The Mathematical Foundations of Quantum Mechanics - John von Neumann and his Impact on Physics in 2025

835. WE-Heraeus-Seminar

25 - 28 May 2025

at the Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 835. WE-Heraeus-Seminar:

John von Neumann's scientific impact ranges from quantum mechanics to economics and computer programming. He must be considered one of the most universal, creative, and influential scientists of the 20th century. This seminar focuses, from today's perspective, on the role of the early seminal contributions by John von Neumann in quantum mechanics.

Already in 1927 von Neumann published a series of articles in which he clarified "The Mathematical Foundations of Quantum Mechanics". This is the title of his core paper, his well-known book from 1932 and, appropriately, of our seminar. His work, including the notion of Hilbert space, the role of operators, and the statistical interpretation of quantum ensembles, is still the basis for every student of the subject. His further work on quantum logic and, especially, operator algebras has developed into active current research fields. Nevertheless, von Neumann's role as one of the founding fathers of quantum theory is often not appreciated.

In addition, von Neumann revolutionized economic theory with his thinking in terms of game strategies, and was a key figure in the theory and construction of early computers. This topic connects again with quantum mechanics via the current endeavours of building a quantum computer. Accordingly, the best way to appreciate the work of this towering genius is to outline current research, while retracing its roots in von Neumann's ideas. An excellent array of active scientists in the fields shaped by von Neumann till today is ready to make these connections, and will attract the attention of scientists from the junior to the senior stage.

The topic of the seminar fits perfectly into the IYQST, the International Year of Quantum Science and Technology proclaimed by the United Nations in June 2024, and the imminent centennials of quantum mechanics.

Scientific Organizer:

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Introduction

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Registration:

Elisabeth Nowotka (WE Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h) and Monday
morning

Program

Program

Sunday, 25 May 2025

17:00 – 21:00	Registration	
18:00	*BUFFET SUPPER and informal get-together*	

Monday, 26 May 2025

08:00 – 10:00	*BREAKFAST*	
10:30 – 11:00	Scientific organizers	**Opening**
	Stefan Jorda	**About the Wilhelm and Else Heraeus-Foundation**

Kick-off Lecture

11:00 – 12:30	Reinhard Werner	**Von Neumann, projections and the functional calculus**
12:30	*LUNCH*	

Quantum Mathematical Structures I

14:00 – 14:45	Roberto Longo	**Von Neumann Algebras over the Years**
14:45 – 15:30	Lauritz van Lujik	**Von Neumann algebraic quantum information theory**
15:30 – 16:00	*COFFEE BREAK*	

Program

Monday, 26 May 2025

Von Neumann beyond Quantum

16:00 – 16:45	Helmut Bölcskei	**Cellular automata, many-valued logic, and deep neural networks**
16:45 – 17:30	Tinne Hoff Kjeldsen	**From mathematization of games to mathematical programming: the significance of von Neumann's minimax theorem, duality and WWII**
18:30	*DINNER*	

Evening Lecture: Game Theory and Economy

19:30 – 20:30	Bernhard von Stengel	**John von Neumann, Game Theory, and Computing**

Program

Tuesday, 27 May 2025

08:00	*BREAKFAST*	

Quantum measurements

09:00 – 09:45	Dagmar Bruß	**Quantum measurements: von Neumann and beyond**
09:45 – 10:30	Michel Brune	**Quantum measurement and decoherence**
10:30 – 11:00	*COFFEE BREAK*	

Quantum Mathematical Structures II

11:00 – 11:45	Pekka Lahti	**Quantum Logic - a short survey**
11:45 – 12:30	Nilanjana Datta	**Quantum Entropies**
12:30	*LUNCH*	

Computer Architectures

14:00 – 14:45	David Divincenzo	**Computer architectures, von Neumann and quantum**
14:45 – 15:30	Kasra Nowrouzi	**Optimal quantum computing architecture through deep co-design**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 18:30	**Poster session**	
18:30	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	

Program

Wednesday, 28 May 2025

08:00	*BREAKFAST*	

History, Quantum Thermodynamics

09:00 – 09:45	Michel Janssen	**Arch and Scaffold: Jordan's statistical transformation theory and von Neumann's Hilbert space formalism**
09:45 – 10:30	Valerio Scarani	**Retrodiction and irreversibility**
10:30 – 11:00	*COFFEE BREAK*	

Quantum Thermodynamics

11:00 – 11:45	Renato Renner	**Moving the cut: von Neumann's measurement**
11:45 – 12:30	Artur Widera	**Quantum thermodynamics with cold atoms**
12:30	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Thursday; however, a self-service breakfast will be provided on Thursday morning

Posters

Posters

Mustafa Bakr	**Toward realization of scalable packaging and wiring for coaxmon superconducting quantum circuits**
Daniel Derr	**Enhancing quantum imaging precision: squeezed light and phase distillation techniques**
Marie Erika Diesenberger	**An introduction to self-adjointness in quantum theory**
Ahana Ghoshal	**Optimising measurement of correlators for fermionic quantum simulators**
Mark Goh	**Overlap gap property limits limit swapping in QAOA**
Ladina Hausmann	**Wigner meets von Neumann in a black hole**
Joel Huber	**A weak measurement based toy model to probe quantum properties in a cosmological setting**
Matthias Hüls	**Applying optimal control to circularize Rydberg atoms**
Niklas Jung	**The quantum optical master equation is of the same order of approximation as the redfield equation**
Ashutosh Mishra	**Gradient evaluation of analytic controls for large Hilbert space**
José Nogueira	**Unexpected consequences of postquantum theories in the graph-theoretical** **approach to correlations**
Fynn Otto	**Hyperinvariant spin network states - an AdS/CFT model from first principles**
Martin Plávala	**All incompatible measurements on qubits lead to multiparticle bell nonlocality**

