of factorisability of a diagram into n-combs and give an example of calculating the appropriate adjustment by means of a technique we call comb disintegration. This turns out to be equivalent (in the semi-Markovian case) to a well-known criterion based on confounding components given by Tian and Pearl. Hence, string diagrams provide a generalisation of this classical criterion to non-semi-Markovian and (possibly) non-classical models.

**Matty Hoban (Invited | University of Oxford)**

*Bipartite Post-Quantum Steering and the Instrumental Scenario*

In a traditional bipartite steering experiment, the assemblages (ensembles of ensembles) into which Alice remotely steers Bob's system may always be explained via quantum mechanics: this is a renowned result by Gisin, Hughston, Jozsa and Wootters. Here we show that steering that is not compatible with quantum theory may still arise in bipartite scenarios for a suitable relaxation of the experimental setup. These setups comprise experiments (i) where Bob can in some way intervene on their share of the system, and (ii) where the causal relations between the parties corresponds to the so-called instrumental scenario. We finally show that post-quantum steering in these scenarios does not necessarily follow from post-quantum correlations in the fully device-independent sense, rendering the phenomenon a genuinely semi-device-independent effect

**Andrew Garner (IQOQI Vienna)**

*Device-independent information processing with spatiotemporal degrees of freedom*

Nonlocality, as demonstrated by the violation of Bell's inequalities, enables device-independent cryptographic tasks that do not require users to trust their apparatus. A pillar of this approach is the black box formalism. In my talk, I will present recent research in collaboration with Markus Müller and Marius Krumm, in which we consider when the inputs



to these boxes are spatiotemporal in nature (e.g. orientations of space, or durations or time). Without assuming the validity of quantum theory, we prove that the statistical behaviour of such boxes must respect their input's symmetries, with profound foundational and technological implications. These include a protocol for witnessing Bell nonlocality in two-angle experiments with fewer measurements than possible without spatiotemporal symmetries, a novel hidden variable model for noisy correlations, and an exact characterization of the “quantum (2,2,2)-behaviours” (probability tables obtainable from a bipartite quantum system with two choices of binary-outcome measurement per party).

**Nitica Sakharwade (Perimeter Institute)**

*Toy model for quantum causality using colouring rules*

In the quest for quantum gravity, Hardy suggests the radical aspects of quantum physics (probabilistic nature) and relativity (dynamic causality) would manifest together. In recent years, this has led to an active study of causally neutral formulations and more particularly the study of indefinite causal structures that allow for perplexing phenomenon such as the quantum switch. In this work, I construct a toy model set in finite topological spaces with  $1+1$  D that have indefinite causal structures emerging from local definite causal orders through graph colouring rules and simple operational rules. In the setting of this toy model, I study indefinite causal structures that emerge from these operational rules and that naturally forbid close-time-like-curves. I study a version of the quantum switch and more such curious possibilities in this toy model and attempt to interpret these. The hope is to help shed some light on the study of indefinite causal structures. Future work will involve generalizing these results to higher dimensions.

**Nicola Pinzani (University of Oxford)**

*Categorical Semantics for Time Travel*

We introduce a general categorical framework to reason about quantum theory and other process theories living in spacetimes where Closed Timelike Curves (CTCs) are available, allowing resources to travel back in time and provide computational speedups. Our framework is based on a weakening of the definition of traced symmetric monoidal categories, obtained by dropping the yanking axiom and the requirement that the trace be defined on all morphisms. We show that the two leading models for quantum theory with closed timelike curves—namely the P-CTC model of Lloyd et al. and the D-CTC model of Deutsch—are captured by our framework, and in doing so we provide the first compositional description of the D-CTC model. Our description of the D-CTC model results in a process theory which respects the constraints of relativistic causality: this is in direct contrast to the P-CTC model, where CTCs are implemented by a trace and allow post-selection to be performed deterministically.

**Some Sankar Bhattacharya (University of Hong Kong)**

*Indefinite causal order enables perfect quantum communication with zero capacity channel*

Quantum mechanics is compatible with scenarios where the relative order between two events is indefinite. Here we show that two instances of a noisy process, used in a superposition of two alternative orders, can behave as a perfect quantum communication



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channel. This phenomenon occurs even if the original processes have zero capacity to transmit quantum information. In contrast, perfect quantum communication does not occur when the message is sent along a superposition of paths, with independent noise processes acting on each path. The possibility of perfect quantum communication through noisy channels highlights a fundamental difference between the superposition of orders in time and the superposition of paths in space.



**Saturday 13<sup>th</sup> July**

**Fabio Costa (University of Queensland)**

*Lessons from Quantum Causality*

**Christina Giarmatzi (University of Queensland)**

*Witnessing quantum memory in non-Markovian processes*

We present a method to detect a quantum memory in a non-Markovian process. We call a process Markovian when the environment does not provide a memory that retains correlations across consecutive system-environment interactions. We define two types of non-Markovian processes, depending on the required memory being classical or quantum. We formalise this distinction using the process matrix formalism, through which a process is represented as a multipartite state. Within this formalism, a test for entanglement in a state can be mapped to a test for quantum memory in the corresponding process. This allows us to apply separability criteria and entanglement witnesses to the detection of a quantum memory. We apply the method to a physically motivated example of a process with quantum memory: two initially entangled qubits, representing system and environment respectively, coupled according to the Ising model with a transverse field. We prove Markovianity and classical memory for the special cases of vanishing coupling and transverse field, respectively. Using the Positive Partial Transpose criterion, we find that for almost all other parameters the process has a quantum memory. As with entanglement witnesses, our method of witnessing a quantum memory provides a versatile experimental tool for open quantum systems

**Denis Rosset (Perimeter Institute)**

*Constructive representation theory and applications to causal structures*

In contrast to textbook examples of applications of representation theory, resources in causal structures can exhibit symmetries that cannot be decomposed easily with usual tricks (such as Schur-Weyl duality). We'll revisit the basic components of group/representation theory (composition of groups through products, composition of representations through sums, products) in the context of applications to causal structures. In particular, we'll identify the primitives that are not straightforward to compute (induced representations, decomposition of tensor products) and present workarounds using numerical methods.

**Ding Jia (Perimeter Institute)**

*Diagrams, Processes, QFTs, and Quantum Gravity*

We present a scheme to construct theories which are (1) correlational, (2) local, (3) specific, and (4) causally neutral. We show how to use this diagrammatic approach to recover the Standard Model without mentioning fields. Even a quantum gravitational theory can be written down, but the challenge is to extract numbers and predictions from the theory.

**Hler Kristjansson (University of Oxford)**

*Quantum Shannon theory with superpositions of trajectories.*

Shannon's theory of information was built on the assumption that the information carriers were classical systems. Its quantum counterpart, quantum Shannon theory, explores the new





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possibilities arising when the information carriers are quantum systems. Traditionally, quantum Shannon theory has focussed on scenarios where the internal state of the information carriers is quantum, while their trajectory is classical. Here we propose a second level of quantisation where both the information and its propagation in spacetime is treated quantum mechanically. The framework is illustrated with a number of examples, showcasing some of the counterintuitive phenomena taking place when information travels simultaneously through multiple transmission lines.

**Julian Wechs**

*Existence of noncausal processes on time-delocalized systems*