# Causalworlds 2024: Book of Abstracts

## Tutorials

**Speaker:** *Robert Spekkens*
**Title: Causal Inference Meets Quantum Physics**
**Abstract:** Can the effectiveness of a medical treatment be determined without the expense of a randomized controlled trial? Can the impact of a new policy be disentangled from other factors that happen to vary at the same time? Questions such as these are the purview of the field of causal inference, a general-purpose science of cause and effect, applicable in domains ranging from epidemiology to economics. Researchers in this field seek in particular to find techniques for extracting causal conclusions from statistical data. Meanwhile, one of the most significant results in the foundations of quantum theory—Bell's theorem—can also be understood as an attempt to disentangle correlation and causation. Recently, it has been recognized that Bell's result is an early foray into the field of causal inference and that the insights derived from almost 60 years of research on his theorem can supplement and improve upon state-of-the-art causal inference techniques. In the other direction, the conceptual framework developed by causal inference researchers provides a fruitful new perspective on what could possibly count as a satisfactory causal explanation of the quantum correlations observed in Bell experiments. Efforts to elaborate upon these connections have led to an exciting flow of techniques and insights across the disciplinary divide. This tutorial will highlight some of what is happening at the intersection of these two fields.

**Speaker:** *Cyril Branciard*
**Title: Indefinite quantum causality**
**Abstract:** Recent advances in quantum foundations have unveiled the idea that the causal order between quantum events may not always be fixed or even well-defined, allowing for some form of *indefinite quantum causality*. This tutorial will introduce the key concepts and motivations behind this rapidly developing area of research. Focusing on one of the main frameworks developed to explore indefinite quantum causality—the process matrix formalism—I will present key theoretical results, highlight the potential of indefinite causal orders as a resource for quantum information processing, and discuss experimental implementations as well as the physical interpretation of indefinite causal structures.

# Invited Talks

**Speaker:** *Thomas Richardson*
**Title: Counterfactual and Graphical Frameworks for Causal Modeling**
**Abstract:** In the Statistics literature there are three main frameworks for causal modeling: counterfactuals (aka potential outcomes), non-parametric structural equation models (NPSEMs) and graphs (aka path diagrams or causal Bayes nets). These approaches are similar and, in certain specific respects, equivalent. However, there are important conceptual differences and each formulation has its own strengths and weaknesses. These divergences are of relevance both in theory and when the approaches are applied in practice. This talk will introduce the different frameworks, and describe, through examples, both the commonalities and dissimilarities. In particular, we will see that the "default" assumptions within these frameworks lead to different identification results when quantifying mediation and, more generally, path-specific effects.

**Speaker:** *Joris M. Mooij*
**Title: Bipartite graphical causal models: beyond causal Bayesian networks and structural causal models**
**Abstract:** Based on the immense popularity of causal Bayesian networks and structural causal models, one might expect that these representations are appropriate to describe the causal semantics of any real-world system, at least in principle. In this talk, I will argue that this is not the case, and motivate the study of more general causal modeling frameworks. In particular, I will discuss bipartite graphical causal models.

Real-world complex systems are often modelled by systems of equations with endogenous and independent exogenous random variables. Such models have a long tradition in physics and engineering. The structure of such systems of equations can be encoded by a bipartite graph, with variable and equation nodes that are adjacent if a variable appears in an equation. I will show how one can use Simon's causal ordering algorithm and the Dulmage-Mendelsohn decomposition to derive a Markov property that states the conditional independence for (distributions of) solutions of the equations in terms of the bipartite graph. I will then show how this Markov property gives rise to a do-calculus for bipartite graphical causal models, providing these with a refined causal interpretation.

**Speaker:** *Giulio Chiribella*
**Title: Indefinite causal order and the arrow of time**
**Abstract:** At the fundamental level, the dynamics of quantum particles and fields is time-symmetric: their dynamical equations are invariant under inversion of the time coordinate, possibly in conjunction with the change of other physical properties, such as charge and parity. At the operational level, the time-symmetry of the fundamental equations implies that certain quantum devices are bidirectional, meaning that the role of their inputs and outputs can be exchanged. Here we characterize the largest set of operations that can in principle be implemented on bidirectional devices, and show that this set includes operations in which the role of the input and output ports of the given devices becomes indefinite. An example of such an operation, called the "quantum time flip," achieves input-output indefiniteness by adding quantum control to the direction in which a single device is used. We show that quantum operations with indefinite input-output directions can in principle achieve information-theoretic advantages over all

possible operations with definite time direction, and can lead to an extremely strong form of indefinite causal order.

**Speaker:** *Mio Murao*
**Title: Higher-order quantum computation and causality**
**Abstract:** Supermaps are higher-order transformations that take maps as input. We explore algorithms for higher-order quantum computation that implement supermaps of unitary operations using multiple calls to a black-box unitary operation. We investigate how the causal order structure of the calls of the unitary black boxes affects their performance in implementing supermaps. We present the analysis of several higher-order quantum computation tasks, inversion, complex conjugation, transposition, comparison, and controlization of black-box operations.

**Speaker:** *Sally Shrapnel*
**Title: Quantum algorithms for classical causal learning**
**Abstract:** Given the large number of proposed quantum machine learning (QML) algorithms, it is somewhat surprising that ideas from this field have not yet been extended to causal learning. While deep learning and generative machine learning models have taken centre stage in the industrial application of automated learning on classical data, it is nonetheless well known that these techniques don't reliably capture causal concepts, leading to significant performance vulnerabilities. Increasingly, classical ML experts are taking ideas from causal inference, a field traditionally limited to small data sets of low dimensionality, and injecting modern ML elements to create new algorithms that benefit from the best of both worlds. These hybrid classical approaches provide new opportunity to search for potential quantum advantage. In this talk I explore this new research direction and propose several new quantum algorithms for classical causal inference.

**Speaker:** *Rafael Chaves*
**Title: Unveiling Non-Classicality via Node and Edge Interventions in Causal Networks**
**Abstract:** Generalizations of Bell's theorem, particularly within quantum networks, are now being analyzed through the causal inference lens. Despite the central role of interventions in causality theory, their potential within quantum networks remains largely unexplored. In this seminar, we will discuss how introducing interventions—beyond mere observation—can reveal quantum violations of classical causal bounds, even in scenarios where no Bell-like violation is observed. That is, through interventions, the quantum behavior of a system that would seem classical otherwise can be demonstrated. We will explore various types of interventions on nodes and edges within causal networks, their distinct applications, and present experimental results that demonstrate these concepts.

**Speaker:** *Alexandro Pozas-Kerstjens*
**Title: Joint measurements on distant physical systems**
**Abstract:** It is not explicitly obvious that relativity and quantum mechanics are consistent with each other. Extensive research has shown that quantum states are consistent with relativity, in that they do not allow for faster-than-light transferring of information.

In contrast, much less research has been done in quantum measurements, and in fact, naive attempts to put together relativity and quantum measurements lead to signaling between space-like separated regions. In this talk I will describe how this same problem arises in non-relativistic quantum physics, where measurements on systems kept spatially separated in general lead to signalling. By giving away the projection postulate, it is possible to alleviate this problem and measure non-local variables without signaling by exploiting pre-shared entanglement as a resource. I will describe a protocol for implementing any joint measurement in a non-signaling manner, and argue that this leads to a complete classification of all joint quantum measurements, based on the required amount of entanglement necessary to measure them.

**Speaker:** *Rainer Verch*
**Title: Quantum non-causality in spacetime may be not exclusively quantum**
**Abstract:** There are several non-causal effects that have been attributed to quantum physics. These include the analogues of "closed timelike curve effects´´ in quantum circuits proposed by David Deutsch (D-CTC), and the "impossible measurements´´ in relativistic quantum field theory discussed by Raphael Sorkin. Based on previous work, it will be pointed out in the talk that the alleged non-causality features arise not only in quantum systems, but in the very same manner in systems that are described in the framework of classical (non-quantum) statistical mechanics or classical field theory. Therefore, although the said non-causality scenarios have been portrayed as pertaining to quantum systems or quantum fields, they are in fact not based on, nor characteristic of, the quantum nature of physical systems.

**Speaker:** *Sumati Surya*
**Title: Quantum discreteness and spacetime causality: what's in the mix?**
**Abstract:** The notion of causality is intimately tied to both, a transitive ordering on events, and the possibility of unrelated events. Thus, any causality structure is a partially ordered set or poset. This is the case in Lorentzian spacetime, which possesses a single time direction. In causal set quantum gravity, this spacetime causality structure is "first quantised" by discretising it. However, as with any dynamical quantum theory of spacetime, background notions of causality are insufficient. I will discuss how ordering and discreteness, as manifested in the sequential growth paradigm, provide a broad framework for quantum dynamical notions of causality.

**Speaker:** *Huw Price*
**Title: Entanglement via Constrained Colliders**
**Abstract:** We propose that Bell correlations are explicable as a combination of (i) collider bias and (ii) a boundary constraint on the collider variable. We show that the proposal is valid for a special class of ('W-shaped') Bell experiments involving delayed-choice entanglement swapping, and argue that it can be extended to the ordinary ('V-shaped') case. The proposal requires no direct causal influence outside lightcones, and may hence offer a way to reconcile Bell nonlocality and relativity.

**Speaker:** *Doreen Fraser*
**Title: Relativistic causality principles in QFT**
**Abstract:** In QFT, one aspect of relativistic causality is the principle of microcausality, which requires that observables associated with spacelike separated regions commute. But this principle is not by itself sufficient to rule out superluminal signalling, as examples of 'impossible' measurements demonstrate. Representations of the dynamics that respect relativity also play a necessary role in upholding relativistic causality in QFT. This talk will focus on the important role that principles of relativistic dynamics play in representations of local measurement in QFT.

**Speaker:** *Jessica Bavaresco*
**Title: Can the quantum switch be deterministically simulated?**
**Abstract:** Higher-order transformations that act on a certain number of input quantum channels with an indefinite causal order, such as the quantum switch, cannot be described by standard quantum circuits that use the same number of calls of the input quantum channels. But could they be simulated, i.e., could their action on their input channels be deterministically reproduced, for all arbitrary inputs, by a quantum circuit that uses on a larger number of calls of the input channels? In this work, we prove that, when only one extra call of each input channel is available, the quantum switch cannot be simulated. We demonstrate the robustness of this result by showing that even when probabilistic and approximate simulations are considered, higher-order transformations that are close to the quantum switch can be at best simulated with a probability strictly less than one. This result stands in stark contrast with the known fact that, when the quantum switch acts exclusively on unitary channels, its action can be simulated. We also show other particular cases where a restricted simulation of the quantum switch is possible. Finally, we discuss the implications of our findings to the analysis of experiments based on the quantum switch.

**Speaker:** *Tein van der Lugt*
**Title: Causally faithful circuits for relativistic realisability, or: What can you do in a spacetime?**
**Abstract:** Multipartite quantum channels realisable in a spacetime obey the no-superluminal-signalling constraints imposed by relativistic causality. But what about the converse: Can every channel that exhibits no superluminal signalling also be realised through relativistically valid dynamics? To our knowledge, only special cases of this question have been studied. For bipartite channels, the answer has been found to be negative in general (Beckman et al., 2001), though we will argue that counterexamples must necessarily involve a form of fine-tuning. Another special case of the question has been extensively explored under the name of nonlocal quantum computation in the context of position-based cryptography. We will pose and motivate the question in generality, conjecture a positive answer for all but the fine-tuned channels, and present results towards proving it, drawing on insights from nonlocal quantum computation and the new field of causally faithful circuit decompositions of unitary transformations (see also Tuesday). Beyond their relevance to spacetime realisability, the circuit decompositions involved in addressing the question also find applications in quantum causal modelling.

**Speaker:** *Anne-Catherine de la Hammette*
**Title:** **Indefinite causal order and quantum reference frames**
**Abstract:** Recent research on quantum reference frames (QRFs) has shown that whether a system is in a superposed state of locations, momenta, and other properties can depend on the quantum reference frame relative to which it is being described. Whether an event is localized in spacetime or not can change under QRF transformations, in that case so-called quantum-controlled diffeomorphisms. This raises a critical question: can quantum reference frame transformations render indefinite causal order definite? In this talk, I propose a relativistic definition of causal order based on worldline coincidences and proper time differences, establishing it as an operationally meaningful observable in both general relativity and quantum mechanics. Using this definition, we can analyse the indefiniteness of causal order in the optical and gravitational quantum switch on equal footing. This analysis suggests an operational rather than a spacetime-based understanding of events. I will compare these findings to other recent results and conclude with broader implications for events in non-classical contexts.

**Speaker:** *Renato Renner*
**Title:** **Fundamental limits on realising quantum processes in spacetime**
**Abstract:** Causality is a core concept in both General Relativity (GR) and Quantum Information Theory (QIT), yet it manifests differently in each domain. In GR, causal cones appear as a defining property of spacetime. Conversely, in QIT, causality relates to the abstract flow of information in quantum processes, independent of spacetime. This raises a crucial question: under what conditions can an abstract quantum process be realised within spacetime? The question is especially intriguing for quantum processes with indefinite causal structure, like the Quantum Switch, which resist classical causal descriptions. In this talk, I will present no-go theorems that reveal fundamental limitations on the realisability of such processes in spacetime and, thus, more generally, on the interplay between GR and QIT.
Based on joint work with V. Vilasini `https://doi.org/10.1103/PhysRevLett.133.080201`

# Colloquium Talk

**Speaker:** *Ciarán Lee*
**Title:** **Causal and counterfactual inference and what they're good for**
**Abstract:** Causal reasoning is vital for effective reasoning in many domains, from health-care to economics. In medical diagnosis, for example, a doctor aims to explain a patient's symptoms by determining the diseases causing them. This is because causal relations, unlike correlations, allow one to reason about the consequences of possible treatments and to answer counterfactual queries. In this talk I will present some recent work done with my collaborators about how one can learn and reason with counterfactual distributions, and why this is importantly for decision making. In all cases I will strive to motivate and contextualise the results with real word examples.

