Book of Abstracts

Emergence of Classicality: New Perspectives on Measurements in Quantum Theory (EoC2024)

15th to 19th of July 2024

Last updated: 14th of July 2024

MONDAY15 July 2024

08:30-09:45	Registration & Introduction	Monday 15 July 2024

Session 1

9:45-10:30	Invited Talk	Monday 15 July 2024

Jarosław Korbicz (Center for Theoretical Physics, Warsaw)

Emergence of classicality through Spectrum Broadcast Structures

Abstract: I will present a brief introduction to Spectrum Broadcast Structures (SBS) and their connection to the quantum-to-classical transition. Spectrum Broadcast Structures are specific, multipartite quantum states encoding a certain operational notion of objectivity. They derive from the quantum Darwinism idea. I will define the states, show how they can be derived from first principles, and discuss their connection to the quantum measurement problem. I will also briefly overview the appearance of SBS in well known models of open quantum systems and comment on their role in the theory.

10:30-11:00	Contributed Talk	Monday 15 July 2024

Sophie Engineer (Heriot-Watt & University of Bristol)

Equilibration of objective observables in a dynamical model of quantum measurements

Abstract: The challenge of understanding quantum measurement persists as a fundamental issue in modern physics. Particularly, the abrupt and energy-non-conserving collapse of the wave function appears to contradict classical thermodynamic laws. The contradiction can be resolved by considering measurement itself to be an entropy-increasing process, driven by the second law of thermodynamics. This proposal, dubbed the Measurement-Equilibration Hypothesis, builds on the Quantum Darwinism framework derived to explain the emergence of the classical world. Measurement outcomes thus emerge objectively from unitary dynamics via closed-system equilibration.

Here, we work within this framework and construct the set of `objectifying observables' that best encode the measurement statistics of a system in an objective manner, and establish a measurement error bound to quantify the probability an observer will obtain an incorrect measurement outcome.

Using this error bound, we show that the objectifying observables readily equilibrate on average under the set of Hamiltonians which preserve the outcome statistics on the measured system. Then, using a random matrix model for this set, we numerically determine the measurement error bound, finding that the error only approaches zero with increasing environment size when the environment is coarse-grained into so-called observer systems. This result indicates the necessity of coarse-graining an environment for the emergence of objective measurement outcomes.

11:00-11:30	Coffee Break	Monday 15 July 2024

Session 2

11:30-12:00	Contributed Talk	Monday 15 July 2024

Mohammad Hamed Mohammady (Slovak Academy of Sciences)

Thermodynamic constraints on the quantum measurement process

Abstract: While quantum theory dictates that the act of measurement must perturb at least some property of the measured system, it does allow for measurements that are minimally invasive. Indeed, the existence of such measurements have played a crucial role in the development of the foundations of quantum theory. For example, the Einstein-Podolsky-Rosen criterion of physical reality implicitly assumes the existence of “ideal” measurements which do not perturb the state of the measured system whenever the measurement outcome can be predicted with certainty.

Assuming the universal validity of quantum theory, a quantum system of interest is measured when it undergoes an appropriate interaction with another quantum system which plays the role of a measuring apparatus. It stands to reason, therefore, that minimally invasive measurements may be ruled out if the measurement process is subjected to constraints imposed by the fundamental laws of nature, such as the laws of thermodynamics. Indeed, the Wigner-Araki-Yanase theorem shows that when the measurement process obeys a conservation law, such as the conservation of energy, then ideal measurements are ruled out for any projection valued measure (PVM) which fails to commute with the conserved quantity [1]. More recently, it has been shown that ideal measurements are ruled out for all projection valued measures when the measurement process is constrained by the third law of thermodynamics [2].

But in the more modern theory of quantum measurement, observables are more properly represented as positive operator values measures (POVMs) which may be fundamentally “unsharp”. One may therefore ask whether the aforementioned constraints on ideal measurements—or non-disturbance more generally—may be circumvented by unsharp POVMs. We show that the laws of thermodynamics can indeed be made compatible with an approximate or unsharp variant of the EPR criterion of physical reality [3], but only if the measured observable is “completely unsharp” so that all measurement outcomes are indefinite in every state—that is, no outcome can be said to obtain or not obtain with probabilistic certainty in any state [4,5].

[1] H. Araki and M. M. Yanase, Measurement of quantum mechanical operators, Phys. Rev. 120, 622 (1960)
[2] Y. Guryanova, N. Friis, and M. Huber, Ideal Projective Measurements Have Infinite Resource Costs, Quantum 4, 222 (2020)
[3] P. Busch and G. Jaeger, Unsharp quantum reality, Found. Phys. 40, 1341 (2010)

[4] M. H. Mohammady, T. Miyadera, and L. Loveridge, Measurement disturbance and conservation laws in quantum mechanics, Quantum 7, 1033 (2023)
[5] M. H. Mohammady and T. Miyadera, Quantum measurements constrained by the third law of thermodynamics, Phys. Rev. A 107, 022406 (2023)

12:00-12:30	Contributed Talk	Monday 15 July 2024

Cyril Elouard (Univiersité de Lorraine)

Thermodynamically reversible quantum measurements and related work costs

Abstract: The measurement-induced dynamics -- that is, the stochastic evolution unavoidably triggered by the observation of a quantum system's property -- stands as one of the most perplexing phenomena in quantum mechanics. This famous effect has been thoroughly verified experimentally, including in nonideal cases like weak or inefficient measurements, and the measured system's dynamics can be efficiently modeled. However, the emergence of such stochastic dynamics from first principle remains an active topic of investigations. Moreover, analysis of the measurement-induced dynamics as a thermodynamic transformation has revealed that the measured system can exchange energy and entropy with the measuring apparatus. The energy received by the system can fuel engine and refrigerator without classical counterparts [1]. This observation raises fundamental questions: What is the origin of the energy received by the system? How much work must be paid to perform a measurement, and how does this depend on the measurement performance (e.g. efficiency or strength)?

To address these topics, we analyze with a nonequilibrium thermodynamic standpoint a generic dynamical model of a quantum measuring apparatus coupled to the measured system. Our model is inspired by insights into the irreversibility of the measurement process that has been related to generation of multiple copies of the measurement's result [2] in degrees of freedom practically inaccessible to the observer -- that is, a reservoir. This process turns the measurement result into an objective fact, stored in classical-behaving degrees of freedom, thereby avoiding paradoxes associated with Wigner's friend scenarios [3]. As it captures the irreversible behavior of the measurement-induced dynamics, it also has a crucial contribution to the thermodynamic analysis.

Therefore, in our model, the apparatus is composed of a probe -- a quantum system interacting with the measured system to acquire information about it, a thermal environment collapsing the probe onto classically distinguishable states, and a classical battery providing the work necessary for the measurement to take place. The final state of the unitary evolution of the global system determines the quality of the measurement.

From the expression of the second law of thermodynamics in our setup, we derive a general lower bound on the total work cost to perform the measurement, in terms of the energy received by the system, and measures of the information acquired by the measurement -- that can be directly related to the measurement quality. This bound generalizes earlier results by Sagawa and Ueda, focused on efficient (purity-preserving) measurements [4].

By analyzing a more concrete setup and protocol, we prove that the lower bound can be reached. As the measurement remains an irreversible process even if the protocol is operated quasi-statically, reaching the lower bound requires to add extra steps devoted to fully exploit the information acquired on the measuring apparatus state in order to extract work, in a way reminiscent to a Maxwell Demon or Szilard Engine protocol. Finally, finite-time analysis of the work cost highlight a double tradeoff between energy cost, measurement efficiency and measurement duration.

Our framework brings no insights about the origin of measurement-induced energy transfers, and opens the possibility to analyze systematically the work cost of quantum measurements as a function of target efficiency and measurement duration, which is a first step towards the energetic optimization of error-correction code.

[1] C. Elouard, D. Herrera-Marti, B. Huard, and A. Auffeves,, Phys. Rev. Lett. 118, 260603 (2017)
[2] W. H. Zurek, Nature Physics 5, 181 (2009)
[3] C. Elouard, P. Lewalle, S. K. Manikandan, S. Rogers, A. Frank, A. N. Jordan, 5, 498 (2021).
[4] T. Sagawa and M. Ueda, Phys. Rev. Lett. 106, 189901 (2011), Phys. Rev. Lett. 102, 250602 (2009).

12:30-14:00	Lunch Break	Monday 15 July 2024

Session 3

14:00-14:30	Contributed Talk	Monday 15 July 2024

Diana A. Chisholm (Queen's University Belfast)

Distinguishing between redundancy and consensus when quantifying quantum objectivity

Abstract: We give rigorous definitions of "redundancy" and "consensus", two different measures of the degree of objectivity of quantum states, with clear operative interpretations that reflect their meaning in the English language.