# Contributed Talks

## Parallel session: Classical causal inference and causal constraints

**Speaker/authors:** *Leihao Chen, Onno Zoeter and Joris Mooij*
**Title:** **Modeling Latent Selection with Structural Causal Models**
**Abstract:** Selection bias is ubiquitous in real-world data, posing a risk of yielding misleading results if not appropriately addressed. We introduce a conditioning operation on simple Structural Causal Models (SCMs) to model latent selection from a causal perspective, which is a more general model class than acyclic SCMs. We show that the conditioning operation transforms an SCM with the presence of an explicit latent selection mechanism into an SCM without such selection mechanism, which encodes as much causal semantics of the selected subpopulation according to the original SCM as possible. Furthermore, we show that this conditioning operation preserves the simplicity, acyclicity, and linearity of SCMs, and commutes with marginalization. Thanks to these properties, combined with marginalization and intervention, the conditioning operation offers a valuable tool for conducting causal modeling, causal reasoning and causal model learning tasks within causal models where latent details have been abstracted away. Through illustrative examples on generalized Reichbach's principle, back-door criterion under selection, intrumental variables under selction, ID-algorithm for subpopulation and causal modeling under selection bias, we demonstrate how this abstraction process diminishes the complexity inherent in these three tasks, emphasizing both the theoretical clarity and practical utility of our proposed approach.

**Speaker/authors:** *Trung Phung, Jaron Lee, Opeyemi Oladapo-Shittu, Eili Klein, Ayse Gurses, Susan Hannum, Kimberly Weems, Jill Marsteller, Sara Cosgrove, Sara Keller and Ilya Shpitser*
**Title:** **Zero Inflation as a Missing Data Problem: a Proxy-based Approach**
**Abstract:** A common type of zero-inflated data has certain true values incorrectly replaced by zeros due to data recording conventions (rare outcomes assumed to be absent) or details of data recording equipment (e.g. artificial zeros in gene expression data).

Existing methods for zero-inflated data either fit the observed data likelihood via parametric mixture models that explicitly represent excess zeros, or aim to replace excess zeros by imputed values. If the goal of the analysis relies on knowing true data realizations, a particular challenge with zero-inflated data is identifiability, since it is difficult to correctly determine which observed zeros are real and which are inflated.

This paper views zero-inflated data as a general type of missing data problem, where the observability indicator for a potentially censored variable is itself unobserved whenever a zero is recorded. We show that, without additional assumptions, target parameters involving a zero-inflated variable are not identified. However, if a proxy of the missingness indicator is observed, a modification of the effect restoration approach of Kuroki and Pearl allows identification and estimation, given the proxy-indicator relationship is known.

If this relationship is unknown, our approach yields a partial identification strategy for sensitivity analysis. Specifically, we show that only certain proxy-indicator relationships are compatible with the observed data distribution. We give an analytic bound for this relationship in cases with a categorical outcome, which is sharp in certain models. For more complex cases, sharp numerical bounds may be computed using methods in Duarte et al. [2023].

We illustrate our method via simulation studies and a data application on central line-associated bloodstream infections (CLABSIs).

**Speaker/authors:** *Shashaank Khanna, Marina Maciel Ansanelli, Matthew Pusey and Elie Wolfe*

**Title: Which causal scenarios might 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 independencies) 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.

## Parallel session: Causality in Wigner's friend scenarios

**Speaker/authors:** *Yìlè Yīng, Marina Maciel Ansanelli, Andrea Di Biagio, Elie Wolfe and Eric Gama Cavalcanti*

**Title: Relating Wigner's Friend Scenarios to Nonclassical Causal Compatibility, Monogamy Relations, and Fine Tuning**

**Abstract:** Nonclassical causal modeling was developed in order to explain violations of Bell inequalities while adhering to relativistic causal structure and faithfulness – that is, avoiding fine-tuned causal explanations. Recently, a no-go theorem stronger than Bell's theorem has been derived, based on extensions of Wigner's friend thought experiment: the Local Friendliness (LF) no-go theorem. Here we show that the LF no-go theorem poses formidable challenges for the field of causal modeling, even when nonclassical and/or cyclic causal explanations are considered. We first recast the LF inequalities, one of the key elements of the LF no-go theorem, as special cases of monogamy relations stemming from a statistical marginal problem; we then further recast LF inequalities as causal compatibility inequalities stemming from a nonclassical causal marginal problem, for a causal structure implied by well-motivated causal-metaphysical assumptions. We find that the LF inequalities emerge from the causal modeling perspective even when allowing the latent causes of observed events to admit post-quantum descriptions, such as Generalised Probabilistic Theories (GPT) or even more exotic theories. We further prove that no nonclassical causal model can explain violations of LF inequalities without violating the No Fine-Tuning principle. Finally, we note that these obstacles cannot be

overcome even if one were to appeal to cyclic causal models.

**Speaker/authors:** *V. Vilasini and Mischa Woods*
**Title: A quantum circuit framework for extended Wigner's friend scenarios: logical and causal reasoning without objective events**
**Abstract:** Observers in quantum theory are typically treated classically, but Extended Wigner's Friend Scenarios (EWFS) go beyond by modeling agents as unitarily evolving quantum systems. This has led to no-go arguments suggesting significant implications for logic, causality, and events. In particular, Frauchiger and Renner argue that quantum agents reasoning about each others' knowledge can arrive at logical contradictions, while the Local-Friendliness theorem highlights a failure of absoluteness of observed measurement events in EWFS (under certain meta-physical assumptions) which poses challenges for causality. This raises a crucial question: Can we reliably make scientific predictions and reason consistently about the world when applying quantum theory universally, without assuming absolute measurement outcomes or violating causality?

We provide a positive answer by developing a comprehensive quantum circuit framework for EWFS that enables quantum agents to make consistent predictions and scientifically reason within a well-defined causal structure. By mapping Heisenberg cuts to distinct quantum channels, our framework resolves all Frauchiger-Renner-type paradoxes in quantum theory and ensures that fundamentally different and relational perspectives in an EWFS are consistently captured in a single quantum circuit without altering the principles of unitary quantum theory, the Born rule or classical logic. Furthermore, although our framework can consistently account for non-absolute events, we also demonstrate that an objective notion of measurement events emerges in real-world experiments where agents do not perform general quantum operations on each others' memories. This offers a unified approach to overcoming logical and causal challenges in EWFS and a concrete pathway for generalising quantum causal models and relativistic causality principles to EWFS without assuming absolute measurement events.

**Speaker/authors:** *Nick Ormrod and Jonathan Barrett*
**Title: Emergent classicality, relativistic causality, and quantum causal structure**
**Abstract:** This talk will explain how classical structures emerge out of a causal notion of decoherence, ultimately leading to a new interpretation of quantum theory. In this new interpretation, causal influences forming a poset play a crucial role. We thus connect the emergence of classicality with relativistic causality, and, further afield, with quantum gravity.

## Parallel session: Classical causal models

**Speaker/authors:** *Patrick Fraser*
**Title: What, in the world, is a violation of causal faithfulness?**
**Abstract:** The causal faithfulness condition (CFC), which says that every causal dependency produces probabilistic correlations between cause and effect, plays a central

role in causal modelling due to its utility in causal search. However, many causal dependencies seem to violate the CFC. This motivates the question: why are we warranted in assuming the CFC in the first place? The main justification for the CFC is found in a famous argument which shows that in the space of all possible causal models associated with a particular target system, the models which violate the CFC are measure zero and so epistemically negligible. Here, I show that the assumptions of this argument are unwarranted and misleading. Specifically, its success requires the introduction of significant structural content to the causal modelling framework that does not represent anything about the target systems being modelled. I show that if one corrects these assumptions, one obtains the opposite conclusion: CFC-violating models have non-zero measure, and are epistemically significant.

**Speaker/authors:** *Robin Lorenz and Sean Tull*
**Title: Classical causal models in string diagrams**
**Abstract:** The framework of causal models provides a principled approach to causal reasoning, applied today across many scientific domains. Here we present this framework in the language of string diagrams, interpreted formally using category theory. A class of string diagrams, called network diagrams, are in 1-to-1 correspondence with directed acyclic graphs. A causal model is given by such a diagram with its components interpreted as stochastic maps, functions, or general channels in a symmetric monoidal category with a 'copy-discard' structure (cd-category), turning a model into a single mathematical object that can be reasoned with intuitively and yet rigorously. Building on prior works by Fong and Jacobs, Kissinger and Zanasi, as well as Fritz and Klingler, we present diagrammatic definitions of causal models and functional causal models in a cd-category, generalising causal Bayesian networks and structural causal models, respectively. We formalise general interventions on a model, including but beyond do-interventions, and present the natural notion of an open causal model with inputs. We also give an approach to conditioning based on a normalisation box, allowing for causal inference calculations to be done fully diagrammatically. We define counterfactuals in this setup, and treat the problems of the identifiability of causal effects and counterfactuals fully diagrammatically.

The benefits of such a presentation of (classical) causal models lie in foundational questions in causal reasoning and in their clarificatory role and pedagogical value. This work aims to be accessible to different communities, from causal model practitioners to researchers in applied category theory and quantum foundations, and discusses many examples from the literature for illustration. As such it in particular seems a useful bridge between the formalisms and languages of the different communities meeting at Causalworlds. Overall, we argue and demonstrate that causal reasoning according to the causal model framework is most naturally and intuitively done as diagrammatic reasoning.

**Speaker/authors:** *Jonathan Barrett, Isaac Friend and Aleks Kissinger*
**Title: Identifying classical Markovian causal models from generalized observation**
**Abstract:** Process-theoretic ideas recently introduced for the study of causal identification for quantum processes also permit the study of new kinds of classical causal identification based on imperfect observations. By basing causal models on diagrams of combs, somewhat akin to single-world intervention graphs, we can flexibly formulate no-

tions of ”observational data” coming from whatever ”classical instruments” are available in a given inference scenario. And the process-theoretic generalization of ”copying” a variable, used to reason with the quantum Markov assumption, gives a way of calculating with conditional independencies even when the value of the variable to be conditioned on is imperfectly known. These innovations yield, among other generalizations of classical identification results, identifiability of any Markovian DAG-based causal model from certain observation schemes that imperfectly report variables' values and may also disturb those values.

This talk is also related to ongoing work with Rob Spekkens and Elie Wolfe.

## Parallel session: Indefinite causal order 1

**Speaker/authors:** *Ravi Kunjwal and Ognyan Oreshkov*
**Title: Generalizing Bell nonlocality without global causal assumptions**
**Abstract:** A Bell scenario can be conceptualized as a “communication” scenario with zero rounds of communication between parties. This constraint leads to a strict hierarchy of correlation sets in Bell scenarios, namely, classical, quantum, and nonsignaling. However, without any constraints on the number of communication rounds between the parties, they can realize arbitrary correlations by exchanging only classical systems. Here we consider a multipartite scenario where the parties can engage in at most a single round of communication, i.e., each party is allowed to receive a system once, implement any local intervention on it, and send out the resulting system once. While no global assumption about causal relations between parties is assumed in this scenario, we do make a causal assumption local to each party, i.e., the input received by it causally precedes the output it sends out. We then propose antinomicity as a notion of nonclassicality for correlations in such scenarios and prove the existence of a strict hierarchy of correlation sets classified by their antinomicity. When the parties do not send any output systems (i.e., in a nonsignaling scenario), antinomicity formally reduces to Bell nonlocality. Our introduction of antinomicity resolves a long-standing conceptual puzzle, namely, the failure of causal inequality violations as device-independent witnesses of nonclassicality. Although formally equivalent to causal inequality violations in bipartite scenarios, antinomicity is sufficient but not necessary for causal inequality violations in general.

This is based on joint work with Ognyan Oreshkov, `https://arxiv.org/abs/2307.02565`.

**Speaker/authors:** *Zixuan Liu and Giulio Chiribella*
**Title: Tsirelson bounds for quantum correlations with indefinite causal order**
**Abstract:** Quantum theory is in principle compatible with processes that violate causal inequalities, an analogue of Bell inequalities that constrain the correlations observed by a set of parties operating in a definite causal order. Since the introduction of causal inequalities, determining their maximum quantum violation, analogue to Tsirelson's bound for Bell inequalities, has remained an open problem. Here we provide a general method for bounding the violation of arbitrary causal inequalities, establishing limits on the correlations achievable by arbitrary local experiments and by arbitrary quantum processes with indefinite causal order. We prove that the maximum violation is generally smaller than the algebraic maximum, and determine Tsirelson-like bounds for a class of causal

inequalities including some of the most paradigmatic examples. Surprisingly, we find that the algebraic maximum of arbitrary causal inequalities can be achieved by a new type of processes that allow for information to flow in an indefinite temporal direction within the parties' laboratories.