Although the two terms are often used interchangeably in discussions on quantum objectivity, they actually represent distinct concepts that capture different aspects of the quantum to classical transition.
Moreover, the key frameworks employed in the study of quantum objectivity, namely spectrum broadcast structure and quantum Darwinism, naturally arise from these measures.While discussing the differences between redundancy and consensus, and their usefulness in interpreting the degree of objectivity of quantum states, we will employ them to show that, in the framework of quantum Darwinism, failing to use the averaged mutual information can lead to misleading results.
Our framework offers a fresh perspective for interpreting both current and future findings in the realm of quantum objectivity and, consequently, the emergence of classical behaviour from the quantum domain.

[1] D.A. Chisholm, L. Innocenti and G.M. Palma; Quantum 7, 1074 (2023).
[2] D.A. Chisholm, L. Innocenti and G.M. Palma; arXiv:2401.04769 (2024).

14:30-15:00	Contributed Talk	Monday 15 July 2024

Alexandre Orthey (Center for Theoretical Physics, Polish Academy of Sciences)

High-dimensional monitoring and the emergence of realism via multiple observers

Abstract: Quantum theory gives a prominent role to the notion of measurements. They are the basic ingredients in several quantum technologies such as measurement-based quantum computation, thermal devices fueled by measurements, measurement-based quantum communication protocol, as well as in several foundational discussions regarding the measurement problem and on the understanding of the quantum-to-classical transition. In particular, the emergence of objective reality has been investigated with the framework of Quantum Darwinism (QD) [A. Touil et al., PRL 128, 010401 (2022)] through the process of redundancy, where multiple copies of information about the quantum system are created in its environment, and from the closely related Spectrum Broadcast Structure, where the environment of a quantum system can be thought of as a spectrum of frequencies, each of them associated with a selected robust state.

Generalized measurements that can interpolate between weak and strong (projective) non-selective regimes were employed to investigate the role of measurements in the emergence of realism from the quantum substratum [Dieguez et al., PRA 97, 022107 (2018)], as quantified by the informational measure known as irrealism [Bilobran et al., EPL 112, 40005 (2015)]. The quantum irrealism measure is based on the contextual realism hypothesis which generalizes the notion of EPR elements of reality by stating that for quantum systems, a measured property becomes well-defined after a projective measurement of some discrete spectrum observable, even when one does not have access to the specific measurement result. In other words, incoherent mixtures of all possible outcomes have realism for the measured observable. Realism was investigated by employing monitoring with continuous variable measurement systems, which showed to have a complementary relation with the available information of a quantum system. The information-realism complementarity suggests that the establishment of realism for some observable is grounded on the encoding of information about it.

In this work, we propose to take a step further and investigate the emergence of realism via monitoring modeled by discrete quantum systems with higher dimensions. We identify that a large qudit-environmental system is sufficient for the establishment of realism for all the range of measurement strengths, corroborating the results obtained with continuous variable monitoring. Moreover, our model introduces a consistent interpolation model for weak to strong measurements with high-dimensional systems. As a starting point, we discuss the qubit regime and address its limitations as well as its direct generalizations. To address the qudit regime, we model the interaction between the system and the environment through generalized observables [Kaniewski et al., Quantum 3, 198 (2019)], described by the Fourier transform of POVMs, which allows the control of their disturbance on the measured quantum system, therefore, allowing an interpolation from a weak to strong projective action. This interpolation regime has been already experimentally investigated for qubits employing a trapped-ion platform, and with photonic weak measurements to investigate the information-realism complementarity.

The most important conclusion of our analysis is that, for high-dimensional discrete monitoring, a state of reality for a given observable can be reached regardless of the intensity of the interaction between the system and the environment, as long as the latter is composed of a sufficiently large number of particles. Following the QD framework, if the system manages to disseminate redundant information about an observable to many particles in the environment, such a system will move towards a state of objectivity. Therefore, we can conclude through our model that objectivity from QD implies the emergence of states of reality for a given observable, as defined by [Bilobran et al., EPL 112, 40005 (2015)].

15:00-15:30	Contributed Talk	Monday 15 July 2024

Arsalan Adil (University of California, Davis)

A search for classical subsystems in quantum worlds

Abstract: Decoherence and einselection have been effective in explaining several features of an emergent classical world from an underlying quantum theory. However, the theory assumes a particular factorization of the global Hilbert space into constituent system and environment subsystems, as well as specially constructed Hamiltonians. In this work, we take a systematic approach to discover, given a fixed Hamiltonian, several factorizations (or tensor product structures) of a global Hilbert space that admit a quasi-classical description of subsystems in the sense that certain states (the ''pointer states'') are robust to entanglement. We show that \textit{every} Hamiltonian admits a pointer basis in the factorization where the energy eigenvectors are separable. Furthermore, we implement an algorithm that allows us to discover a multitude of factorizations that admit pointer states and use it to explore these quasi-classical ``realms'' for both random and structured Hamiltonians. We also derive several analytical forms that the Hamiltonian may take in such factorizations, each with its unique set of features. Our approach has several implications: it enables us to derive the division into quasi-classical subsystems, demonstrates that decohering subsystems do not necessarily align with our classical notion of locality, and challenges the conventional wisdom that the propensity of a system to exhibit classical dynamics relies on minimizing the interaction between subsystems. From a quantum foundations perspective, these results pose interesting ramifications for relative-state interpretations. From a quantum engineering perspective, these results may be useful in characterizing decoherence free subspaces and other passive error avoiding protocols.

15:30-16:00	Coffee Break	Monday 15 July 2024

Session 4

16:00-16:30	Contributed Talk	Monday 15 July 2024

Tomonori Matsushita (Hiroshima University)

Quasiprobabilities in the back action dynamics of quantum measurements

Abstract: Obtaining information about the physical properties of a system through an external meter requires some dynamical process of interaction between the system and the external meter. In classical mechanics, we assume that the meter receives a force characterized by the physical property of the system, determined before this interaction. The quantum analogue for such an assumption would be that the meter receives a force as a unitary transformation, characterized by an eigenvalue of the target observable. However, this analogy requires that the eigenvalue of the target observable can be identified, e.g. in a subsequent measurement of the system. If we instead choose to measure a different observable in this subsequent measurement, the effects of the system on the meter can contradict the assignment of an eigenvalue to the physical property being measured. A complete characterization of the measurement process must therefore combine the effects of the system on the meter with additional information obtained in a subsequent measurement.

Understanding the relation between the outcome of the subsequent measurement and the quantum statistics of the initial state is a non-trivial problem since the relation is partly determined by the effects of the back-action of the initial measurements. Here, we show that the problem can be addressed by using quasiprobabilities of the Kirkwood-Dirac type to evaluate the effects on the meter as a function of the outcome of a subsequent measurement. Specifically, we consider a measurement of the path taken by a particle in a multi-path interferometer, as expressed by the projection operator representing the detection of the particle in that path. In the limit of weak measurement interactions, the correlation between the meter response and the subsequent measurement is described by the Kirkwood-Dirac quasiprobability of the initial state, as expected from previous research. As the strength of the interaction increases, it is possible to relate the changes in the statistics of the subsequent measurement caused by the back-action of the initial measurement with the quasiprobabilities of the input state. We find that anomalous values of the quasiprobabilities (values below zero or above one) are correlated with particularly large back-action effects, indicating that the statistical distribution of the backaction effects plays an essential role in avoiding a direct contradiction between the anomalous quasiprobabilities and the observed statistics of the actual measurement outcomes.

16:30-17:00	Contributed Talk	Monday 15 July 2024

Lorena Ballesteros Ferraz (Université de Lorraine, CNRS, LPCT)

Exploring the role of weak measurements in dissipative quantum systems

Abstract: A quantum weak measurement is a four-step procedure that involves a target system and an ancillary meter [1]. In the initial phase, pre-selection occurs, necessitating the careful choice of the system's initial state. Proceeding to the second step, a weak interaction occurs via a unitary operator that entangles both the ancillary meter and the system of interest. The third step encompasses a post-selection procedure applied to the system, including a projective measurement process along with subsequent filtration. Eventually, the meter wave function is readout. The meter wavefunction exhibits two shifts. In the position representation, the shift is proportional to the real component of the weak value $A_w = \langle\psi_f | \hat{A}|\psi_i\rangle/\langle\psi_f |\psi_i\rangle$. In contrast, the shift observed in the momentum representation holds aproportionality to the imaginary part of the weak value.

In practice, genuine isolation of quantum systems remains an unattainable ideal. Under certain approximations, the evolution of the system's dynamics can be effectively characterized by a Markovian master equation. This equation comprises a primary term derived from the von Neumann equation governing the evolution of density matrices. The second term is the application of the dissipator to the density operator, which presides over the dissipative dynamics of the system, involving dissipation, decoherence, and dephasing. This term is proportional to the dissipation rates.

We investigate weak measurements accompanied by dissipation, specifically exploring scenarios where dissipation takes place subsequent to the weak interaction but before the post-selection stage [2]. Notably, this scheme is present in any experimental setup with a time delay between the unitary interaction and the post-selection. We assume a short duration of the weak interaction to neglect concurrent dissipation.