**Speaker/authors:** *Raphaël Mothe, Alastair Abbott and Cyril Branciard*
**Title: Correlations and quantum circuits with dynamical causal order**
**Abstract:** Requiring that the causal structure between different parties is well-defined imposes constraints on the correlations they can establish, which define so-called causal correlations. Some of these are known to be "dynamical" in that their causal structure is not fixed a priori but is instead established on the fly, with for instance the causal order between future parties depending on some choice of parties in the past. Here we identify a new way that the causal order between the parties can be dynamical: with at least four parties, there can be some dynamical order, which can nevertheless not be influenced by the choice of past parties. This leads us to introduce an intermediate class of correlations with what we call non-influenceable causal order, in between the set of non-dynamical correlations and the set of general causal correlations. We then define analoguous classes of processes, considering the recently introduced classes of quantum circuits with classical or quantum control of the causal order—the latter being the largest class within the process matrix formalism known to have a clear interpretation in terms of coherent superpositions of causal orders. This allows us to formalise precisely in which sense certain quantum processes can have both indefinite and dynamical causal orders.

## Parallel session: Quantum causality and compositionality

**Speaker/authors:** *Robin Lorenz and Tein van der Lugt*
**Title: Causally faithful unitary circuit decompositions**
**Abstract:** Unitary maps play a distinguished role in the study of quantum causal structure, in quantum foundations and generally within quantum information theory. This is due to both their fundamental role within quantum theory and their special mathematical properties. In particular every unitary map U has a well-defined causal structure, given by which input systems can influence which output systems. At the face of it, this is the algebraic structure of U: it specifies how subalgebras evolve and interact with each other through U. An important question is to what degree one can also understand it purely as compositional structure – through the existence of a decomposition of the map that makes evident all causal constraints and shows how the influences are in fact mediated. This question has been studied over the past few years and has been argued to be pertinent to foundations and generally quantum information theory. Here we present one further piece in this general quest: a complete characterisation of those causal structures that imply a 'causally faithful' circuit decomposition for any unitary with that causal structure.

In this talk – with the interdisciplinary audience at Causalworlds in mind – we intend to not just share the characterisation result of this new piece of work, but first give a general introduction to the wider research programme of causal decompositions of unitary maps, as well as the different perspectives on, and motivations, to the technical questions at its centre.

**Speaker/authors:** *Augustin Vanrietvelde, Octave Mestoudjian and Pablo Arrighi*
**Title: Partitions in quantum theory, and causal decompositions of 1D Quantum Cellular Automata**
**Abstract:** In this dual submission, we present two tightly interlinked projects; the first one, besides being of foundational interest on its own, provides the necessary theory to prove the second one's main result. In the first project, we present a theory of partitions of quantum systems, i.e. of what it means to partition a "large" quantum system into smaller subsystems. Adopting the view that subsystems correspond to sub-C* algebras, we show how the inclusion of non-factor C* algebras as legitimate systems leads to subtleties whenever one is partitioning into more than three parts. Building on meaningful physical examples, we propose a sound mathematical definition of partitions into any number of subsystems and examine the main features of such partitions. Finally, we discuss the repesentability of partitioned systems, proving that some (for instance the ones that arise in fermionic quantum theory) admit no faithful representations as algebras of operators over a suitably partitioned Hilbert space. In the second project, we prove that 1D Quantum Cellular Automata (QCAs), a discretised model of quantum dynamics in Minkowski spacetime, admit causal decompositions, i.e. that they can always be written as sequences of nearest-neighbour interactions. This yields the first known constructive form for 1D QCAs (at any causality radius), and displays a powerful equivalence between causal structure and compositional structure in quantum theory.

**Speaker/authors:** *Bob Coecke and Robin Lorenz*
**Title: Causality of meaning in compositional language models (an invitation to collaborate)**
**Abstract:** This extended abstract concerns running natural language models for text on quantum computers, with the aim to learn things about that text that go beyond what may be possible on classical computers. In particular, within this context we consider how the study of causal structure in circuits in quantum foundations relates to the study of causal properties of texts. The correspondence between quantum foundations and natural language goes back to the origins of the compositional models of meaning, namely categorical quantum mechanics [1, 6]. This is also an initial motivation for considering a quan- tum computer as a fairly natural habitat for these models. That questions of the 'causal structure' of meaning flows in text circuits cannot be ignored is essentially due to the compromises imposed by efficient implementations on a quantum computer. This is, above all, an invitation to collaborate.

## Parallel session: Quantum reference frames

**Speaker/authors:** *Chris Fewster, Daan Janssen, Leon Loveridge, Kasia Rejzner and James Waldron*
**Title: Quantum reference frames, measurement schemes and the type of local algebras in quantum field theory**

**Abstract:** We develop an operational framework, combining relativistic quantum measurement theory with quantum reference frames (QRFs), in which local measurements of a quantum field on a background with symmetries are performed relative to a QRF. This yields a joint algebra of quantum-field and reference-frame observables that is invariant under the natural action of the group of spacetime isometries. For the ap- propriate class of quantum reference frames, this algebra is parameterised in terms of crossed products. Provided that the quantum field has good thermal properties (expressed by the existence of a KMS state at some nonzero temperature), one can use modular theory to show that the invariant algebra admits a semifinite trace. If furthermore the quantum reference frame has good thermal behaviour (expressed in terms of the properties of a KMS weight) at the same temperature, this trace is finite. We give precise conditions for the invariant algebra of physical observables to be a type $II_1$ factor. Our results build upon recent work of Chandrasekaran, Longo, Pen- ington and Witten [JHEP 2023, 82 (2023)], providing both a significant mathematical generalisation of these findings and a refined operational understanding of their model.

**Speaker/authors:** *Josh Kirklin and Philipp A. Höhn*
**Title: Fighting non-locality with non-locality: microcausality and boundary conditions in QED**
**Abstract:** It has been claimed that non-locally dressed observables in gauge theories and gravity necessarily violate microcausality. We revisit this claim, pointing out that the status of microcausality in a given theory is intimately linked with the boundary conditions one chooses to impose. Working within the example of QED in a finite region, we demonstrate that an appropriate choice of boundary conditions renders a large family of boundary-dressed observables local to a timelike codimension 1 bulk surface, in a way that is consistent with microcausality. A key feature of these boundary conditions is that they constrain the edge mode sector of the theory in a non-local way — but from the point of view of large-gauge-invariant bulk physics, they are equivalent to ordinary local boundary conditions. The choice of boundary conditions is linked with the existence of a preferred dynamical frame for making microcausally consistent observations in the bulk. We explain how multiple possible choices of such a frame may be made within the same theory, each consistent with a version of microcausality — but that the observables relative to one frame do not necessarily commute with spacelike separated observables relative to the other frame. Thus, the status of microcausality is frame-dependent. Next, we describe a canonical quantization of the theory, and show that microcausality is upheld. Here we make the interesting observations that the vacuum is frame-dependent, and that there is not a unique causally local net of von Neumann algebras relevant for an AQFT treatment of the theory; rather there is a separate one for each choice of frame. Finally, we discuss the lessons to be learned from our QED case study, and the prospects for the generalization of our results to non-Abelian gauge theories and gravity.

**Speaker/authors:** *Ofek Bengyat, Caslav Brukner and Marios Christodoulou*
**Title: Quantum Permutations as Quantum Coordinate Transformations**
**Abstract:** Quantum permutations, or 'magic unitaries', are a mathematical object of interest in operator theory, intended to generalize the notion of permutations to the quantum [1]. In this study, we explore the possibility of these entities merging the two kinds

of symmetries of modern physics — the unitary symmetry of Quantum Mechanics and the coordinate symmetry of General Relativity — to encapsulate a concept of quantum coordinates. We show that these entities can be thought of as quantum coordinate transformations on a Hilbert space with an introduced descriptive redundancy — a degeneracy in the position operator. This allows to relativize quantum notions such as superposition, entanglement or mixedness by transferring them from the physical system to its quantum coordinate description. In a second part, we further show that the quantum-controlled unitaries known in the Quantum Reference Frame (QRF) literature are a type of magic unitaries. However, magic unitaries of this form are known in the mathematical literature as not truly quantum, since the projections on the control system all commute [1]. Truly quantum magic unitaries, on the other hand, allow to generalize this notion of QRF transformations by introducing into them the essence of quantum theory: non-commutativity. We show that those generalizations can allow — in contrast to the quantum-controlled unitaries — something akin to e.g. controlling on both position and momentum within one unitary transformation. Such unitaries may be of use in further understanding the scope of the quantum notion of reference systems.
[1] M. Weber, Quantum permutation matrices, Complex Anal. Oper. Theory 17 (2023).

## Parallel session: Quantum causal models

**Speaker/authors:** *Daniel Centeno Díaz and Elie Wolfe*
**Title: Quantum Latents: Distinguishing causal scenarios with indistinguishable classical analogs**
**Abstract:** Since causal inference techniques were initially developed for causal structures with only classical latent nodes, causal scenarios where some latent nodes have other latent nodes as parents are overlooked. This omission is due to the existence of an exogenization procedure that relies on the ability to clone classical information, enabling the construction of a DAG that is observationally equivalent (i.e., produces the same set of possible observed correlations) but includes only exogenous latent nodes, meaning no latent node has latent parents. However, this procedure fails when quantum resources are introduced, as quantum information cannot be cloned. Consequently, a large family of causal structures involving non-classical latent nodes remains unexplored.

In this work, we explore when the presence of multiple layers of latent nodes (i.e., latent nodes with latent parents) in a DAG affects the set of probability distributions compared to the set of distributions derived from the exogenous version of the DAG. We also study whether different scenarios with two layers of latent nodes, originating from the same one-layer DAG, are observationally equivalent. Finally, we investigate the significance of the classicality or non-classicality of intermediate latent nodes for the probabilities that can be observed. Additionally, we obtain some entropic monogamy relations. Although this is not a new concept, they are the first entropic monogamy relations of this flavour

**Speaker/authors:** *Carla Ferradini, Victor Gitton and V. Vilasini*
**Title: Cyclic causal modelling with a graph separation property in classical and quantum theories**
**Abstract:** Connecting causal explanation to correlations is crucial in science. To achieve

this, causal modelling and inference frameworks have been developed to link correlation and causation. These models use directed graphs to represent causal relationships, where nodes and edges denote systems and transformations within a theory. The causal modelling literature often focuses on acyclic causal graphs, where a well-defined probability rule can be used to evaluate correlations among observed variables and useful graph-theoretic properties, such as the d-separation theorem, apply. However, in cyclic causal models these results do not always hold. While classical cyclic causal models have been studied, finding graph-separation properties which hold in the general cyclic case is an active area of research. In quantum scenarios, existing frameworks have only considered a subset of consistent cyclic causal models, and graph-separation properties for cyclic quantum models have not been previously studied. In this work, we propose a causal modelling framework applicable to any (but a handful of pathological) quantum and classical cyclic causal models and present a graph separation property, p-separation that we prove to be sound and conjecture to be complete for all cyclic classical and quantum causal models on finite and discrete systems. We achieve this by showing that cyclic causal models can be mapped to acyclic models with post-selection, using the post-selected quantum teleportation protocol. This lays a foundation for building more general cyclic causal discovery algorithms and importing interesting open problems and techniques for acyclic informational networks (such as the marginal problem, and device-independent certification of non-classicality) to cyclic causal structures and networks.

**Speaker/authors:** *Ardra Kooderi Suresh, Markus Frembs and Eric Cavalcanti*
**Title: A Semantics for Counterfactuals in Quantum Causal Models**
**Abstract:** We introduce a formalism for the evaluation of counterfactual queries in the framework of quantum causal models, by generalising the three-step procedure of abduction, action, and prediction in Pearl's formalism of counterfactuals in classical causal models. To this end, we define a suitable extension of Pearl's notion of a 'classical structural causal model', which we denote analogously by 'quantum structural causal model'. We show that every classical structural causal model can be extended to a quantum structural causal model, and prove that counterfactual queries that can be formulated within a classical structural causal model agree with their corresponding queries in the quantum extension – but the latter is more expressive. Counterfactuals in quantum causal models come in different forms: we distinguish between *active* and *passive* counterfactual queries, depending on whether or not an intervention is to be performed in the action step. This is in contrast to the classical case, where counterfactuals are always interpreted in the active sense. Another distinction is that unlike in the classical formalism of Pearl, in our semantics counterfactuals do not always have truth values, due to the underlying indeterminism of quantum causal models – which represents a precise sense in which a notion of "counterfactual definiteness" is violated in the quantum case. We argue however that this is not the particularly nonclassical feature of quantum counterfactuals, but rather another remarkable result: unlike in the classical case, *quantum counterfactuals allow for counterfactual dependence without causal dependence*, shedding new light on the nature of quantum causality.

## Parallel session: Indefinite causal order 2

**Speaker/authors:** *Maarten Grothus, Alastair A. Abbott and Cyril Branciard*
**Title: Routing Quantum Control of Causal Order**
**Abstract:** In recent years, various frameworks have been proposed for the study of indefinite causal order. In this contribution, we connect Quantum Circuits with Quantum Control of Causal Order (QCQCs), a broad class of physical supermaps, with Routed Quantum Circuits (RQC), which can be used to decompose all purifiable processes established so far into a finer-grained routed circuit decomposition to illustrate the information flow within the respective process. Specifically, we prove that for any number of parties, starting from a single routed graph, one can obtain any QCQC with this number of parties by using an appropriate fleshing out. We detail these constructions explicitly. We conclude by pointing out how this construction can be useful to tackle various open problems within the field of indefinite causal order.

**Speaker/authors:** *Hlér Kristjánsson, Tatsuki Odake, Satoshi Yoshida, Philip Taranto, Jessica Bavaresco, Marco Quintino and Mio Murao*
**Title: Simulating the quantum switch using causally ordered circuits requires at least an exponential overhead in query complexity**
**Abstract:** Quantum theory is consistent with a computational model permitting black-box operations to be applied in an indefinite causal order, going beyond the standard circuit model of computation. The quantum switch—the simplest such example—has been shown to provide numerous information-processing advantages. Here, we prove that the action of the quantum switch on two $n$-qubit quantum channels *cannot* be simulated deterministically and exactly by any causally ordered quantum circuit that uses $M$ calls to one of the two channels, if $M \leq \max(2, 2^n - 1)$. This demonstrates the first exponential enhancement in quantum query complexity provided by indefinite causal order.

**Speaker/authors:** *Samuel Fedida, Anne-Catherine de la Hamette, Viktoria Kabel and Caslav Brukner*
**Title: Knot invariants and indefinite causal order**
**Abstract:** We explore indefinite causal order between events in the context of quasiclassical spacetimes in superposition. We propose new quantifiers to measure the degree of indefiniteness of the causal order for an arbitrary finite number of events and spacetime configurations. By establishing diagrammatic and knot representations of the causal order between events, we find that the definiteness or maximal indefiniteness of the causal order is topologically invariant. This reveals an intriguing connection between the field of quantum causality and knot theory. If time permits, we will also provide an operational encoding of indefinite causal order and discuss how to incorporate a measure of quantum coherence into our classification.

## Parallel session: Network non-locality 1

**Speaker/authors:** *Xiangling Xu, Marc-Olivier Renou and Laurens Ligthart*
**Title: Two convergent NPA-like hierarchies for the quantum bilocal scenario**

**Abstract:** Characterising the correlations that arise from locally measuring a single part of a joint quantum system is one of the main problems of quantum information theory. The seminal work [M. Navascués et al, NJP 10,7,073013 (2008)], known as the NPA hierarchy, reformulated this question as a polynomial optimisation problem over non-commutative variables and proposed a convergent hierarchy of necessary conditions, each testable using semidefinite programming. More recently, the problem of characterising the quantum network correlations, which arise when locally measuring several independent quantum systems distributed in a network, has received considerable interest. Several generalisations of the NPA hierarchy, such as the Scalar Extension [Pozas-Kerstjens et al, Phys. Rev. Lett. 123, 140503 (2019)], were introduced while their converging sets remain unknown. In this work, we introduce a new hierarchy, prove its equivalence to the Scalar Extension, and characterise its convergence in the case of the simplest network, the bilocal scenario, and explore its relations with the known generalisations.

**Speaker/authors:** *<u>Maria Ciudad-Alañón</u>, Emanuel-Cristian Boghiu, Paolo Abiuso and Elie Wolfe*
**Title: Escaping the Shadow of Bell's Theorem in Network Nonlocality**
**Abstract:** The study of causal models with quantum resources naturally raises certain open questions. It is in particular natural to ask when it is possible to guarantee that a network nonclassical behavior is also nontrivial, i.e., not merely a logical consequence of quantum advantage in the standard Bell scenario. In our work, as also noted by others, we highlight that many significant correlations in networks can be traced back to standard Bell nonclassicality. The latter question has led to various studies and proposed definitions on what one should consider as genuine network nonclassicality. We revisited those works and argue why their definitions are insufficient to identify Bell-unrelatedness. Moreover, we propose a novel notion of network nonclassicality which we name Minimal Network Nonlocality (MNN). Our definition is constructed so as to ensure that MNN correlations cannot be simulated via underlying embeddings of standard Bell nonclassicality. To illustrate the limitations of previous definitions as well as examples of our novel definition, we study in detail what is arguably the simplest non-trivial causal scenario that manifest nonclassicality, namely 3-chain scenario involving 3 parties and two independent sources (Fig. 1b). This scenario, already in its simplest form (with output cardinalities of 2-2-2 and input cardinalities of 2-1-2), present a rich hierarchy and phenomenology of nonclassical correlations (compatible with quantum theory) that has not been previously studied.

**Speaker/authors:** *<u>Davide Poderini</u>, Ranieri Nery, George Moreno, Santiago Zamora, Pedro Lauand and Rafael Chaves*
**Title: Observational-Interventional Bell Inequalities**
**Abstract:** Generalizations of Bell's theorem, particularly within quantum networks, are now being analyzed through the causal inference lens. However, the exploration of interventions, a central concept in causality theory, remains significantly unexplored. In this work we give an initial step in this direction, by analyzing the instrumental scenario and proposing novel hybrid Bell inequalities integrating observational and interventional data. Focusing on binary outcomes with any number of inputs, we obtain the complete characterization of the observational-interventional polytope, equivalent to a Hardy-like

Bell inequality albeit describing a distinct quantum experiment. To illustrate its applications, we show a significant enhancement regarding threshold detection efficiencies for quantum violations also showing the use of these hybrid approach in quantum steering scenarios.

## Parallel session: Causality in spacetime physics

**Speaker/authors:** *Jan Głowacki*
**Title:** Towards Relational Quantum Field Theory
**Abstract:** In this talk, I want to introduce a newly developed relational approach to relativistic quantum physics steaming from the theory of operational quantum reference frames (QRFs). I will begin by introducing the QRF framework in the context of Special Relativity by taking the Poincare group as the underlying symmetry structure. From these considerations, a novel and relational perspective on the notion of a quantum field emerges, which is then extended to curved geometries by replacing the Poincare group with a Lorentz bundle. The formalism is also capable of dealing with indefinite background geometries when formulated in the context of the frame bundles. The talk is based on a recent preprint `http://arxiv.org/abs/2405.15455`. I have also attached a pdf file with a research proposal motivating this program.

**Speaker/authors:** *Wayne Myrvold*
**Title:** Making Sense of Relativistic Causality Condition
**Abstract:** Relativistic causality conditions, such as the microcausality condition typically imposed on relativistic quantum field theories, impose nontrivial constraints on theories. On the other hand, concerns have been raised about whether causality considerations can be brought to bear on fundamental physical theories. A solution of the dynamical equations of the theory specifies what happens at all times, past, present, and future. It is not clear what it would mean for one part of the system to change the state of another, or to talk of cause-effect relations, or of sender-receiver signalling relations. II will argue that these worries can be alleviated.

**Speaker/authors:** *Chris Heunen and Nesta van der Schaaf*
**Title:** Relativistic Concepts in Point-Free Spaces
**Abstract:** The existence of infinitesimal points in spacetime manifolds is considered philosophically unsatisfactory. We propose the use of "ordered locales" as a first step towards a framework of point-free spacetimes. It was showed in earlier work that ordered locales form a suitable point-free generalisation of ordered topological spaces, so in particular of spacetimes with their canonical causal order. In this talk we show how several important notions from relativistic causality theory may be developed in the point-free setting for ordered locales. Mainly, we define a notion of "causal coverage," which forms a type of generalised Grothendieck topology, and show this naturally gives rise to domains of dependence. We also discuss how "ideal points" in spacetime can equivalently be described as the points of a certain locale, which hints towards a general point-free causal boundary construction.

## Parallel session: Network non-locality 2

**Speaker/authors:** *Pedro Lauand, Davide Ponderini, Rafael Rabelo and Rafael Chaves*
**Title:** **Quantum non-classicality in the simplest causal network**
**Abstract:** Bell's theorem is arguably the most important result of the foundations of quantum theory. From a modern perspective, we can describe Bell's theorem as the mismatch between the predictions of quantum theory and classical theories under some specific causal assumption. In the last decade, the generalization of Bell's theorem to causal networks has sparked new applications and new kinds of nonclassical behavior and, consequently, the field of causal inference has gained much attention from the physics community. These generalizations prompt us with a fundamental inquiry: what is the simplest scenario leading to the incompatibility between quantum correlations and the classical theory of causality? Here we demonstrate that quantum non-classicality is possible in a network consisting of only three dichotomic variables, without the need of the locality assumption neither external measurement choices. We also show that the use of interventions, a central tool in the field of causal inference, significantly improves the noise robustness of this new kind of non-classical behaviour.

**Speaker/authors:** *Tamás Kriváchy*
**Title:** **Limitations of causal models of the triangle network, in the symmetric subspace and beyond**
**Abstract:** The study of correlation through the lens of an underlying network-structured causal model is relevant both foundationally and in applications. However, even for small networks, such as a triangle network, it is difficult to characterize the set of correlations that are reproducible. We demonstrate how intuition and numerical, neural-network based techniques can be used to map the set of achievable distributions that are symmetric, and how one can conjecture inequalities that bound these distributions. Moreover, we adapt rigidity-based arguments to prove that a significant region of the symmetric simplex is infeasible using classical triangle-causal models. With this, we contribute to the analytic understanding of a regime of distributions which previously remained elusive.

## Parallel session: Interface of information-theoretic and relativistic causality

**Speaker/authors:** *Matthias Salzger and John Selby*
**Title:** **A decompositional framework for process theories in spacetime**
**Abstract:** There has been a recent surge in interest in quantum foundations coming from incorporating ideas from general relativity and quantum gravity. In particular, the field of indefinite causal order has emerged and is now an important research topic in its own right. Many of the tools that we use in quantum foundations and information, are, however, totally agnostic as to the underlying spacetime in which the quantum systems live. To give a practical example, whenever we draw a quantum circuit we are not taking into account the connectivity of the physical qubits which will realize this circuit. 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 implementations of a process, which are decompositions of the process. A process is then embeddable if one of its implementations can be embedded in such a way that all the processes are localized and all wires follow time-like paths. The set of all implementations of a process is a rather unwieldy object but we show that there exists a subset with useful properties which tells us everything we need to know about the remaining implementations and the embeddability of a process. We call this subset minimal representatives. Future directions include plans to define and analyse the compositional structure of the framework more rigorously, extending the framework to indefinite causal structures, studying exotic causal influence and using the minimal representatives to probe the decompositional structure of quantum theory and beyond.

**Speaker/authors:** *Maarten Grothus and V. Vilasini*
**Title: Characterizing Signalling: Connections between Causal Inference and Space-time Geometry**
**Abstract:** Causality is pivotal to our understanding of the world, presenting itself in different forms: information-theoretic and relativistic, the former linked to the flow of information, the latter to the structure of space-time. Leveraging a framework introduced in PRA, 106, 032204 (2022), which formally connects these two notions in general physical theories, we study their interplay. Here, information-theoretic causality is defined through a causal modelling approach. First, we improve the characterization of information-theoretic signalling as defined through so-called affects relations. Specifically, we provide conditions for identifying redundancies in different parts of such a relation, introducing techniques for causal inference in unfaithful causal models (where the observable data does not "faithfully" reflect the causal dependences). In particular, this demonstrates the possibility of causal inference using the absence of signalling between certain nodes. Second, we define an order-theoretic property called conicality, showing that it is satisfied for light cones in Minkowski space-times with $d > 1$ spatial dimensions but violated for $d = 1$. Finally, embedding our causal models in space-time and imposing no superluminal signalling (NSS), we investigate the behavior of the information-theoretic and spatio-temporal causal orders. Specifically, we find that when an information-theoretic causal model is embedded compatibly with NSS in a space-time, the two types of causal orders can behave differently and need not align. However, we prove that in conical space-times and in causal models that are faithful, a useful parallel emerges between these order relations. This indicates a connection between informational and geometric notions of causality, and offers new insights for studying the relations between the principles of NSS and no causal loops in different space-time geometries and theories of information processing.

# Flash Talks

**Speaker/authors:** *Pablo Arrighi, Amelia Durbec and Matt Wilson*
**Title: Generalized tensors and partial traces over quantum networks**
**Abstract:** Considerations of core features of quantum theory and general relativity lead to a natural expectation for quantum theories of gravity - that the configuration of spacetime may be subject to the quantum superposition principle. In a superposition of spacetimes however, what constitutes a good notion of locality or causality (and so prohibition on superluminal influence)? Prior to this question is an even more fundamental question, what even constitutes a good notion of subsystem?

Motivated by these questions, we generalise quantum operations to act over entire quantum superpositions of graphs. In this setting, it is possible for nodes to be in a quantum superposition of being connected or not. For instance, Alice may be both a neighbour of Bob, and not, in a quantum superposition. We then ask what it means for an operation to be causal in the presence of such quantum superpositions of quantum geometries. For instance, can Alice signal to Bob in such a strange situation? To answer these questions we provide robust notions of locality and causality, by means of a detour in which tensor products and traces are generalised to subsystems in which the neighborhood around a point is subject to the quantum superposition principle.

**Speaker/authors:** *Victor Gitton and Renato Renner*
**Title: The Elegant Joint Measurement is nonlocal in the triangle network**
**Abstract:** Proving the incompatibility of a distribution with a classical causal structure is generally a difficult task, due to the non-convex nature of the problem. This task needs to be tackled to provide examples of quantum nonlocality, i.e., examples of distributions that are compatible with a quantum causal structure but incompatible with the corresponding classical causal structure. Even in the simple triangle network, few examples of quantum nonlocality are known. A candidate is the the Elegant Joint Measurement (EJM) distribution, a highly symmetric distribution that can be obtained using quantum states and measurements in the triangle network. This distribution has been conjectured to be nonlocal 6 years ago. Motivated by this long-standing conjecture about a seemingly simple problem, we developed a highly-optimized implementation of the inflation technique, which allows to certify the incompatibility of a distribution with a causal structure. Our implementation allowed us to produce a computer-assisted proof of nonlocality for the EJM distribution, thereby opening new avenues to advance the state of the art for certifying causal incompatibility in general classical causal structures.