We explore the interplay between dissipation and weak values when the dissipation time approaches infinity. For non-degenerate systems, as this dissipation time increases, the distinctive characteristics of the weak value disappear gradually as it converges towards the operator's expectation value. In the case of degenerate steady state systems, a contrasting phenomenon emerges : anomalous weak values can persist even as the dissipation time extends infinitely.

Weak values can also be used at short times to extract information about the dissipative dynamics of the system, notably to differentiate non-Markovian from Markovian dynamics. Our theoretical

framework allows us to glean insights into dissipative processes occurring over short time of dissipation and featuring low dissipation rates. It is useful to determine if dissipation is relevant in experiments.

We exemplify the model by using a two-level atom as the quantum system of interest, and a single-photon cavity field serving as the meter. The weak measurement is obtained through the short passage of the atom by the cavity. Subsequently, the atom suffers dissipation, by interacting with a quantized radiation field. The radiation field is composed by a reservoir with an infinite number of degrees of freedom. After post-selection, the real and imaginary parts of the weak value are measured by reading out the quadratures of the cavity field. Interestingly, dissipation rates are observed through the ancillary state across varying durations of dissipation with increased sensitivity. When considering a non-Markovian dissipation, under certain circumstances, this type of dissipation can be differentiated from a Markovian one, exploiting weak-value amplification.

[1] Yakir Aharonov, David Z Albert, and Lev Vaidman. How the result of a measurement of a component of the spin of a spin-1/2 particle can turn out to be 100. Physical review letters,
60(14) :1351, 1988.
[2] Lorena Ballesteros Ferraz, John Martin, and Yves Caudano. On the relevance of weak measurements in dissipative quantum systems. arXiv preprint arXiv :2308.00722, 2023.

17:00-17:30	Contributed Talk	Monday 15 July 2024

Giuseppe Antonio Nisticò (Università della Calabria)

Classical behaviour enforced by Quantum Theory itself

Abstract: A first approach to address the problem of the emergence of classicality consisted in verifyng that the predictions of quantum theory for the expected values have a behaviour obeying classical theories in the limit h-->0 where h is the Planck constant [1]. However, this behaviour holds only for short times and under specific conditions for the initial quantum state. Another approach, avoiding this limitation, is based on the concept of decoherence. According to this approach, also a weak interaction with the environment destroys the superposition, i.e. causes the collapse of a genuine superposition state and a classical behaviour emerges. A different interesting investigation has been pursued [2] showing how the classical trajectories of a particle in a cloud chamber emerge, without making resort to the idea of collapse, but, instead, by a pure quantum theoretical treatment. The present work gives evidence of a more fundamental theoretical mechanism that determines a classical behaviour as the size of the system grows, in complete agreement with quantum theory. To make clearer the subject, we restrict to the case of a "rigid" body, i.e. a quantum system formed by a large number of identical particles, whose quantum state ψ(rig) satisfies a definite rigidity condition. Non-classicality of quantum theory, in its Hilbert space realization where observables are identified with self-adjoint operators, traces back to the following basic feature: whenever two observables, identified by the self-adjoint operators A and B do not commute, then the same specimen of the system cannot be assigned values a, b for A, B as objective properties of that specimen; in particular they cannot be measured together. The possibility of emergence of classicality for a rigid body is equivalent to the possibility of assigning the same specimen of the body values for the "classical" observabels, e.g. the position of the center of mass q(cm) and its velocity v(cm). In general, the self-adjoint operators Q and V representing these observables do not commute. Therefore the emergence of classicality should be ruled out. Now, by making use of a concept of 'evaluation' introduced in [3] we prove that if A and B do not commute, but the quantum state ψ admits another self-adjoint operator T such that Aψ=Tψ and [T,B]=0, to assign A the value obtained for T in a simultaneous measurement of T and B is consistent with all actually performed measurements and with all predictions of quantum theory. The

consistency of this value assignment depends on the quantum state ψ. We prove that the condition of rigidity for our body implies that a self-adjoint operator T exists such that Tψ(rig)=V(cm)ψ(rig). Therefore, a system of a large number of particles can be consistently assigned both the values of the position (directly measured) and of the velocity (evaluated by measuring T) of its center of mass, if its quantum state characterizes the system as a rigid body. Thus, classicality is enforced by quantum theory itself. The argument can be extended to more general sets of classical observables.

[1] Robert D. Helv.Phys.Acta, 71 44
[2] Teta A. Eur.J.Phys. 31 215
[3] Nisticò G., Sestito A. Int.J.Theor.Phys. 55:1798–1810

TUESDAY 16 July 2024

Session 5

09:30-10:15	Invited Talk	Tuesday 16 July 2024

Howard Wiseman (Griffith University)

No-go for Classicality? What the Local Friendliness theorem says.

Abstract: The quantum measurement problem (or the emergence of “classicality”), like the problem of consciousness, has an easy form and a hard form. I am concerned with the hard form — explaining the experience of a single measurement outcome, occurring with the Born-rule probability, without using any aspect of quantum measurement theory. Our recent Local Friendliness No-Go theorem is relevant here, effectively refining the possible space of theories that claim to solve the hard QMP. The theorem does not need to assume that quantum mechanics is perfectly unitarity, only that some measurements can be approximately reversed. I will discuss the most recent version of our theorem, a “thoughtful” one, as giving the best candidate for a definitive experiment.

10:15-10:45	Contributed Talk	Tuesday 16 July 2024

Florian Meier (TU Wien)

On the 2nd law of thermodynamics in isolated quantum systems

Abstract: The second law of thermodynamics states that the entropy of an isolated system can only increase over time. Isolated quantum systems, however, evolve unitarily and this preserves the von Neumann entropy and yet, we find that with respect to most observables, such systems equilibrate. These three concepts, (1) the second law of thermodynamics, (2) isolated quantum system evolution and (3) equilibration raise the main question of this talk: In what sense does the entropy of a isolated quantum system increase over time?

Historically, for classical systems, this question has been solved using a statistical interpretation, where the high entropy states are simply the more likely ones. For open quantum systems a similar reasoning works, but for isolated quantum systems whose von Neumann entropy does not change in time, this argument does not go through. It has been found, though, that under mild assumptions on the dynamics, systems equilibrate relative to most observables on average. We build upon this approach by investigating different entropies that are defined with respect to some observable and recover a variant of the second law -- the entropy (relative to a given observable) for isolated quantum systems tends towards it's equilibrium value. Entropy fluctuations as shadows of the underlying reversible evolution are also possible and they are suppressed more the stronger they are and the larger the system under observation.

10:45-11:15	Coffee Break	Tuesday 16 July 2024

Session 6

11:15-11:45	Contributed Talk	Tuesday 16 July 2024

Philip Taranto (The University of Tokyo)

Landauer vs. Nernst: what is the true cost of cooling a quantum system?

Abstract: Quantum computation can be performed using logically reversible gates in principle, but also demands the initialisation of pure input registers, thus ultimately requiring irreversible information erasure. However, information does not solely reside in the logical domain but must be encoded in physical systems: information is physical. This is the cornerstone of Landauer's seminal work connecting information and thermodynamics, which demonstrated that a (non-zero) minimum amount of heat must be dissipated in any logically irreversible process. Heat is detrimental to reliable quantum information processing as it induces errors and short coherence times rendering any `quantum advantages' a mirage; hence, we must understand the limits of efficiently resetting quantum systems.

In attempting to do so, we are confronted with Nernst's third law of thermodynamics, stating that an infinite amount of resources is needed to cool a system to the ground state. The precise nature of these resources, however, was previously left in the dark, leaving one to grasp for isolated examples. Landauer's protocol, for instance, minimises the energy cost, but must take place quasi-statically and hence requires diverging time. On the other hand, by investing a diverging amount of energy, one can create a pure state in minimal time by swapping the target system with a sufficiently pure state of an auxiliary machine system. Does this mean that one of these two resources---energy or time---must diverge in order to cool perfectly?

As I will discuss, the answer is, perhaps surprisingly: No. For any quantum system, we show how one can prepare a pure state with minimal energy and time. Subsequently, we identify the hidden resource behind this seemingly paradoxical statement: control complexity. Specifically, we show that for an unconstrained level of control (i.e., diverging control complexity), finite energy and finite time suffice for perfect cooling; whereas, in the spirit of Nernst, finite control complexity is insufficient in such a

finite-time, finite-energy protocol. In addition to providing this deep conceptual insight, our proofs are constructive in the sense that we present protocols that attain these ultimate limits.

Saturating the Landauer limit requires fine-tuned control that can only be implemented via a coherent external work source, i.e., a quantum battery, highlighting the crucial role of control on a more abstract level. From a thermodynamic perspective, this may seem unsatisfactory, as the joint system-plus-machine is not energetically closed. To this end, we extend our analysis to include a thermodynamic energy source (i.e., a heat bath) and close the joint system by restricting to global energy-conserving unitaries. This incoherent control setting corresponds to minimal control, where an agent need only switch on and off an interaction to generate spontaneous transformations. In this paradigm, we show that the Landauer bound is not attainable (even asymptotically). In its stead, we derive a novel ultimate limit---which we dub the Carnot-Landauer bound---and provide protocols that saturate this fundamental bound.

Our work thus both generalises Landauer's erasure principle and, at the same time, unifies it with the laws of thermodynamics. By explicitly accounting for the level of control and introducing the notion of control complexity, we emphasise a crucial resource that is typically overlooked in quantum thermodynamics. We anticipate that this work will initialise a shift in the way that resources are perceived, especially in quantum thermodynamics, but also more broadly in all areas of quantum information processing, from quantum computing to quantum sensing and beyond. In particular, our results lay the foundations for a plethora of practically relevant follow-up opportunities concerning finite-resource trade-offs in quantum technologies and the resulting intricate relationship between energy, time and control complexity.

11:45-12:15	Contributed Talk	Tuesday 16 July 2024

Armen Allahverdyan (Alikhanian National Laboratory)

Energy densities in quantum mechanics

Abstract: Quantum mechanics does not provide any ready recipe for defining energy density in space, since the energy and coordinate do not commute. To find a well-motivated energy density, we start from a possibly fundamental, relativistic description for a spin-1/2 particle: Dirac's equation. Employing its energy-momentum tensor and going to the non-relativistic limit we find a locally conserved non-relativistic energy density that is defined via the Terletsky-Margenau-Hill quasiprobability (which is hence selected among other options). It coincides with the weak value of energy, and also with the hydrodynamic energy in the Madelung representation of quantum dynamics, which includes the quantum potential. Moreover, we find a new form of spin-related energy that is finite in the non-relativistic limit, emerges from the rest energy, and is (separately) locally conserved, though it does not contribute to the global energy budget. This form of energy has a holographic character, i.e., its value for a given volume is expressed via the surface of this volume. Our results apply to situations where local energy representation is essential; e.g. we show that the energy transfer velocity for a large class of free wave-packets (including Gaussian and Airy wave-packets) is larger than its group (i.e. coordinate-transfer) velocity.

12:15-14:00	Lunch Break	Tuesday 16 July 2024

Session 7

14:00-14:30	Contributed Talk	Tuesday 16 July 2024

Henning Kirchberg (University of Pennsylvania)

Maxwell Demon revisited: a microscopic protocol for quantum measurement, information gain, work extraction and & energetic cost

Abstract: In many applications, the process of information gain is discussed without considering the time and energy cost required to obtain information, with the assumption that the Maxwell Demon can acquire information instantaneously at no additional energy cost except from memory erasure to a heat bath.

This work addresses these issues. We examine a two-level system interacting with a (quantum) free particle as a meter. We employ the two-step Von-Neumann measurement protocol to analyze two aspects separately: (i) the evolution of the coupled system and meter and the entanglement between them considered as functions of the coupling and its duration, and the information gained during this process, and (ii) the fundamental energetic cost for coupling and decoupling the system and meter. This makes it possible to consider the energetic cost of acquiring information. Additionally, by including photon-induced stimulated emission in the protocol we investigate the information-driven work extraction from the measured system. Our analysis focuses on the ratio between the work generated from the obtained information and the energy invested to acquire it, as well as the power output (energy per measurement duration) and its optimization.

14:30-15:00	Contributed Talk	Tuesday 16 July 2024

Shintaro Minagawa (Graduate School of Informatics, Nagoya University)

Universality of the second law of information thermodynamics

Abstract: This work explores the conditions under which the second law of information thermodynamics holds, focusing on the work involved in quantum measurement, feedback control and erasure protocols similar to Maxwell's Demon. While previous research required several operationally unjustified assumptions, here we derive work formulas applicable to completely general quantum measurement processes and feedback control protocols. This generalized approach proves that the second law of information thermodynamics, previously shown to hold only in very special situations, is in fact a universal law as long as the protocol obeys the laws of thermodynamics.

The second law of thermodynamics, a cornerstone of physics, appears to be challenged when considering information obtained through measurement, as exemplified by Maxwell's demon paradox [1]. This paradox suggests a potential violation of the second law by reducing entropy via measurement and feedback control without adiabatically injecting work.

The consensus, both in classical and quantum theories, is that any work advantage gained through feedback control should be offset by the work required for measurement and the erasure of the information extracted by the measurement–a principle termed the second law of information thermodynamics [2-4]. The setup, now considered standard, is the following: the system interacts with the demon's memory, acting as the measuring device, followed by feedback control based on the obtained measurement outcome, and memory erasure through interaction with a thermal bath.

However, these results were based on several assumptions about quantum measurement and feedback control processes that severely limit the validity of the second law of information thermodynamics derived from them. The most important assumptions are: first, the outcome objectification, i.e., the measurement process on the demon's memory, is a projection. Second, the measurement process on the target system is efficient (for each outcome, the measurement process has a single Kraus operator). Third, feedback control is a unitary operation only on the target system. Fourth, thermal equilibrium states are assumed as the initial states of both the target system and the memory.

The natural question then is: are such assumptions essential? Indeed, by imposing these assumptions from the beginning, the scope of the second law of information thermodynamics is unclear. In our work [5], we fill this gap by providing a complete characterization of quantum feedback control and erasure protocols consistent with the second law of thermodynamics. To do so, we eliminate the assumption imposed by the previous results and derive general work formulas of the protocols. This leads to the conclusion that the second law of information thermodynamics holds for any thermodynamically consistent quantum feedback control and erasure protocols. In this sense, the second law of information thermodynamics is indeed universal. Our result remains, however, compatible with previous studies, which can be reproduced using the same or even fewer assumptions.

[1] J. C. Maxwell, Theory of heat (Appleton, London, 1871).
[2] T. Sagawa and M. Ueda, Phys. Rev. Lett. 100, 080403 (2008).
[3] T. Sagawa and M. Ueda, Phys. Rev. Lett. 102, 250602 (2009).
[4] T. Sagawa and M. Ueda, Phys. Rev. Lett. 106, 189901 (2011) (erratum of [3]).
[5] S. Minagawa, M. H. Mohammady, K. Sakai, K. Kato, and F. Buscemi, arXiv: 2308.15558 (2023).

15:00-15:30 Contributed Talk Tuesday 16 July 2024

Paul Skrzypczyk (University of Bristol)

How to use arbitrary measuring devices to perform almost perfect measurements

Abstract: I will present novel results concerning the problem of 'measurement reproduction'. I will consider the problem of reproducing one quantum measurement given the ability to perform another. For example, I will show how to use available "imperfect" measurements a small number of times to implement a target measurement with average error that drops off exponentially with the number of imperfect measurements used. In the most general setting, both the available and target measurements are arbitrary generalised quantum measurements. I will show that this general problem in fact reduces to the ability to reproduce the statistics of (complete) von Neumann measurements, and that in the asymptotic limit of infinitely many uses of the available measurement, a simple protocol based upon 'classical cloning' can perfectly achieve this task. This can be used to show that asymptotically all (non-trivial) quantum measurements are equivalent. Finally, in a setting where we perform multiple measurements in parallel, it is possible to achieve finite-rate measurement reproduction, by using block-coding techniques from classical information theory. These results are all contained in https://arxiv.org/abs/2203.02593.

15:30-17:30	Discussion Time	Tuesday 16 July 2024

17:30-19:30	Poster Session (venue: Science Gallery)	Tuesday 16 July 2024

Wednesday 17 July 2024

Session 8

09:30-10:15	Invited Talk	Wednesday 17 July 2024

Lina Jansson (University of Nottingham)

Explanation and Emergence: Ontic, Epistemic and Pragmatic

Abstract: Different types of philosophical accounts of explanation correspond to different types of explanatory emergence. In this talk, I defend an epistemic account of explanation as a viable alternative to metaphysical and pragmatic accounts. I will go on to show how some traditional interpretative challenges look different when formulated in epistemic terms.

10:15-10:45	Contributed Talk	Wednesday 17 July 2024

Caroline Jones (IQOQI Vienna)

Thinking twice inside the box: is Wigner's friend really quantum?

Abstract: There has been a surge of recent interest in the Wigner's friend paradox, sparking several novel thought experiments and no-go theorems [1–3]. The main narrative has been that Wigner's friend highlights a counterintuitive feature that is unique to quantum theory, and which is closely related to the quantum measurement problem. In our paper, we challenge this view. We argue that the gist of the Wigner's friend paradox can be reproduced without assuming quantum physics, and

that it underlies a much broader class of enigmas in the foundations of physics and philosophy. To show this, we first consider several recently proposed extended Wigner's friend scenarios, and demonstrate that their implications for the absoluteness of observations [4] can be reproduced by classical thought experiments that involve the duplication of agents. Crucially, some of these classical scenarios are technologically much easier to implement than their quantum counterparts. We claim that the similarities between our classical thought experiments and the quantum extended Wigner's friend experiments (and, in particular, in their metaphysical consequences) motivate us to ask about the common structural and mathematical elements of such scenarios.