**Speaker/authors:** *Ryszard Paweł Kostecki*
**Title: Paraconsistency of relativistic nonsignalling, and some other features of causal spectral toposes**
**Abstract:** Topos-theoretic approaches to general relativity and to quantum theory have been developed in parallel, yet separately from each other, each one with its own merits and challenges. We propose a new approach, aimed to partially bridge this gap. It is based on the representation of orthocomplemented (not necessarily orthomodular) lattices in spectral presheaves, widely enhancing the range of applicable syntactic (logical) and semantic (geometric) toolbox, and featuring the appearance of bi-intuitionistic and relevant paraconsistent logics. First, we consider lattices formed by the causally closed regions of

lorentzian space-times, allowing for considerable variability of the definition of causal closure/nonsignalling (and, thus, of the corresponding lattices). Neither global hyperbolicity nor the absence of closed time-like curves is assumed. Nonsignalling becomes represented, via outer daseinisation, by the relevant paraconsistent negation. Among the new structures appearing in this extension of relativistic causality are: 1) the Zarycki–Lawvere boundary operator, satisfying the Leibniz rule, acting on the sheaf representations of causal sublattices; 2) the monotone correspondence between the strength of the paraconsistent negation and the strength of the constraints on nonsignalling. Secondly, we apply an analogous construction to the lattice of sub-W*-algebras of a W*-algebra, equipped with an algebraic commutant as the orthocomplementation. Next, we generalise Haag's postulate for the setting of vacuum algebraic q.f.t., by replacing an orthohomomorphism from the causal lattice to the lattice of sub-W*-algebras by a Galois connection. Finally, we define a topos-theoretic vacuum algebraic q.f.t. as a functor that joins all of the above constructions into a commutative diagram. This way we establish a relationship between orthocomplementation in a causal lattice, commutant in a W*-algebra, and relevant paraconsistent negation in a spectral presheaf. We also formulate a topos-theoretic generalisation of Haag's duality, and show a natural interpretation of this setting in terms of the del Rio–Kraemer–Renner resource-theoretic framework.

**Speaker/authors:** *Marina Maciel Ansanelli*, *Elie Wolfe and Robert Spekkens*
**Title: Everything that can be learned about a causal structure with latent variables by observational and interventional probing schemes**
**Abstract:** What types of differences among causal structures with latent variables are impossible to distinguish by statistical data obtained by probing each visible variable? If the probing scheme is simply passive observation, then it is well-known that many different causal structures can realize the same joint probability distributions. Even for the simplest case of two visible variables, for instance, one cannot distinguish between one variable being a causal parent of the other and the two variables sharing a latent common cause. However, it is possible to distinguish between these two causal structures if we have recourse to more powerful probing schemes, such as the possibility of intervening on one of the variables and observing the other. Herein, we address the question of which causal structures remain indistinguishable even given the most informative types of probing schemes on the visible variables. We find that two causal structures remain indistinguishable if and only if they are both associated with the same mDAG structure (as defined by Evans (2016)). We also consider the question of when one causal structure dominates another in the sense that it can realize all of the joint probability distributions that can be realized by the other using a given probing scheme. (Equivalence of causal structures is the special case of mutual dominance.) Finally, we investigate to what extent one can weaken the probing schemes implemented on the visible variables and still have the same discrimination power as a maximally informative probing scheme.

**Speaker/authors:** *Charles Alexandre Bédard*
**Title: From Locality to Causality in the Heisenberg Picture**
**Abstract:** As it provides a local and complete description of quantum systems, the Heisenberg picture yields many insights about locality. But what does it teach us about causality? I show that developing causal structures with the framework of Heisenberg-

picture descriptions naturally yields the quantum causal structures of ABHLS2017 and BLO2019.

**Speaker/authors:** *Alastair Abbott, Victor Barizien, Cyril Branciard, Pavel Sekatski and Jean-Daniel Bancal*

**Title: Self-testing quantum supermaps, with an application to the quantum switch**

**Abstract:** Self-testing provides the most complete description of a system under study that is achievable in a black-box setting, i.e. in a situation where neither an internal description of the system is available, nor of the additional devices used to analyse it. For this reason, self-testing is sometimes considered the strongest form of certification for quantum systems. Such trustworthy certification has been demonstrated for quantum states, measurements and channels, and plays a key role in certifying the result of quantum computations performed in the circuit model.

Recently, there has been growing interest in higher order quantum operations, known as "quantum supermaps" or "processes". Quantum supermaps have numerous applications in computation, communication, or even describing strategies in quantum metrology. Particular interest has been aroused by the fact that some quantum supermaps describe computations combining operations without any well-defined causal order between them, describing a potential new paradigm for quantum information processing beyond the standard causally ordered approach. The archetypal supermap of this kind is known as the quantum switch. Although its causal indefiniteness cannot be certified directly in a device-independent way, several recent works show that this can be done in certain network scenarios. It has remained unclear, however, whether it could be self-tested in any way. Indeed, the notion of self-testing has not yet been considered at all in the context of quantum supermaps.

Here, we discuss how the self-testing of supermaps could be defined and identify two forms of self-testing statements for supermaps in black-box network settings. We apply these approaches to the quantum switch, identifying a procedure exhibiting statistics only compatible with a process implementing the quantum switch, thereby self-testing it. We discuss the operational perspective that this test provides on causally non-separable processes.

**Speaker/authors:** *Timothée Hoffreumon and Ognyan Oreshkov*

**Title: Higher-order Quantum Processes are Characterized by the Logic of their Signaling Relations**

**Abstract:** Quantum transformations of quantum transformations, here called higher-order quantum processes (HOQP), are the mathematical structures necessary for indefinite causal order. Recently, efforts have been made towards a general characterization of these processes, and several frameworks have been proposed. We identify four ways to improve the existing frameworks: 1) comparing any two classes of HOQP can be computationally difficult; 2) assessing the possible causal relations that a given kind of HOQP can feature is not direct from its characterization; 3) there exist discrepancies in the mathematical definition of a higher-order map across the literature; 4) there are no systematic ways to switch between the frameworks nor to relate them.

From the theoretical developments needed to fix these four points, a 'unifying frame-

work' to characterize higher-order quantum processes emerges. This framework is based on channel-state duality and the utilization of superoperator projectors: any class of HOQP is associated with such a projector. Their use makes the framework 'unifying' in the sense that projectors can actually be used in all of the previous approaches, making it their common thread.

The key assumption of our approach consists of substituting causal relations with signaling relations, in which case the algebra of projectors is shown to exactly reflect the possible signaling relations of the HOQP they are characterizing. This algebra is furthermore shown to be a Boolean lattice in a way that can be interpreted as (almost a model for linear) logic. This leads to the core message of our work: higher-order processes are characterized by the logic of their signaling relations. This implies, on the one hand, that every class of processes can be described through its signaling relations. And, on the other hand, that comparing two classes of HOQP can be done solely through logic relations.

**Speaker/authors:** *Julian Wechs* and *Ognyan Oreshkov*

**Title: Subsystem decompositions of quantum circuits and transformations between causal perspectives**

**Abstract:** One can conceive of quantum processes in which the causal order between multiple parties is indefinite. A central question is which of these processes have a physical interpretation, and whether indefinite causal order can be realised within standard physics. It has been found that some causally indefinite processes can take place as part of standard quantum evolutions, described by acyclic quantum circuits, if the latter are described with respect to subsystems that can be delocalised in time. Here, we provide a general framework to describe transformations between subsystem decompositions of quantum circuits. On this basis, we analyse transformations between different causal perspectives in the quantum switch, which turn out to be inequivalent from the subsystem perspective we developed.

**Speaker/authors:** *Michael Miller*

**Title: Cluster Decomposition and Two Senses of Isolability**

**Abstract:** In the framework of quantum field theory, one finds multiple load-bearing locality and causality conditions. One of the most important is the cluster decomposition principle, which requires that scattering experiments conducted at large spatial separation have statistically independent results. The principle grounds a number of features of quantum field theory, especially the structure of scattering theory. However, the statistical independence required by cluster decomposition is in tension with the long-range correlations characteristic of entangled states. In this paper, we argue that cluster decomposition is best stated as a condition on the dynamics of a quantum field theory, not directly as a statistical independence condition. This redefinition avoids the tension with entanglement while better capturing the physical significance of cluster decomposition and the role it plays in the structure of quantum field theory.

**Speaker/authors:** *Tales Rick Perche* and *Eduardo Martín-Martínez*

**Title: The geometry of spacetime from quantum measurements**

**Abstract:** We provide a setup by which one can recover the geometry of spacetime from

local measurements of quantum particle detectors coupled to a quantum field. Concretely, we show how one can recover the field's correlation function from measurements on the detectors. Then, we are able to recover the invariant spacetime interval from the measurement outcomes, and hence reconstruct a notion of spacetime metric and causality. This suggest that quantum particle detectors are the experimentally accessible devices that could replace the classical 'rulers' and 'clocks' of general relativity while providing an operational notion of causal relations between events.

# Posters (accepted and will be presented)

**Authors:** *Amrapali Sen, Matthias Salzger and Łukasz Rudnicki*
**Title:** **An operational analysis of superluminal observers**
**Abstract:** The theory of relativity is generally assumed to provide us with a speed limit for all interactions. 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, Ekert and Dragan have argued that in a world with superluminal observers local determinism is impossible. In this way, the inherent randomness of quantum theory could be not just reconciled with the theory of relativity but the former can be understood as a consequence of the latter. The aim of our work is to develop an operational framework that allows for superluminal observers in a theory independent way. We analyze several scenarios which hint at superluminal observers and superluminal Lorentz transformations being inconsistent with fundamental physical principles and experimental procedures known to be possible in the real world regardless of the underlying theory. This also sheds new insights into why we possibly should not observe superluminal observers as the connection between relativity and quantum theory.

**Authors:** *Andrea Di Biagio, Richard Howl, Časlav Brukner, Carlo Rovelli and Marios Christodoulou*
**Title:** **When does relativistic locality imply subsystem locality?**
**Abstract:** Relativity and quantum information theory use different notions of locality. In relativity, locality is tied to spacetime regions while, in QI, locality is based on the notion of subsystems. What is the precise relation between these notions? In this talk we will investigate this question for a simple quantum field theory model and see how relativistic causality implies subsystem locality—approximately. We will then comment on whether we can expect this result to generalise to more realistic QFTs, and how it relates to no-go theorems about low-energy quantum gravity.

Based on `https://arxiv.org/abs/2305.05645`.

**Authors:** *David O'Connell*
**Title:** **Quantum Fields on Non-Hausdorff Backgrounds**
**Abstract:** Non-Hausdorff spacetimes are a type of spacetime in which points may be "doubled" or superimposed on top of each other. Although seemingly unwieldly, non-Hausdorff spacetimes may always be constructed by gluing together ordinary spacetimes

along isometric open subspaces. In this poster we will leverage this observation to define QFTs on non-Hausdorff backgrounds by "gluing" quantum fields defined on ordinary globally-hyperbolic spacetimes. We provide a categorical narrative in terms of the Locally-Covariant QFT formalism, as well as the concrete example of Klein-Gordon fields on non-Hausdorff Trousers space. The existence of the latter is in contradistinction to the Hausdorff trousers space, where such fields are ill-behaved.

**Authors:** *Gabriele Carcassi and Christine A. Aidala*
**Title: Generalized ensemble spaces**
**Abstract:** We present an approach we are developing to define a theory of physical states that applies to all physical systems. Classical and quantum systems are seen as further specializations of this structure, while some properties/theorems are proven in the more abstract setting. The fundamental axioms of this framework can be justified on physical grounds, so that all mathematical objects have a clear physical correspondence. The work connects ideas from convex spaces, information geometry, and other fields.

**Authors:** *Gecia Bravo-Hermsdorff, Lee Gunderson and Kayvan Sadeghi*
**Title: Causal Worlds for Growing Networks**
**Abstract:** Fully-exchangeable models of networks (such as graphons) frequently have difficulty describing real-world networks. For example, they are unable to describe sparse networks, essentially treating them all as equivalent to the empty network. While various modifications have been suggested to cope with this issue, many of the hallmarks of real-world networks do not sit comfortably in this framework. However, real-world networks do not (typically) pop into existence fully-developed. Much like the assumption of a "Last Universal Common Ancestor" in evolutionary biology, or the "Past Hypothesis" in cosmology, to better understand the state of a system at any given point in time, it is often insightful to model the history leading up to that point. This temporal evolution naturally introduces a notion of causality. In this work, we provide a taxonomy for causal graphical models over dyads between a growing set of nodes. By systematically searching the space of possible causal models for growing networks, we find statistically-streamlined models for growing networks that easily exhibit many of the emergent features characteristic of real-world networks.

**Authors:** *Ghislain Fourny*
**Title: On the interpretation of quantum theory as games between physicists and nature played in Minkowski spacetime**
**Abstract:** In 2019, we introduced games in Minkowski spacetime as a generalization of game theory to special relativity that subsumes games in normal form (spacelike separation) and games in extensive form (timelike separation). Many concepts including Nash equilibria naturally extend to spacetime games. We also emphasized the importance of these games to model quantum experiments such as Bell experiments and more generally any adaptive measurements. Subsequent work suggested to formalize a special case of such games in terms of strategy presheaves. In the case that measurements have a unique causal bridge and if a natural cover is taken, we show that the two frameworks are isomorphic to each other and provide complementary perspectives. Spacetime games provide a visual and intuitive framework that also captures the distinction between joint

experiments and either-or experiments, so that they are rich enough in their causal structure to imply a natural cover for the corresponding causal contextuality scenario. Based on this observation, we suggest to define the strategy presheaf directly based on the pure strategies (and restrictions thereof) of the spacetime game, and we show that the sheaf property obtains for the games at hand. The argument is rather simple and similar to event sheaves for the flat case. Finally, we explain how, in the other direction, the failure of the sheaf property on strategy distribution presheaves is consistent with our previous argument that Nash game theory is not compatible with quantum physics. This shows that the insights of the two frameworks, taken together, can contribute positively to the advancement of the field of quantum foundations.