This leads us to formulate a feature that we call "Restriction A", which we argue is the essential structural ingredient of scenarios in classical, quantum and indeed more general settings. In a nutshell, Restriction A states that a physical theory cannot give us a probabilistic description of the observations of all agents. We give an analysis of (extended) Wigner's friend scenarios as well as our classical thought experiments in terms of Restriction A, and, furthermore, argue that this difficulty is at the core of other puzzles in the foundations of physics and philosophy, demonstrating this explicitly for cosmology's Boltzmann brain problem. Our analysis suggests that Wigner's friend should be studied in a larger context, addressing a frontier of human knowledge that exceeds the boundaries of quantum physics: to obtain reliable predictions for experiments in which these predictions can be privately but not intersubjectively verified.

[1] Č. Brukner, On the quantum measurement problem, in Quantum [Un]Speakables II: Half a Century of Bell's Theorem, Springer (2017).
[2] D. Frauchiger and R. Renner, Quantum theory cannot consistently describe the use of itself, Nat. Commun. 9, 3711 (2018).
[3] K.-W. Bong, A. Utreras-Alarcon, F. Ghafari, Y.-C. Liang, N. Tischler, E. G. Cavalcanti, G. J. Pryde, and H. M. Wiseman, A strong no-go theorem on the Wigner's friend paradox, Nat. Phys. 16, 1199–1205 (2020)
[4] H. M. Wiseman, E. G. Cavalcanti, and E. G. Rieffel, A "thoughtful" Local Friendliness no-go theorem: a prospective experiment with new assumptions to suit, Quantum 7, 1112 (2023).

10:45-11:15	Coffee Break	Wednesday 17 July 2024

Session 9

11:15-11:45	Contributed Talk	Wednesday 17 July 2024

William Zeng (Unitary Fund)

Towards violations of Local Friendliness with quantum computers

Abstract: Experimental quantum mechanics has a long history of evidence that reality is different than that expected by naive human intuition. In some cases, these experimental results go further than supporting specific quantum mechanical predictions to give evidence against whole classes of physical theories that obey certain principles. For example, Bell inequalities not only provide evidence for quantum mechanics but also that reality is not described by theories that have both local agency and

predetermination. These results are part of experimental metaphysics in that they give evidence about possible physical theories at the meta-level.

In recent years, new tests in experimental metaphysics have been proposed to study the metaphysical property of Local Friendliness (LF). LF is loosely the conjunction of objective reality across observers and local agency. Thus a violation of the LF property provides evidence that one of these two assumptions needs to be jettisoned. It turns out that thought experiments can be designed whereby textbook quantum mechanics looks to violate the assumption of LF. One such experiment is the extended Wigner's friend scenario (EWFS) that was introduced as an extension of the original thought experiment initially proposed by Wigner and later refined by Deutsch. In the referenced work, the authors experimentally implemented the EWFS using a photonic qubit to play the role of each of the friends to attain Bell-type inequality violations. Under reasonable assumptions, these violations imply that absoluteness of observed events (AOE); every observed event happens for all observers and local agency (LA); events are uncorrelated with other events outside its future light cone are incompatible notions.

One may question whether a single photon as used in the experimental setting is a physical system of sufficient complexity to be deemed as an observer and hence whether the outcome of the experiment is metaphysically significant. To this end, we encode the EWFS as a quantum circuit such that the components of the circuit that define the friend are quantum systems of increasing size. We run this circuit on quantum simulators and hardware devices and observe inequality violations as the system sizes scale.

Additionally, we propose using the branch factor, recently introduced by Taylor and McCulloch, to quantify the observerness of a friend. We obtain violations of the LF inequalities while we increase the friend size in such a way that the branch factor of the quantum state of the friend also increases. We think of the branch factor as a measure of observerness, so as we increase the size of the friend system such that the branch factor increases, the friend system gets closer to becoming an observer. The improvement of quantum technology through academic and industrial development opens up new avenues for studying fundamental scientific questions. We are optimistic that a program of LF violations can motivate continued development and benchmarking of quantum technology by testing important aspects of reality.

11:45-12:15	Contributed Talk	Wednesday 17 July 2024

Johannes Fankhauser (University of Innsbruck)

Epistemic horizons from dynamical laws: Lessons from a nomic toy theory

Abstract: In physical theorizing the observer is often not explicitly modeled as a physical system itself. Whereas in classical physics the observer has no special relevance, in quantum theory it is often claimed to play a crucial role in the description, and that the system cannot be separated from the observer. However, these claims are lacking a rigorous and satisfactory foundation.

As a first step we study the subject-object relationship in a simple toy theory that reproduces certain aspects of quantum theory. More concretely, we provide a description of toy world where the observer, i.e. the subject, is explicitly introduced in the theory as a toy system. A minimal set of assumptions will characterize this system as an agent that can acquire information about toy objects through measurement interactions.

This specification of an information gathering and prediction making subject together with a natural assumption on the dynamics of the theory we show that measurement interactions back-react on the

object such that it cannot fully be accessed, represented, and predicted. The results reconcile us to features of quantum theory and the fully fledged Spekkens toy theory as aspects of the inseparability of subject and object.

12:15-14:00	Lunch Break	Wednesday 17 July 2024

Session 10

14:00-14:30	Contributed Talk	Wednesday 17 July 2024

Markus Frembs (Okinawa Institute of Science and Technology)

Coming full circle? A cyclic perspective on Kochen-Specker contextuality

Abstract: The very problem of the emergence of classicality rests upon a series of no-go theorems by Bell, Kochen and Specker [Rev. Mod. Phys., 38, 447 (1966), J. Math. Mech. 17, 59 (1967)], demonstrating that quantum theory does not admit a classical description — unless it is either nonlocal or (more generally) contextual. Contextuality therefore is the distinguishing feature between classical and quantum physics. In turn, understood as a resource for quantum computation, contextuality is expected to hold the key to quantum advantage.

Yet, despite its long recognised importance in quantum foundations and, more recently, in quantum computation, the true essence of contextuality remains elusive. In particular, there is a glaring discrepancy between the original definition of noncontextuality as introduced by Kochen and Specker on the one side, and the modern approach of studying noncontextual correlations on the other [Rev. Mod. Phys., 94, 045007 (2022)].

Similar to Bell local correlations, nonconcontextual correlations form a polytope, and can thus be studied in terms of its facet-defining noncontextuality inequalities. One would expect - and consistency between the respective notions demands - that the noncontextuality polytope captures the essence of Kochen-Specker noncontextuality. However, this turns out not to be the case. While every proof of the Kochen Specker theorem can be cast as a noncontextuality inequality that is violated by quantum mechanics, the converse is false: there exist noncontextuality inequalities that do not give rise to a proof of the Kochen-Specker theorem [Phys. Rev. Lett, 108, 030402 (2012)]. The issue is thus quite severe: more than half a century after its discovery, we seem to lack a proper understanding of this core principle underlying quantum mechanics.

In my talk, I will advocate a framework for contextuality which subsumes various existing notions and approaches. Within this framework, I will motivate and introduce a conceptually and mathematically new tool, which for the first time allows to fully characterise the notion of Kochen-Specker noncontextuality, in the form of algebraic noncontextuality constraints.

I will then draw a number of consequences from this characterisation. Most importantly, I will resolve the apparent discrepancy between the original notion of contextuality, as introduced by Kochen and Specker, and the modern notion captured by noncontextuality inequalities.

This is the first time a full algebraic characterisation of Kochen Specker noncontextuality has been obtained. Given the central role contextuality plays in quantum foundations, quantum information and quantum computation, our characterisation is expected to be of similar impact.
First, an algebraic characterisation of contextuality has been the missing piece to quantifying contextuality as a resource, which remains a central open problem in the field of quantum computation.
Second, our algebraic formulation unifies a number of existing frameworks for contextuality, thereby connecting various results that had previously seemed unrelated and surprising. For instance, the existence of noncontextual models due to Meyer, Clifton and Kent [Stud Hist Philos M P, 35, 151 (2004)] arises as a straightforward consequence in our setting.
Third, our framework opens the way to a new geometric proof of the Kochen-Specker theorem. Since contextuality is the fundamental obstruction to a classical state space description of quantum theory, such a proof would highlight, in geometric terms, the distinction between classical and quantum theory, and possibly point towards quantum geometries in fundamental physics.
Finally, we expect our characterisation to hold new insights into the emergence of classicality. Concretely, an intriguing direction would be to analyse physical regimes that avoid our algebraic noncontextuality constraints, thus leading to a better understanding of the boundary between quantum to classical.