**Authors:** *Giulio Chiribella, Lorenzo Giannelli and Carlo Maria Scandolo*
**Title: Bell Nonlocality in Classical Systems Coexisting with other System Types**
**Abstract:** The realistic interpretation of classical theory assumes that every classical system has well-defined properties, which may be unknown to the observer but are nevertheless part of reality and can, in principle, be revealed by measurements. Here we show that this interpretation can, in principle, be falsified if classical systems coexist with other types of physical systems. To make this point, we construct a toy theory that (i) includes classical theory as a subtheory and (ii) allows classical systems to be entangled with another type of systems, called anticlassical. We show that our toy theory allows for the violation of Bell inequalities in two-party scenarios where one of the settings corresponds to a local measurement performed on a classical system alone. Building on this fact, we show that measurement outcomes in classical theory cannot, in general, be regarded as predetermined by the state of an underlying reality.

**Authors:** *Gustavo Pimentel, Victoria Wright and Hippolyte Dourdent*
**Title: Certifying indefinite causal orders in the quantum switch via contextuality**
**Abstract:** In the process matrix formalism [1], a process is said to be causally non-separable if it cannot be decomposed as a convex combination of process matrices compatible with a definite causal order. The canonical example of a quantum process displaying causal non-separability is known as the quantum switch (QS) [2]. In some cases, causal non-separability can be witnessed in a device independent way via the violation of causal inequalities. However, it has been shown that these cannot be violated by correlations obtained via the QS[3, 4].

Recent works have derived a new type of inequality, known as the DRF inequality, which requires an additional locality assumption [5, 6]. Statistics produced by the quantum switch are able to violate this inequality, allowing for indefinite causal orders to be device-independently certified, i.e. by only considering measurement statistics. This result demonstrates that the measurement outcomes obtained by the spacelike separated party are correlated in a nonclassical way with the causal order in the QS.

In this work we investigate an alternative certification which relies on the operational equivalence of preparation procedures rather than on the additional locality assumption [7, 8]. To do so, we use an invertible map between contextuality and non-locality scenarios [9]. As a result, a new kind of inequality is derived, whose violation by the quantum switch

provides a witness of nonclassical control of causal order. This result demonstrates that indefinite causal orders in the QS can be certified semi-device-independently in a simple “prepare-measure” scenario.

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**Authors:** *Haruki Emori and Hiroyasu Tajima*

**Title: Error and Disturbance as Irreversibility with Applications: Unified Definition, Wigner—Araki—Yanase Theorem and Out-of-Time-Order Correlator**

**Abstract:** Since the proposal of Heisenberg’s uncertainty principle, error and disturbance of quantum measurements have been fundamental notions in quantum mechanics. As is often the case when defining physical quantities in quantum physics, there is no single way to define the error and the disturbance, and many independent definitions of them have been given. Here we establish a novel formulation of the error and disturbance as special cases of the irreversibility of quantum processes, which unifies the existing formulations of them. Our formulation enables us to apply the knowledge of irreversibility in stochastic thermodynamics and quantum information theory to the error and disturbance in quantum measurements. To demonstrate this strength, we extend the quantitative Wigner—Araki—Yanase theorem, the universal restriction on a measurement implementation under some conservation laws, to the errors and disturbances of arbitrary definitions and processes. Furthermore, we reveal that our formulation covers the out-of-time-orderd-correlator, the measure of quantum chaos in a quantum many-body system, as the irreversibility in analogy with the measurement context, and provide its experimental evaluation method.

**Authors:** *Haruki Emori, Masanao Ozawa and Akihisa Tomita*

**Title: Disturbance Evaluation Circuit in Quantum Measurement**

**Abstract:** The performance evaluation of quantum measurements is essential for the advancement of quantum information processing. Here, we propose a novel evaluation method for the quantum root-mean-square disturbance. Furthermore, we demonstrate the effectiveness of our method in comparison with the existing approaches, known as the three-state method (TSM) and the weak measurement method (WMM), through a simulation and experiment using a quantum computer. The results capture the key features of the TSM, WMM, and our method, providing insights into the strengths and

limitations of these methods.

**Authors:** *Hippolyte Dourdent and Antonio Acin*
**Title: Breaking Local Indistinguishability with Superposition of Classical Communications**
**Abstract:** In Local Operations and Classical Communication (LOCC) protocols, each party can apply arbitrary quantum operations to their system, while the inter-partite communication remains classical [1]. LOCC cannot generate entangled states from product states, raising the fundamental question of what measurements can be made with this resource. Unlike quantum states, measurements can be “nonlocal” without entanglement, meaning there are measurements in perfectly distinguishable and unentangled product-state bases that are locally unmeasurable, unable to be perfectly discriminated with LOCC [2]. These ensembles are said to exhibit the so-called “quantum nonlocality without entanglement” (QNLWE), or local indistinguishability.

On the other hand, it has been shown that the set of local operations with classical communications in a causal loop coincides with the set of separable operations [3] ; and more generally that quantum interactions with closed-timelike curves (CTCs) allow to distinguish perfectly any set of quantum states [4]. Classical communications without causal orders might be considered as a potential candidate to circumvent the local indistinguishability of QNLWE measurements. However, such causal structures are deemed pathological, due to their potential for logical paradoxes.

The “process matrix formalism” [5] was introduced to describe global processes while assuming ordinary local physics laws remain valid. Initially introduced as a generalisation of quantum communications, a classical, deterministic version of formalism [6] was proposed as a possible model for CTCs. A simple characterisation was found for all Npartite processes [7] and, remarkably, examples of logically consistent classical processes without global past where identified for $N \geq 3$. In [8], it was shown that the first tripartite example of such classical processes - the Lugano process [9] - can be used with local operations to perform the SHIFT measurement, i.e. perfectly discriminate the states of a QNLWE ensemble. Furthermore, multipartite generalizations of the the Lugano process can be systematically transformed into multiqubit ensembles that exhibit QNLWE, allowing local indistinguishability to be traded with definite causal order (causality of correlations), despite maintaining classical communication.

In our work, we surprisingly demonstrate that the SHIFT measurement can also be performed by local operations with a quantum control of two classical communication channels, known as the “quantum switch” [10]. Our set up involves sending one qubit of the SHIFT state to be measured to Alice, one to Bob, and using the last one as a control of the classical communications between Alice and Bob’s operations, which is measured by a third final party, Fiona. The causally nonseparable distributed measurement [11] based on the SHIFT ensemble thus has two realisations with local operations and classical communications : using the Lugano process or the quantum switch.

Unlike the Lugano process, the quantum switch, despite being causally nonseparable, cannot produce noncausal correlations [12,13]. Our result may thus initially seem to be in contradiction with the previously established correspondence between noncausality and QNLWE, but, under analysis, this conflict is illusory. By examining the Lugano process realization of the SHIFT measurement in terms of time-delocalized subsystems [14,15], we demonstrate its equivalence to a classical switch circuit between two parties

(Alice and Bob), controlled by the qubit from the SHIFT basis received by the third party (Charlie), who is "time-delocalized", i.e. acts "before and after" Alice and Bob. By judiciously dividing Charlie into two parties representing a global past and a global future, the Lugano process performing the SHIFT measurement can then be transformed into a quantum switch. More generally, we define the class of local operations with superposition of classical communications (LOCCSup), and show that all QNLWE multiqubit ensembles associated with a multipartite generalized Lugano process can also be measured with LOCCSup (work in progress, this is at least true for the generalisation in [16]), thus shedding new light on the relation between indefinite causal order and local indistinguishability.

**Authors:** *Jaron Lee, Amir Ghassami and Ilya Shpitser*
**Title:** **A General Identification Algorithm For Data Fusion Problems Under Systematic Selection**
**Abstract:** Identification of causal effects can be hampered by confounding, selection bias, and other complications. Data fusion is one approach to addressing these difficulties, through the inclusion of auxiliary data on the population of interest. Such data may measure a different set of variables, or be obtained under different experimental or observational conditions than the primary dataset. In particular, selection of experimental units into different datasets may be systematic; similar difficulties are encountered in missing data problems. However, existing methods for combining datasets either do not consider this issue, or assume simple selection mechanisms. In this paper, we propose a general approach, based on graphical causal models, for causal inference from data on the same population that is obtained under different experimental conditions. Our framework allows both arbitrary unobserved confounding, and arbitrary selection processes into different experimental regimes in our data. We describe how systematic selection processes may be organized into a hierarchy similar to censoring processes in missing data: selected completely at random, selected at random, and selected not at random. Finally, we provide a novel general identification algorithm for interventional distributions in this setting.

**Authors:** *Julien Bouchat and Yves Caudano*
**Title:** **On the analogy between the Goos-Hänchen effect in classical optics and the quantum tunnelling time problem**
**Abstract:** A quantum weak measurement consists of (1) a preparation of a quantum state, (2) a weak interaction of the quantum system with a meter to probe an observable without disturbing much the system state, (3) a projective measurement of the system called post-selection that sets the system final state, and (4) a meter measurement conditional on successful post-selection. Observations in quantum weak measurements depend on a complex number called a weak value. Weak values are called anomalous when they do not correspond to any possible expectation value of the observable of interest. When the prepared and post-selected states are nearly orthogonal, anomalous weak values enable probing small parameters with increased sensitivity, as they become very large. Weak value amplification enables probing fundamental optical phenomena, such as the Goos-Hänchen effect. The Goos-Hänchen shifts are tiny deviations, in the incidence plane, from the laws of geometrical optics, which are observed when applying these laws to the

central axes of incident and reflected light beams. The axis of the reflected beam does not generally emanate from the surface at the incidence point of the impinging beam (spatial shift) and the angle of the axis of the reflected beam does not generally match exactly the incidence angle (angular shift). We are exploring opportunities provided by weak measurements and weak values to discuss fundamental optical phenomena related to the Goos-Hänchen shifts. In particular, we study the classical spatial and angular optical shifts in connection to the quantum tunnelling time problem (where the group velocity of the wavepacket appears superluminal), for the case of a frustrated total internal reflection.

**Authors:** *Laurens Walleghem, Rui Soares Barbosa, Matthew Pusey and Stefan Weigert*
**Title: Strong contextuality and Wigner's friends: refining the Frauchiger–Renner paradox**
**Abstract:** We investigate Wigner's friend-type paradoxes in quantum theory, starting from the Frauchiger–Renner (FR) paradox [Nat. Comms. 9, 3711 (2018)]. The FR paradox was proposed to argue for the inconsistency of the naive use of quantum theory to describe itself, by means of a scenario where agents model other agents quantumly and reason about each other's knowledge in such a way that a contradiction arises. We observe that logical locality (à la Hardy) is the key ingredient powering the FR paradox, and we provide a stronger paradox based on the strongly nonlocal GHZ–Mermin scenario. As opposed to the FR paradox, this GHZ–FR paradox does not require post-selection nor any reasoning by observers that are modelled quantumly; only classical observers use the Born rule and make statements that they communicate classically, resulting in a contradiction. Measurement protocols similar to that of the GHZ–FR paradox were presented by Żukowski and Markiewicz in [Phys. Rev. Lett. 126, 130402 (2021)] and by Leegwater in [arXiv:1811.02442 (2018)], but with a different analysis and weaker no-go theorems, due to the additional part of our paradox involving reasoning steps à la FR. If one accepts the universality of quantum theory including superobservers, to resolve the GHZ–FR paradox these no-go theorems suggest a natural extension of Peres' dictum. This principle can be used to correctly state predictions, but its implementation may depend on the interpretation of quantum mechanics one favours. Finally, we also shortly comment on the relation with the Local Friendliness no-go theorem and explain how to construct extended Wigner's friend paradoxes based on contextuality that is not nonlocality, as we have shown in other work with R. Wagner, D. Schmid and Y. Yıng [arXiv:2310.06976 (2023)].

This work is in final phase of revision and will appear soon on the arxiv.

**Authors:** *Lionel Jeevan Dmello, Laurens T. Ligthart and David Gross*
**Title: Entanglement-swapping in generalised probabilistic theories, and iterated CHSH games**
**Abstract:** While there are theories that show stronger bipartite non-locality than quantum mechanics, there are causal structures in which they no longer out-perform QM at certain information processing tasks. One such situation is the CHSH value at the extremities of a n-partite line scenario. This is because, this causal structure involves both bipartite states and measurements. And, all known examples of such theories have a strictly smaller set of measurements than QM. In this paper we set out to investigate

if it is indeed true that post-quantum theories are bounded by Tsirelson's bound, for CHSH games in the n-partite line scenario, in the framework of generalised probabilistic theories (GPTs). In particular, we introduce the iterated CHSH game, which quantifies the power of a GPT to preserve non-classical correlations, in terms of the largest CHSH value obtainable between the extremities, in the n-partite line setting. Our main result is the construction of a GPT that achieves the maximal CHSH value of 4 in the iterated CHSH game. This addresses a question about the optimality of quantum theory for such games recently raised in the literature. One challenge faced when treating this problem is that there seems to be no general framework for constructing GPTs which are consistent in the n-partite line structure. Therefore, we introduce an algorithmic construction that turns a bipartite GPT into a multipartite GPT which supports the n-partite line, if consistently possible.