14:30-15:00	Contributed Talk	Wednesday 17 July 2024

Roberto Dobal Baldijao (ICTQT -- University of Gdansk)

Emergence of Noncontextuality under Quantum Darwinism

Abstract: Quantum Darwinism proposes that the proliferation of redundant information plays a major role in the emergence of objectivity out of the quantum world. Is this kind of objectivity necessarily classical? We show that if one takes Spekkens's notion of noncontextuality as the notion of classicality and the approach of Brandão, Piani, and Horodecki to quantum Darwinism, the answer to the above question is "'yes," if the environment encodes the proliferated information sufficiently well. Moreover, we propose a threshold on this encoding, above which one can unambiguously say that classical objectivity has emerged under quantum Darwinism.

15:00-15:30	Contributed Talk	Wednesday 17 July 2024

Carlo Cepollaro (University of Vienna)

Emergence of classicality from coarse-grained meaurements

Abstract: Among the several approaches to modeling the transition from quantum mechanics to classical mechanics, a textbook definition of the classical limit is that quantum mechanics reduces to classical mechanics when the value of the Planck constant approaches zero. This limit has two significant consequences. Firstly, it imposes a kinematic condition on the states – since the Heisenberg uncertainty is removed, it's possible to choose states that are simultaneous eigenstates of position and momentum. Secondly, in this limit, the Feynman propagator reduces to the exponential of the classical action, and any other contribution to the evolution vanishes, meaning that the evolution of the system obeys Liouville's evolution. This happens when the ratio between the Planck constant and the classical action of the system tends to zero. However, for no system, regardless of how macroscopic it may be, this ratio is exactly zero. Even in the most classical scenario, the ratio will be

very close to zero, but still strictly positive. Thus, if we had incredibly precise measurement instruments, we could still witness quantum effects, even for macroscopic systems (in the hypothesis of isolated system, and hence absence of decoherence). This suggests that the classical limit should not emerge from the properties of the systems alone, but from the interplay between the measurement apparatus and the system. Conversely to the example above, if a truly quantum system (with action of the same order as the Planck constant) is measured with very low precision, its behavior will be indistinguishable from the one of a classical system. In the talk I will present some results that address and quantify these ideas. Specifically, I will introduce a type of coarse-grained measurement for position and momentum and study the behavior of quantum systems when the coarse grain parameter changes. I will show that increasing the coarse grain parameter leads to the same effects of the limit of the Planck constant approaching zero. This means that the coarse-grained measurement defines a classical limit, with a more insightful and operational definition than the textbook one: it shows that classical mechanics emerges from quantum mechanics under imprecise measurements, and the amount of precision that we need to measure quantum mechanical effects depends on the system. Concretely, I will show that a broad class of quantum systems under sufficiently coarse-grained measurements can be approximated as Dirac's delta distributions or convex combinations thereof, without changing the measurement probabilities. This means that under coarse-grained measurement, we can assume classical mechanics to be valid to explain the physical predictions: this shows that for this class of states, the kinematical aspect of the classical limit is recovered. Furthermore, I will show that under certain conditions, the probability of coarse-grained measurement for these states evolves following Liouville's evolution, hence displaying classical dynamics. This result hence highlights that the emergence of classical mechanics comes from an interplay between the features of the system at study and the measurement apparatus, and not from the system alone, as the textbook definition suggests. Furthermore, this paves the way for future research, involving the study of systems that do not have a well-defined classical limit under coarse-grained measurements, hence displaying a sort of resilience in their quantum properties: such systems may be understood as non macrorealistic, hence violating Leggett-Garg inequalities.

15:30-16:00	Coffee Break	Wednesday 17 July 2024

Session 11

16:00-16:30	Contributed Talk	Wednesday 17 July 2024

Carlos Pineda (Universidad Nacional Autonoma de Mexico)

Fuzzy measurements and coarse graining in quantum many-body systems

Abstract: Using the quantum map formalism, we provide a framework to construct fuzzy and coarse grained quantum states of many-body systems that account for limitations in the resolution of real measurement devices probing them. The first set of maps handles particle-indexing errors, while the second deals with the effects of detectors that can only resolve a fraction of the system constituents. By construction, both maps are simply related via a partial trace, which allow us to concentrate on the properties of the former. We fully characterize the fuzzy map, identifying its symmetries and invariants spaces. We show that the volume of the tomographically accessible states decreases at a double exponential rate in the number of particles, imposing severe bounds to the ability to read and use information of a many-body quantum system. We investigate the volume of the preimages of the effective states, allowing to look for typical states observed under imperfect measurement devices.

16:30-17:00	Contributed Talk	Wednesday 17 July 2024

Finn Schmolke (Universität Stuttgart)

Measurement-induced synchronization and ergodicity breaking

Abstract: An intrinsic feature of quantum mechanics is measurement backaction that randomly perturbs the state of a measured system. As a consequence, observing a quantum object may dramatically affect its dynamics in a non-classical manner.

We show that a continuously monitored quantum many-body system can undergo a spontaneous transition from stochastic dynamics to noise-free stable synchronization at the level of individual quantum trajectories, when subject to standard homodyne detection. This effect can occur in generic many-body quantum systems based on the existence of decoherence-free subspaces. Such a synchronization transition is always associated to the localization of the state in Hilbert space. On the trajectory level, ergodicity is thus typically broken and synchronization may appear along individual realizations while being absent at the ensemble level.

In general, knowledge of the ensemble average is, hence, not sufficient to provide information about the synchronized behavior of single realizations. Measurement-induced synchronization appears as a genuine non-classical form of synchrony. On the other hand, if the stochastic disturbance is due to a classical noise source, the randomness no longer depends on the state of the system, quantum evolution is ergodic and synchronization transitions are absent.

17:00-17:30	Contributed Talk	Wednesday 17 July 2024

Lev Vaidman (Tel Aviv University)

From interaction-free measurements to counterfactual communication

Abstract: A bomb explodes when anything interacts with it: Can it be found without exploding it? Can we find that the bomb is not present in a particular place without any probe being there? Which tasks can be achieved without particles in the transmission channel: transmission of a classical message, teleportation of a quantum state, establishing a secret key? I will review the claims that these tasks can be done and will argue that only some of them are true.

18:00-	**Conference Dinner** (departure by coach from Nassau Street at 6pm)	Wednesday 17 July 2024

Thursday 18 July 2024

Session 12

09:30-10:15	Invited Talk	Thursday 18 July 2024

V. **Vilasini** (Inria University Grenoble Alpes)

Generalised quantum circuits for Extended Wigner's Friend Scenarios: logically and causally consistent reasoning without objectivemeasurement events

Abstract:When using quantum theory, observers (or agents) are usually treated classically. In Extended Wigner's Friend Scenarios (EWFS) the agents are also modelled as unitarily evolving quantum systems, with no-go results asserting that this would have radical implications for physics. In EWFS, Frauchiger and Renner (FR) have claimed that agents reasoning using quantum theory will arrive at logical paradoxes, while other works, such as the Local-Friendliness theorem, reveal the absence of an objective notion of measurement events, argued to lead to serious problems for causality. Is it possible to reliably make and test scientific predictions, consistently reason about the world when applying quantum theory universally, without assuming that observed measurement outcomes are absolute and while adhering to causal principles? We give a positive answer by developing a general quantum circuit framework for EWFS, providing concrete rules by which quantum agents can consistently reason and make predictions while respecting a well-defined causal structure. Formalising the concept of Heisenberg cuts by mapping them to distinct channels in a quantum circuit, we prove that FR-type paradoxes can be fully resolved by making explicit the conditioning on the quantum channels used in the reasoning process. Although the framework allows measurement events to be fundamentally subjective in EWFS, we show that an objective notion of measurement events and classical measurement records nevertheless emerges in real-world experiments (which are formally distinguished from Wigner's Friend type thought experiments). Our work demonstrates the possibility of a relational and yet operational framework overcoming challenges to logical and causal reasoning in EWFS, without modifying the Born rule, quantum unitarity or the axioms of classical logic and probability theory applied to measurement outcomes. This also provides a unifying formalism for analysing different EWFS arguments, including agent-based as well as more meta-physical aspects.

Based on initial results presented in: V. Vilasini and Mischa P. Woods, arXiv:2209.09281 (2022).

10:15-10:45	Contributed Talk	Thursday 18 July 2024

Simon Milz (Trinity College Dublin)

Hidden Quantum Memory Effects and Genuinely Quantum Processes

Abstract: In classical physics, memoryless dynamics and Markovian statistics are one and the same. This is not true for quantum dynamics, first and foremost because quantum measurements are invasive. Going beyond measurement invasiveness, there exist additional distinctions between classical and quantum processes, namely the possibility of hidden quantum memory: While Markovian statistics of classical processes are always reproduceable by a memoryless dynamical model, this fails to hold in quantum mechanics. Specifically, there exist examples of non-Markovian memory effects whose manifestation depends on whether or not a previous measurement is performed — an impossible phenomenon for memoryless dynamics. This result is strengthened by the possibility of quantum processes which are Markovian independent of how they are probed, but nonetheless still incompatible with memoryless quantum dynamics. These phenomena establish the existence of hidden quantum memory — memory that is not detected on the level of observed statistics but nonetheless requires memory for their creation. One of the main ingredients for these peculiarities to be displayed is measurement invasiveness, a concept that is, in principle, also possible in classical physics. This begs the question of whether or not there are truly quantum effects in the temporal realm, i.e., those that cannot be mimicked by classical stochastic processes with active interventions. However, as I will discuss, there are indeed genuinely quantum processes; that is, processes that can never be probed in a non-invasive way, no matter the choice of instrument, thus establishing a distinct demarcation line between classical and quantum processes.

10:45-11:15	Coffee Break	Thursday 18 July 2024

Session 13

11:15-11:45	Contributed Talk	Thursday 18 July 2024

Nick Ormrod (University of Oxford)

Classicality from Causality

Abstract: This talk will introduce a new paradigm for decoherence and emergent classicality, based on quantum causal structures.

Whereas decoherence is usually defined in terms of the properties of, or the evolution of, a quantum state, this talk will define it entirely in terms of the causal structure of a unitary process. It will then show that this causal decoherence singles out unique sets of projectors relative to every set of systems involved in the process. Remarkably, the set of projectors that are singled out by causal decoherence always give rise to a probability distribution in a natural way – technically speaking, they generate a decoherent (or “consistent”) set of histories.

This means that we can think of those projectors as describing stochastic, classical events. In this way, causal decoherence singles out a unique classical reality relative to every set of systems in a unitary process. Classicality emerges from quantum causality.

Loosely based on: https://arxiv.org/pdf/2401.18005.pdf.

11:45-12:15	Contributed Talk	Thursday 18 July 2024

Nicholas LaRacuente (Indiana University Bloomington)

Emergent Classicality from Quantum Complexity

Abstract: The emergence of classical phenomena, such as in measurements, is often explained as the amplification of information from its original quantum medium to macroscopic scales. Such processes rapidly and redundantly encode information into the environment and its entanglement structure, accelerating decoherence in a preferred basis (Zurek 2003). While current technology usually cannot reverse measurements, whether it should be possible in principle to re-cohere ``measured'' quantum systems remains a famous puzzle and debate. In the "Wigner's friend" thought experiment, the "friend" who performs an experiment observes the irreversible onset of classicality, while "Wigner" may at first observe his friend become reversibly entangled with the measured system. Adding semi-classical spacetime to the model, irreversible decoherence arises when entanglement stretches across causal boundaries. For instance, electromagnetic/gravitational radiation emitted by a system can be lost behind causal horizons such as that of a black hole or escape to infinity (Danielsen, Satishchandran, & Wald 2022 & 2023). In semiclassical theories, that information is permanently, objectively lost. In quantum gravity, however, spacetime itself may admit a quantum description. One may again ask: could a more technologically advanced agent in principle recohere the system from Hawking quanta (Hayden & Preskill 2007) or other local degrees of freedom (Bousso & Pennington 2023)? We propose that irreversible decoherence in the semiclassical theory corresponds to runaway growth of complexity to restore the quantum system's original state. This correspondence builds on proposed dualities between causal horizons in gravity and information-scrambling quantum dynamics. The duals of objects such as black holes may induce initially exponential complexity growth that would be impossible to match in approximately flat spacetime (Jian, Swingle & Xian 2021). Furthermore, such systems and correspondences may exhibit pseudorandomness as a barrier to information reconstruction (Bouland, Fefferman & Vazirani 2020). This correspondence is specifically analyzed in the duality between the Sachdev-Ye-Kitaev (SYK) model and Jackiw–Teitelboim (JT) gravity (Kitaev 2015. Mertens & Turiaci 2022. Maldacena & Stanford 2016). A fully quantum but computationally limited Wigner may conclude that while a friend's measurement in principle preserves quantumness and invertibility, the presence of causal horizons anywhere in space makes measurement practically irreversible. This presentation includes joint work with Daine Danielsen and Victor Zhang at UChicago. D.L.D. acknowledges his support as a Fannie and John Hertz Foundation Fellow holding the Barbara Ann Canavan Fellowship, and as an Eckhardt Graduate Scholar in the Physical Sciences Division at the University of Chicago. N.L. was previously supported by IBM as a Postdoctoral Scholar at the University of Chicago. V.G.Z. is supported by the NSF Grant No. 21-05878 to the University of Chicago. This material is based upon work supported by the National Science Foundation under Grant CCF-2044923 (CAREER).

12:15-14:00	Lunch Break	Thursday 18 July 2024

Session 14

14:00-14:30	Contributed Talk	Thursday 18 July 2024

José Luis Gaona Reyes (Università degli Studi di Trieste)

Incorporation of a collapse mechanism in the Wheeler-DeWitt equation

Abstract: A quantum theory of gravity implies a structure of spacetime which is fundamentally quantum. On the other hand, the description of spacetime provided by General Relativity is done at a classical level. The some holds for a wide range of observations in a cosmological context. This requires a quantum-to-classical transition. In this talk, I will discuss how dynamical collapse models of the wave function provide a mechanism to allow for a quantum-to-classical transition, either in the case of quantum fields in a classical spacetime, as well as in the structure of spacetime itself. In particular, I will describe how the incorporation of collapse terms in certain Wheeler-DeWitt equations with a well-defined clock variable allows the emergence of a well-defined geometry in the Universe starting from a quantum superposition of different geometries.

14:30-15:00	Contributed Talk	Thursday 18 July 2024

Alessandro Tosini (University of Pavia)

Information and disturbance in a physical theory

Abstract: Any experiment is intended to provide information on a system via a measurement. However, as we learn from quantum theory, it is generally not possible to extract information without disturbing the state of the system or its correlations with other systems. The interplay between information and disturbance has been largely investigated as a quantum/classical divide and the no-information without disturbance theorem has been proved in quantum theory. The traditional notions of information and disturbance are deeply anchored to the properties of quantum theory. In particular, the notion of disturbance considers only the fate of the system state after the measurement. However, the fact that the system state is left untouched ensures that also correlations are preserved only in the presence of local tomography. We introduce a notion of disturbance that holds for an arbitrary theory and prove that a system satisfies no-information without disturbance if and only if the identical evolution cannot result form the coarse-graining of other operations. We then prove a structure theorem for probabilistic theories, showing that any system decomposes into a classical system and a system that satisfies no-information without disturbance. Via concrete examples we exhibit the independence of no-information without disturbance from other typical quantum features as local tomography and states purification.

15:00-	Social programme	Thursday 18 July 2024

Friday 19 July 2024

Session 15

09:30-10:15	Invited Talk	Friday 19 July 2024

Nicole Yunger Halpern (NIST & University of Maryland)

Non-Abelian thermodynamics

Abstract: Thermalization helps define time's arrow and promotes classicality. It happens when asystem and environment interact: the two exchange quantities—heat, particles, electric charge, etc.—that are conserved globally. If quantum, the quantities are represented by Hermitian operators. We often assume implicitly that the operators commute with each other—for instance, in derivations of the thermal state's form. Yet operators' ability to not commute underlies quantum phenomena such as uncertainty principles. What happens to thermodynamics if conserved quantities fail to commute with each other? This question, mostly overlooked for decades, underlies the growing field of non-Abelian thermodynamics. Noncommutation of conserved thermodynamic quantities turns out to decrease entropy-production rates, enhance average bipartite entanglement, alter basic assumptions behind many-body thermalization, and more. These results, though initially information-theoretic, have been extending into many-body physics and experiments.

[1] Majidy, Braasch, Lasek, Upadhyaya, Kalev, and NYH, Nat. Rev. Phys. 5, 689-698 (2023).

10:15-10:45	Contributed Talk	Friday 19 July 2024

Benjamin Yadin (University of Siegen)

Thermodynamics with indistinguishable particles: symmetries and paradoxes

Abstract: The notion of indistinguishable particles has been at the heart of statistical mechanics since Gibbs and Boltzmann. A proper counting of microstates was necessary to derive the correct thermodynamic entropy of an ideal gas, and to resolve the Gibbs paradox on the entropy of mixing. This issue also relates to the observer-dependent nature of entropy. In quantum mechanics, the topic is substantially richer, with indistinguishability arising from symmetry of an experimenter's available operations under particle permutations or rotations of a hidden degree of freedom. Here, we present a mathematical toolbox for such settings, and an overview of results showing how the thermodynamics of indistinguishable quantum particles can be strikingly different from the classical case.