**Authors:** *Matt Wilson and Nick Ormrod*
**Title: On the Origin of Linearity and Unitarity in Quantum Theory**
**Abstract:** We reconstruct the transformations of quantum theory using a formal postulate motivated by relativistic causality principles. This postulate states that transformations should be "locally applicable", an abstract and theory-neutral formalisation of prohibition on superluminal signalling and of commutativity with space-like separated observations which we demonstrate recovers the linear unitary maps from pure quantum theory, as well as the completely positive, trace-preserving maps from mixed quantum theory. Notably, in the pure case, linearity with respect to the superposition rule is derived rather than assumed (and without any continuity assumptions).

**Authors:** *Pascal Rodríguez-Warnier*
**Title: On causality and free energy**
**Abstract:** The present talk aims to give philosophical insights into the interrelation between causality and thermal physics through a concept that has not been widely explored as a bridge between the two, namely, free energy. I argue that using free energy enables understanding the conditions for causal processes and state transitions in an operationally intuitive way. Additionally, it provides a clearer notion of the arrow of causation, through the idea of dissipation of free energy (or work dissipation), than, for instance, entropy and its different meanings in different contexts. I adopt a methodological operationalism and I take resource theories as a particular instance of them. This enables my conceptual results to bring insights into how causality at different levels relate, with special emphasis on theoretical and experimental physics, as well as helping to understand why causal inferences are possible.

**Authors:** *Peter Bierhorst*
**Title: Consistency and Causality of Interconnected Nonsignalling Resources**
**Abstract:** This paper examines networks of n measuring parties sharing m independent nonsignaling resources that can be locally wired together. A specific framework is provided for studying probability distributions arising in such networks, and the framework is used to directly prove some accepted, but often only implicitly invoked, facts about the paradigm including soundness, nonsignaling, and causality of the induced distribution.

For an application, we study inequalities that witness genuine three-party nonlocality according to the local-operations-shared-randomness definition, and show how most examples can be derived from the inequality of Mao, Li, Yu, and Fan [Phys. Rev. Lett. 129:150401 (2022)]

**Authors:** *Redi Haderi, Aziz Kharoof and Cihan Okay*
**Title: Unifying causality and contextuality in the framework of simplicial distributions**
**Abstract:** This work explores the unification of causality and contextuality within the framework of simplicial distributions. Quantum measurements yield probability distributions exhibiting contextual behavior, an essential computational resource. Existing frameworks, such as those based on sheaf theory and cohomology, have been encapsulated by simplicial distributions, which describe families of probability distributions indexed by simplices of a space. Our current work extends simplicial distributions to include causality by adopting a bundle perspective. By employing categorical tools, we present a mapping scenario construction that captures the adaptivity of measurements and allows for the natural construction of causal scenarios. A deeper study of our constructions will lead to a fruitful interplay of causality, contextuality, and topology.

**Authors:** *Saba Etezad-Razavi and Daine Danielson*
**Title: In quantum gravity, who's quantum clock Is right?**
**Abstract:** In local quantum field theory, any physical process inherits a definite causal ordering among Cauchy surfaces in any given foliation. In (perturbative) quantum gravity, however, the gauge redundancies of gravity suggest that only relationally-defined notions of time are physically meaningful in the presence of timelike isometries of the background manifold. Previous authors [1,2] have shown that, by modeling the presence of a physical, quantum mechanical clock, a suitable notion of "relational time" can be defined for systems to which the clock is gravitationally coupled. In the presence of multiple such quantum mechanical clocks, however, situations can arise in which no single preferred notion of time presents itself vis a vis gauge-invariant observables. We study the (possibly indefinite) causal structure of joint correlations between two "local laboratories," each following a protocol relative to its own, respective, quantum mechanical clock.

References:

[1] Giacomini et al. 2017, arXiv:1712.07207

[2] Witten 2023, arXiv:2303.02837

**Authors:** *Vanessa Brzić*
**Title: Higher order quantum transformations for known input state**
**Abstract:** In the context of higher-order quantum computing, one is usually considering the question of transforming arbitrary $d$-dimensional unitary $U_d$ into $f(U_d)$, assuming the output transformation $f(U_d)$ to be a valid quantum transformation on an arbitrary *unknown* state. Nevertheless, in practice, we often do know the state which we prepare and on which we want to implement our unitary. In this work, we, therefore, consider a problem of transforming unknown unitary quantum operations $U_d \mapsto f(U_d)$, assuming that the output transformation is applied on an arbitrary but *known* input state $\rho$. We will consider the cases where the function $f$ is *homomorphism* or *antihomomorphism*,

more concretely, we will consider the cases of transposition $f(U_d) = U_d^T$, conjugation $f(U_d) = U_d^*$, inversion $f(U_d) = U_d^{-1}$ and $f(U) = U$ with a *delayed input state* (storage and retrieval scenario). Our results show that, in most cases, knowing the input allows us to increase the performance and success probabilities when compared to the unknown state case scenarios. For the case $k = 1$ call of the unitary operation $U_d$ we solve analytically for supermaps obtaining optimal performances. When $k = 3$ calls are available, we show that deterministic and exact implementation of qubit unitary transposition and inversion is possible. We also show that, in tasks with multiple calls, sequential strategies outperform parallel ones, whereas indefinite causality provides an advantage in some instances of the problem.

**Authors:** *Wataru Yokojima, Marco Túlio Quintino, Akihito Soeda and Mio Murao*
**Title: Consequences of preserving reversibility in quantum superchannels**
**Abstract:** Similarly to quantum states, quantum operations can also be transformed by means of quantum superchannels, also known as process matrices. Quantum superchannels with multiple slots are deterministic transformations which take causally independent quantum operations as inputs and are enforced to respect the laws of quantum mechanics but the use of input operations may lack a definite causal order. While causally ordered superchannels admit a characterization in terms of quantum circuits, a similar characterization of general superchannels in terms of standard quantum objects with a clearer physical interpretation has been missing. In this paper we provide a mathematical characterization for pure superchannels with two slots (also known as bipartite pure processes), which are superchannels preserving the reversibility of quantum operations. We show that the reversibility preserving condition restricts all pure superchannels with two slots to be either a causally ordered quantum circuit only consisting of unitary operations or a coherent superposition of two pure causally ordered circuits. The latter may be seen as a generalization of the quantum switch, allowing a physical interpretation for pure two-slot superchannels. An immediate corollary is that purifiable bipartite processes cannot violate device-independent causal inequalities.

# Other accepted posters (not being presented)

**Authors:** *Dragos Cristian Manta, Jithendaraa Subramanian, Mansi Rankawat and Tristan Deleu*
**Title: A latent variable model with Generative Flow Networks**
**Abstract:** Structure learning aims to uncover the underlying structure of probabilistic models, such as Bayesian Networks, by identifying dependencies and relationships among a set of causal variables to construct a Directed Acyclic Graph (DAG) that accurately represents these interactions. The exponential number of possible DAGs, even for a small set of causal variables, presents significant computational challenges. Additionally, in many applications, the causal variables are unobserved or latent and must be inferred from low-level data, further complicating the structure learning problem. This problem has been studied through various approaches, including Bayesian methods, machine learning algorithms, constraint-based techniques, and information-theoretic methods. In this work, we focus on the Bayesian approach, leveraging Bayesian inference principles to learn a posterior distribution over DAGs and causal variables.

Recently, a new class of probabilistic models called GFlowNets has been proposed, combining the principles of flow networks and generative modeling to learn complex data distributions. GFlowNets generate samples sequentially by modeling the flow of probability mass through a network of states, making them well-suited for exploring the vast search space of possible DAG structures. DAG-GFN [1] utilizes GFlowNets for Bayesian structure learning by inferring a distribution over DAGs with the assumption that causal variables are fully observed. In this work, we propose extending DAG-GFN to infer a joint distribution over both DAGs and latent variables given the observed data, which we call latent-DAG-GFN. This is accomplished through a two-step process: first, we traverse the state-space of DAGs and construct the graph by sequentially adding edges until a special action signifies the completion of DAG construction; in the second phase, we sample the latent variables corresponding to the sampled DAG. Our experiments on simpler settings of a few latent causal variables show that for both continuous and discrete latent causal variables, latent-DAG-GFN can accurately approximate the joint posterior distribution given observed data.

**Authors:** *Edwin Peter Lobo, Sahil Gopalkrishna Naik, Samrat Sen, Ram Krishna Patra, Manik Banik and Mir Alimuddin*
**Title: Certifying beyond quantumness of locally quantum no-signaling theories through a quantum-input Bell test**
**Abstract:** Physical theories constrained with local quantum structure and satisfying the no-signaling principle can allow beyond-quantum global states. In a standard Bell experiment, correlations obtained from any such beyondquantum bipartite state can al- ways be reproduced by quantum states and measurements, suggesting the local quantum structure and no-signaling to be the axioms to isolate quantum correlations. In this Letter, however, we show that if the Bell experiment is generalized to allow local quantum inputs, then beyond-quantum correlations can be generated by every beyond-quantum state. This gives us a way to certify the beyond quantumness of locally quantum no-signaling theories and in turn suggests the requirement of additional information principles along with the local quantum structure and no-signaling principle to isolate quantum correlations. More importantly, our work establishes that the additional principle(s) must be sensitive to the quantum signature of local inputs. We also generalize our results to multipartite locally quantum no-signaling theories and further analyze some interesting implications.

**Authors:** *Francisco Pipa*
**Title: Quantum theory, non-relationalism, and its compatibility with relativistic causality**
**Abstract:** It's often considered that in order for quantum theory (QT) to be compatible with relativistic causality, we either MOD) need to modify the fundamental equations of QT like some collapse or gravity-causes collapse theories, SUP) adopt a superdeterministic or retrocausal approach to QT or REL) adopt a relationalist approach to QT in which measurement outcomes are relative for example to worlds, systems, or reference frames. Concerning the approach REL), it has been suggested by others that quantum causal models should be modified to account for various scenarios in order to be able to provide a local common cause explanation of the extended Wigner's friend scenarios via a relationalist approach. I will present a new approach to quantum theory (QT) called En-

vironmental Determinacy-based Quantum Theory (EnDQT), which doesn't adopt strategies MOD), SUP), and REL), while advocating that we shouldn't adopt the approach *). Finally, I will draw some lessons from EnDQT that can be applied to other approaches that aim to make QT compatible with relativistic causality.

**Authors:** *Jacob Barandes*
**Title: New Prospects for a Causally Local Formulation of Quantum Theory**
**Abstract:** All arguments about local causality in quantum theory require grappling with the meaning of causation in some way. Many examples of such arguments, including the EPR paper, Bell's 1964 no-go theorem, and the GHZ theorem, rely explicitly on an interventionist conception of causation. According to this conception of causation, to say that B causally influences A is to say that an abstract agent intervening on B produces a change in A. It is unsurprising that these arguments rely on interventionism, because according to the standard textbook formulation of quantum theory, all connections between the mathematical ingredients of quantum theory and its empirical predictions occur through interventions consisting of measurements.

The trouble is that interventions by abstract agents are clearly not microphysically fundamental things. In simpler words, interventions are not phrased fully 'at the level of the atoms.' It is therefore far from clear how to infer from interventionist arguments anything definitive about local causality in a microphysically fundamental theory like quantum theory.

One of the virtues of Bell's updated 1975 no-go theorem is that it moves beyond an interventionist conception of causation by replacing measurement interventions with local matters of fact, which Bell calls "local beables." However, Bell's 1975 arguments do not introduce an alternative definition of causation. Instead, Bell proceeds indirectly by positing what he claims is a necessary, downstream consequence of any reasonable theory of local causation. This supposedly necessary consequence is a factorization condition based on Reichenbach's principle of common causes.

To be more precise, Bell's 1975 paper argues that if A and B are spacelike-separated local beables that are statistically correlated, then there must exist a rich enough set of other local beables C in the overlap of the past light cones of A and B that conditioning on C screens off the correlations between A and B, in the sense that the joint probability distribution for A and B, when conditioned on C, factorizes. Assuming that one can put aside several well-known loopholes, Bell shows that any formulation of quantum theory satisfying his factorization criteria leads to the CHSH inequality, a generalization of Bell's original 1964 inequality, both of which are known to be violated in quantum theory. Bell therefore concludes that quantum theory, according to any empirically adequate formulation, entails nonlocal causation.

The strongest present-day arguments that quantum theory exhibits nonlocal causation therefore rest on the credibility of Bell's 1975 claim that any reasonable theory of local causation should satisfy his factorization criteria. Bell, however, was fully aware that this claim was tenuous, and humbly warned that it "should be viewed with the utmost suspicion."

The most obvious way to challenge Bell's criteria for local causality would be to provide a non-interventionist, microphysical definition of causal influences, as well as an explicit condition for those causal influences to be local in nature, together with a proof that quantum theory is locally causal according to those new criteria.

Remarkably, by stepping outside the wave-function paradigm, one can reformulate quantum theory in terms of old-fashioned configuration spaces together with 'unistochastic' laws, which feature a novel form of non-Markovian behavior known as 'indivisibility.' These unistochastic laws take the form of directed conditional probabilities, which turn out to provide a hospitable foundation for defining microphysical causal relationships.

This unistochastic reformulation provides quantum theory with a simpler and more transparent axiomatic foundation, plausibly resolves the measurement problem, and deflates various exotic claims about superposition, interference, and entanglement. It also opens the door to new methods for quantum simulations, possible generalizations of quantum theory beyond the Hilbert-space paradigm, and perhaps even previously unexplored approaches to quantum gravity.

Making use of this reformulation of quantum theory, one can introduce a new principle of local causality that arguably improves on Bell's criteria, and show directly that systems that remain at spacelike separation cannot exert causal influences on each other, according to that new principle. These results therefore lead to a general hidden-variables interpretation of quantum theory that is arguably compatible with local causality.

**Authors:** *Jef Pauwels, Stefano Pironio and Armin Tavakoli*
**Title: Information capacity of quantum communication under natural physical assumptions**
**Abstract:** Quantum communication has been studied under various physical assumptions on the emitted states. We discuss how these assumptions are conceptually and formally related. We then identify to which all others relax, corresponding to a limitation on the accessible information. This motivates us to study the optimal state discrimination probability of a source subject to these various physical assumptions. We derive general and tight bounds for states restricted by their dimension, vacuum component, overlap, the magnitude of higher-dimensional signals and the experimenter's trust in their device. Our results constitute a first step towards a more unified picture of semi-device-independent quantum information.

**Authors:** *José Manuel Rodríguez Caballero*
**Title: A causal loop model of terrorist activity**
**Abstract:** The study explores the application of Dragon-King theory to global terrorism, emphasizing the causal structure underlying terrorist activities. The goal is to develop a model that explains how certain conditions lead to extreme events (Dragon-Kings) and to use this understanding to inform counterterrorism strategies.

The research introduces a self-reinforcing DAG to represent the causal structure of terrorism. This graph is finite and directed, with no cycles. It includes nodes representing variables related to terrorist activities and a subset of self-reinforcing loops that capture feedback mechanisms. These loops illustrate how past terrorist attacks increase the likelihood of future attacks.

The model uses a Bayesian network to describe the probabilistic relationships between variables in the DAG. It incorporates self-reinforcing loops to show how terrorism can escalate over time due to internal feedback processes. This network helps in understanding the complex interplay between different factors influencing terrorist activities.

The self-reinforcing process models the probability of terrorist attacks as a sequence

of random variables. This process introduces memory effects, where the likelihood of an event is influenced by prior occurrences. It captures the essence of Dragon-King scenarios, reflecting how the probability of attacks increases after initial events.

For regions like France, a memoryless model is used, where events occur independently of each other. Conversely, for regions like Israel, a self-reinforcing model is applied. This model shows how past attacks significantly raise the probability of future events, indicating the presence of Dragon-King events.

Simulations analyze annual terrorist dynamics using the proposed models. In France, a memoryless model with a constant probability of attacks shows no Dragon-King events. In Israel, a self-reinforcing model with parameters reflecting increased probabilities after attacks indicates the presence of Dragon-King events.

The self-reinforcing DAG model provides a robust framework for understanding the causal dynamics of terrorism. By identifying feedback loops and probabilistic relationships driving extreme events, the model offers insights into the conditions leading to Dragon-Kings. This understanding is crucial for developing effective counterterrorism strategies to anticipate and mitigate the risks of such extreme events

**Authors:** *Nicolas Courtemanche and Claude Crépeau*
**Title: Nonlocal Games with a Promise**
**Abstract:** Nonlocal games are a type of protocol commonly used for the study of nonlocality. Many protocols devised to be resistant against quantum adversaries use this model. The study of nonlocality has also uncovered a theoretical but powerful resource, supra-quantum no-signaling channels, which can also be used in nonlocal games. As attempts are made to create secure protocols against these theoretical no-signalling channels, a framework in which they can be defined mathematically has also been established. In this work, we explore a new way of defining the distribution of inputs of nonlocal games which uses multi-prover interactive proofs as their underlying structure. We introduce the notion of promises, meaning that we change the probability of occurrence of certain inputs and observe the changes in potential real-world security of our protocol following those changes. We will show how the importance of this notion has appeared to us as we studied nonlocal games involving no-signalling channels. We use as our main example a 3-prover bit commitment protocol from a paper by S. Fehr and M.J. Fillinger to illustrate the impact that the application of a promise on the protocol's inputs would have on its security, reducing it from no-signalling-resistant to quantum-resistant. We conclude our work by presenting a reworked security model of nonlocal games which allows for promises on games and channels, and show the impact it may have on the security of these games.

**Authors:** *Nikolaos Kollas, Sandra Gewehr, Spiros Mourelatos and Ioannis Kioutsioukis*
**Title: Robust measures of causal interaction in non-linear systems**
**Abstract:** Utilizing an extension of Pearson's correlation in the case of random vectors, we improve the empirical dynamic modeling causal analysis of non-linear systems. We demonstrate the effectiveness of the use of such an extension by applying it to a system of interacting populations, described by a coupled logistic map, as well as to a real world example of a paramecium-didinium protozoan system. In both examples it is shown that the causal analysis based on the extended metric is more robust under changes of

the embedding dimension of the reconstructed manifold compared to the usual method of measuring the correlation between observed and predicted values of a single vector component making it more reliable for inferring the causal relationship between variables.

**Authors:** *Saheli Mukherjee, Bivas Mallick, Sravani Yanamandra, Samyadeb Bhattacharya and Ananda G. Maity*

**Title: Interplay between the Hilbert-space dimension of the control system and the memory induced by quantum SWITCH**

**Abstract:** Several recent studies have demonstrated the utility of the quantum SWITCH as an important resource for enhancing the performance of various information processing tasks. In a quantum SWITCH, the advantages appear significantly due to the coherent superposition of alternative configurations of the quantum components which are controlled by an additional control system. Here we explore the impact of increasing the Hilbert-space dimension of the control system on the performance of the quantum SWITCH. In particular, we focus on a quantifier of the quantum SWITCH through the emergence of non-Markovianity and explicitly study their behavior when we increase the Hilbert-space dimension of the control system. We observe that increasing the Hilbert-space dimension of the control system leads to the corresponding enhancement of the non-Markovian memory induced by it. Our study demonstrates how the dimension of the control system can be harnessed to improve the quantum SWITCH-based information processing or communication tasks.

**Authors:** *Sahil Gopalkrishna Naik, Samrat Sen, Ram Krishna Patra, Ananya Chakraborty, Mir Alimuddin, Pratik Ghoshal and Manik Banik*

**Title: Multiparty Local Bit Hiding: Non-Causal Advantage and Super-Activation of Causal Indefiniteness**

**Abstract:** Super-activation, or super-additivity, refers to the *sui generis* phenomenon where the collective utility of multiple resources surpasses the sum of their individual contributions. Several instances of this phenomenon have been recognized while processing information using the static resource of quantum states and the dynamic resource of quantum channels. Notably, both of these resources, as described within the standard framework of quantum theory, assume a fixed and definite causal structure. The recently introduced framework of process matrices, however, accommodates the notion of indefinite causal structure. In this study, we present evidence of super-activation phenomenon for causal indefiniteness. To achieve this, we introduce an information theoretic task called multiparty Local-Bit-Hiding (LBH). As we demonstrate, while performing the LBH task, agents with access to indefinite causal processes generally outperform those embedded in a definite causal structure. Furthermore, we provide pairs of bipartite process matrices, neither of which is individually more effective than definite causal processes for the bipartite LBH task; but their combination, a logically valid new process matrix, achieves nontrivial success in the task. Apart from this we also find that there exists qubit processes that give non trivial success in LBH task without any entanglement assistance. We also explore higher-dimensional and multipartite variants of the task, thereby shedding light on various unexplored aspects of indefinite process matrices.

**Authors:** *Shubhayan Sarkar*

**Title:** **Causal links between operationally independent events 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. The work is published now at Phys. Rev. A 109, L040202(2024) `https://doi.org/10.1103/PhysRevA.109.L040202.`

**Authors:** *Stefano Gogioso and Nicola Pinzani*

**Title:** **Quantifying Causal Separability**

**Abstract:** In this paper we associate convex polytopes of compatible behaviours to a general class of causal assumptions, and formalise a quantitative measure of causal separability expressed as the solution of a linear program. We demonstrate the phenomenon of relative causal inseparability: a theory independent certification of indefinite causality applicable to arbitrary partial causal assumptions. We showcase that quantum theory equipped with the quantum control of causal orders gives rise to causally indefinite correlations with respect to some partial causal assumptions.

**Authors:** *Tamal Guha, Saptarshi Roy and Giulio Chiribella*

**Title:** **Quantum networks boosted by entanglement with a control system**

**Abstract:** Networks of quantum devices with coherent control over their configuration offer promising advantages in quantum information processing, including quantum communication, computation, and sensing. So far, the investigation of these advantages assumed that the control system was initially uncorrelated with the data processed by the network. Here, we explore the power of quantum correlations between data and control, showing two communication tasks that can be accomplished with information-erasing channels if and only if the sender shares prior entanglement with a third party (the "controller") controlling the network configuration. The first task is to transmit classical messages without leaking information to the controller. The second task is to establish bipartite entanglement with a receiver, or, more generally, to establish multipartite entanglement with a number of spatially separated receivers.

**Authors:** *Thomas Galley, Albert Aloy, Caroline Jones, Stefan Ludescher and Markus Mueller*

**Title:** **Spin-bounded correlations: rotation boxes within and beyond quantum theory**

**Abstract:** How can detector click probabilities respond to spatial rotations around a fixed axis, in any possible physical theory? Here, we give a thorough mathematical analysis of this question in terms of "rotation boxes", which are analogous to the well-known notion of non-local boxes. We prove that quantum theory admits the most general rotational correlations for spins 0, 1/2, and 1. For spins 3/2 and greater we show the existence of correlations beyond the quantum set. We prove a multitude of fundamental results about these correlations, including an exact convex characterization of the spin-1 correlations, a Tsirelson-type inequality for spins 3/2 and higher, and a proof that the general spin-J correlations provide an efficient outer SDP approximation to the quantum set. Our results illuminate the foundational question of how space constrains the structure of quantum theory, they build a bridge between semi-device-independent quantum information and spacetime physics, and they demonstrate interesting relations to topics such as entanglement witnesses, spectrahedra, and orbitopes.

**Authors:** *V. Vilasini and Roger Colbeck*
**Title: Information-processing in theories constrained by no superluminal causation vs no superluminal signalling**
**Abstract:** Relativistic causality principles place fundamental constrains on information processing possibilities in space-time. No superluminal causation (NSC) and no superluminal signaling (NSS) are two distinct principles, both of which are normally taken to hold and with relatively little work addressing their differences. What would happen in a theory satisfying NSS but not NSC? To answer this we analyse the generation of non-classical correlations. We find a spacetime configuration in which non-classical correlations cannot be generated in any theory (classical, quantum or post-quantum) satisfying NSC. However, we show that if NSC is violated but NSS holds, non-classical correlations can be generated in this configuration, already within classical theories. Furthermore, in this scenario, we show that non-communicating agents sharing classical resources and assisted by an effect called jamming, can generate PR-box correlations.

Surprisingly, this remains possible even when (in some frame) the measurement outcomes occur arbitrarily earlier in time than the measurement settings, suggesting a form of retrocausality. In a world that allows superluminal causation, we show that our protocol would enable this to be certified without violating NSS. Our work offers insights into the role different relativistic causality principles have on fundamental physics, and paves a way for future work exploring the information processing power of theories obeying such principles. The full paper is `https://arxiv.org/abs/2402.12446`.

**Authors:** *Vishal Johnson and Torsten Enßlin*
**Title: When Everett observes Greenberger, Horne, and Zeilinger meeting Wigner's Friend**
**Abstract:** There is a tension between quantum theory and special relativity as highlighted by the Bell experiments. This article considers another perspective on this tension — a Wigner's friend scenario applied to the GHZ state augmenting the GHZ paradox. A resolution is proposed by reconsidering the notion of reality of outcomes: objective reality combined with observer network states in unitary quantum theory.

**Authors:** *W.M. Stuckey and Michael Silberstein*
**Title: Unifying Special Relativity and Quantum Mechanics via Acausal Global Constraints**

**Abstract:** We explain how the disparate kinematics of quantum mechanics (finite-dimensional Hilbert space of QM) and special relativity (Minkowski spacetime from the Lorentz transformations of SR) can both be based on one principle (relativity principle). This is made possible by the axiomatic reconstruction of QM via information-theoretic principles, which has successfully recast QM as a principle theory a la SR. That is, in the quantum reconstruction program (QRP) and SR, the formalisms (Hilbert space and Lorentz transformations, respectively) are derived from empirically discovered facts (Information Invariance & Continuity and light postulate, respectively), so QM and SR are "principle theories" as defined by Einstein. While SR has a compelling fundamental principle to justify its empirically discovered fact (relativity principle), QRP has not produced a compelling fundamental principle or causal mechanism to account for its empirically discovered fact. To unify these disparate kinematics, we show how the relativity principle ("no preferred reference frame" NPRF) can also be used to justify Information Invariance & Continuity. We do this by showing that when QRP's operational notion of measurement is spatialized, Information Invariance & Continuity entails the empirically discovered fact that everyone measures the same value for Planck's constant h, regardless of their relative spatial orientations or locations (Planck postulate). Since Poincare transformations relate inertial reference frames via spatial rotations and translations as well as boosts, the relativity principle justifies the Planck postulate just like it justifies the light postulate. Essentially, NPRF + c is an adynamical global constraint over the spacetime configuration of worldtubes for bodily objects while NPRF + h is an adynamical global constraint over the distribution of quanta among those bodily objects.

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