Firstly, foundational implications for the emergence of classicality are seen in a quantum upgrade of the Gibbs paradox [Nat. Commun. 12, 1471 (2021)]. When two gases with a hidden distinguishing degree of freedom are mixed, classical thermodynamics says that an observer without access to that degree of freedom should see no entropy increase. In a quantum model with bosons or fermions, we find a non-classical mixing entropy. Notably, this entropy does not vanish in the macroscopic limit but

in fact scales extensively. The emergence of classicality here is therefore explained by the complexity of measurements and operations required to observe this effect.

Next, we show how non-classical effects of indistinguishability may be realised in experiments with collectively controlled atomic ensembles. Group theory methods can be used to obtain thermodynamical properties when in contact with a thermal environment, showing a quantum enhancement to an Otto engine cycle [Phys. Rev. Research 5, 033018 (2023)]. We further push these open-system models to describe collective engines operating between two heat baths, examining the role of emergent exotic exchange symmetries beyond bosonic and fermionic [to appear].

10:45-11:15	Coffee Break	Friday 19 July 2024

Session 16

11:15-11:45	Contributed Talk	Friday 19 July 2024

Karen Hovhannisyan (University of Potsdam)

Long-time equilibration can determine transient thermality

Abstract: Equilibration of many-body systems is a central topic in virtually all nonequilibrium physics. While the equilibrium itself is well researched, very little is known about what happens during the transient period leading to it. The problem is especially challenging when the system's constituents are strongly coupled. Here we show that the transient dynamics is much more tractable than previously thought.

We consider the generic scenario of two initially thermal many-body systems starting to interact strongly. Their transient states quickly become non-Gibbsian, even if the systems eventually equilibrate. To see beyond this apparent lack of structure during the transient regime, we use a refined notion of thermality, which we call g-local. A system is g-locally thermal if the states of all its small subsystems are marginals of global thermal states. We numerically demonstrate for two harmonic lattices that whenever the total system equilibrates in the long run, each lattice remains g-locally thermal at all times, including the transient regime. This is true even when the lattices have strong long-range interactions within them. In all cases, we find that the equilibrium is described by the generalized Gibbs ensemble, with three-dimensional lattices requiring special treatment due to their extended set of conserved charges.

The unveiled thermal structure of the transient dynamics has far-reaching implications for nonequilibrium transport and thermodynamics, particularly for ultrafast phenomena in solid-state physics, where having a description of transient dynamics is vital. There, the so-called two-temperature model is commonly used to describe transient dynamics. We compare our findings with the two-temperature model, and while its standard form is not valid beyond weak coupling, we show that at strong coupling it can be partially salvaged by adopting the concept of a g-local temperature.

11:45-12:15	Contributed Talk	Friday 19 July 2024

Giulia Rubino (University of Bristol)

Revising the quantum work fluctuation framework to encompass energy conservation

Abstract: Work is a process-based quantity that typically requires interaction with a system and a measuring device at different times. While classical systems allow non-invasive interactions and accurate measurements, quantum systems present unique challenges due to the influence of the measuring device on the final value of work.

Recent studies have shown that for thermal states, any positive operator-valued measure (POVM) that satisfies the Jarzynski Equality (JE) -a relation linking the free energy difference between two states to the irreversible work along their connecting trajectories- must be consistent with the two-point measurement (TPM) scheme. Conversely, for coherent quantum states, it has been shown that it is impossible for any state-independent scheme using POVM to both obey energy conservation and accurately reproduce the results of the TPM scheme. This highlights an inherent challenge in formulating a universal definition of work applicable to coherent quantum systems that aligns with the JE. In this talk, I will propose a way to overcome this challenge by introducing a quantum correction to the JE and a framework for measuring quantum work that verifies the quantum-corrected JE. This new approach to measuring work for coherent quantum states ensures energy conservation and maintains close alignment with the TPM scheme. I will further underscore the practicality and effectiveness of this framework by providing a detailed circuit implementation of my proposed scheme.

12:15-14:00	Lunch Break	Friday 19 July 2024

Session 17

14:00-14:30	Contributed Talk	Friday 19 July 2024

Eoin Carolan (University College Dublin)

Operator growth and spread complexity in open quantum systems

Abstract: Information scrambling and chaos are two related phenomena for quantum systems undergoing unitary evolution, with the former strictly necessary for the latter. The desire for dynamical measures of quantum chaos in an analogous way to their classical counterparts has lead to the development of out-of-time-order correlators (OTOCs) as a way to capture the spread of initially local information. OTOCs fail as an indicator of quantum chaos at long times when the system of interest is exposed to an external environment. Motivated by Krylov complexity and the operator growth hypothesis, we propose the entropy of the population distribution for an operator in time as a way to capture the complexity of the internal information dynamics of a system when subject to the environment. We demonstrate its effectiveness by applying it to the maximally chaotic Sachdev-Ye-Kitaev model. We explore the dynamics of the system in both its Krylov basis and a basis of string operators. In both cases we probe the long-time dynamics of the model and the phenomenological effects of decoherence on the complexity of the dynamics.

14:30-15:00	Contributed Talk	Friday 19 July 2024

Thiago Rodrigues de Oliveira (Universidade Federal Fluminense)

Continuous Transition Between Weak and Strong Thermalization using Rigorous Bounds on Equilibration of Isolated Systems

Abstract: We analyze strong and weak thermalization regimes from a perspective of rigorous mathematical upper bounds on the equilibration of isolated quantum systems. We show that weak equilibration can be understood to be due to the small effective dimension of the initial state. Furthermore, analyzing the scaling of an upper bound on the fluctuations, we show that the observable fluctuations decay exponentially with the system size for both weak and strong thermalization indicating no sharp transitions between these two regimes.

Based on: https://arxiv.org/abs/2310.13392

15:00-15:30	Contributed Talk	Friday 19 July 2024

Jiaxuan Zhang (University of Oxford)

Compatible Complexity for n-dimensional Quantum Measurements

Abstract: Measurement incompatibility is one of the key concepts in quantum physics, which was first articulated in the famous Uncertainty Principle (Heisenberg, 1927). Traditionally, measurement compatibility has been understood in terms of commuting observables. While commutativity relationships are sufficient for characterizing compatibility for projective measurements, the latter does not exhaust the most general process. For general quantum measurements, represented by positive-valued operator measures (POVMs), a broader notion of compatibility is necessary, and non-commuting measurements can still be compatible. Compatible measurements allow for classical memory instead of quantum memory in experiments. However, more measurement outcomes increase the difficulty of implementing the measurement in practice. Thus, reducing the complexity for compatible families of POVMs is important from the application point of view.

Despite the large amount of works studying the compatible complexity of qubit measurements (Bavaresco et al., 2017; Skrzypczyk et al., 2020; Zhang et al., 2023), relevant research on higher dimensions is rare. In this work, we study the compatibility complexity for the n-dimensional POVMs, especially the qutrit case. We are interested in how noisy a n-dimensional quantum system must be before all measurements performed on it become compatible.

We adopt the notion of joint measurability for compatibility. A family of POVMs is joint measurable if and only if there exists some ''parent'' measurement that, with some classical processing, can substitute the function of the family of compatible ''children'' measurements (Skrzypczyk et al., 2020). We consider two definitions of the parent POVM: the canonical parent involves only coarse-graining of measurement outcomes, and the probabilistic parent allows for a stochastic processing of the outcomes. Both forms lead to equivalent properties of whether a family of POVMs is compatible (Skrzypczyk et al., 2020). However, the sizes of parent POVMs are usually sufficiently smaller in the latter case.

We use canonical parents for families of dichotomic and trichotomic children to find lower bounds. By verifying the positivity constraint for these parents, we establish lower bounds for arbitrary cross-

sections of the qutrit and ququart measurement space. Our method can be directly applied to higher dimensions. We also adopt the geometric method for finding lower bounds for planar qubit measurement from previous work (Zhang et al., 2023), expanding the results to the qutrit case.

For upper bounds, we use semidefinite programming (SDP) adjusted from previous works (Bavaresco et al., 2017; Zhang et al., 2023) to simulate dichotomic or trichotomic planar children POVMs. We prove the parent POVMs with the longest Bloch vectors are optimal for simulating larger families of children POVMs. Our results show that trichotomic children behave better in finding lower bounds, while dichotomic children behave better in finding upper bounds.

Our study offers novel analyses of compatibility complexity in quantum measurements beyond the 2-dimensional qubit systems. Our results can facilitate many quantum operations requiring measurement incompatibility, like quantum steering (Uola, 2020). Since the noise between the state and measurements can be exchanged, studying the robustness of incompatible measurements also helps us learn about the noise the states can tolerate during transmission. There are increasing number of groups working on implementing quantum computation using qutrits (Gokhale, 2020; Blok, 2021; Roy, 2023). Understanding the properties of higher dimensional quantum measurement will allow us to expand the applications and enhance our understanding of quantum phenomena.

15:30-15:45	Closing Words	Friday 19 July 2024

15:45	End of Conference & Departure	Friday 19 July 2024