Posters

Thomas Schulte-Herbrüggen	**Lie meets von Neumann for symmetry characterisation of compact lie algebras**
Anja Seegebrecht	**Work, heat and internal energy in autonomous quantum systems**
Miralem Sinanovic	**Non-markovian ensemble propagation**
Alexander Stottmeister	**Relative entropy in lattice CFT**
Lea Van Dellen	**Spectral compatibility and analytical constraints in quantum marginal problems**
Nicolas Wittler	**Co-designing transmon devices for control with simple pulses**

Abstracts of Talks

(in alphabetical order)

Cellular automata, many-valued logic, and deep neural networks

Helmut Bölcskei

ETH Zurich, Switzerland

Abstract: This talk is devoted to the program set out in John von Neumann's 1948 Hixon Symposium paper "The general and logical theory of automata". Specifically, we develop a theory characterizing the fundamental capability of deep neural networks to learn, from evolution traces, the logical rules governing the behavior of cellular automata (CA). This is accomplished by first establishing a novel connection between CA and Łukasiewicz propositional logic. While binary CA have been known for decades to essentially perform operations in Boolean logic, no such relationship exists for general CA. We demonstrate that many-valued (MV) logic, specifically Łukasiewicz propositional logic, constitutes a suitable language for characterizing general CA as logical machines. This is done by interpolating CA transition functions to continuous piecewise linear functions, which, by virtue of the McNaughton theorem, yield formulae in MV logic characterizing the CA. Recognizing that deep rectified linear unit (ReLU) networks realize continuous piecewise linear functions, it follows that these formulae are naturally extracted from CA evolution traces by deep ReLU networks. A corresponding algorithm is provided. Finally, we show that the dynamical behavior of CA can be realized by recurrent neural networks.

Quantum Measurement and Decoherence

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Rydberg atoms and microwave photons stored in a high Q cavity constitutes a nearly ideal system for realizing a "photon box" in the spirit of gedanken experiments introduced by Einstein and Bohr for emphasizing the unbelievable strangeness of quantum theory. We will show how real experiments illustrate fundamental features of quantum measurement theory: state projection, quantum jumps and decoherence. On the basis on a quantum non-demolition (QND) photon counting method [1,2], we will present quantum trajectories revealing field evolution and Schrödinger cat state decoherence [3].

[1] S. Gleyzes, S. Kuhr, C. Guerlin, J. Bernu, S. Deléglise, U. Busk Hoff, M. Brune, J.-M. Raimond and S. Haroche, "Quantum jumps of light recording the birth and death of a photon in a cavity", Nature 446, 297-300 (2007).

[2] C. Guerlin, J. Bernu, S. Deléglise, C. Sayrin, S. Gleyzes, S. Kuhr, M. Brune, J.-M. Raimond and S. Haroche, "Progressive field-state collapse and quantum non-demolition photon counting", Nature, article, Nature 448, (2007).

[3] S. Deléglise, I. Dotsenko, C. Sayrin, J. Bernu, M. Brune, J. M. Raimond & Serge Haroche, "Reconstruction of non-classical cavity field states and movie of their decoherence", Nature 455, 510 (2008).

Quantum measurements: von Neumann and beyond

Raphael Brinster, Nikolai Wyderka, Hermann Kampermann, and Dagmar Bruß

Institute for Theoretical Physics III, Heinrich Heine University Düsseldorf, Germany

A von Neumann measurement is described by a set of projective operators. General measurements - so-called POVMs - may contain non-projective operators. They perform better than von Neumann measurements for certain tasks like unambiguous state discrimination. A POVM can always be represented as a projective measurement in a higher-dimensional space. However, the dimension of a quantum system is a resource that is possibly restricted: what about the situation when no additional degrees of freedom are available? If a POVM can be simulated by projective measurements acting on the same Hilbert space it is called projectively simulable. In general, determining whether a given POVM is projectively simulable or not is a hard problem. Analogously to entanglement witnesses, we construct non-simulability witnesses. The experimental implementation of these witnesses can prove that a given measurement is non-simulable, i.e. has properties that are truly beyond von Neumann measurements.

Quantum Entropies

Nilanjana Datta

University of Cambridge, Cambridge, U.K.

Entropies play a fundamental role in (classical and quantum) information theory. The most familiar entropy in quantum information theory (QIT) is named after von Neumann himself. The talk will start with the von Neumann entropy and then move on to several other related entropic quantities. There will be a discussion of some of their interesting mathematical properties, as well as their operational interpretations as optimal rates of various information-theoretic tasks in QIT, in the so-called "asymptotic memoryless setting". Next, analogous families of entropies in the more realistic "one-shot setting" of QIT will be discussed. Then, two important families of relative entropies (or divergences) which act as parents to the other entropies will be mentioned and their operational interpretations will be briefly discussed. The talk will end with the mention of a "grandparent entropy" which heads a large family tree (or zoo) of entropies, and which thus provides a unifying mathematical framework for the study of these quantities. The above topics draw upon various papers which will be mentioned during the talk.

Computer Architectures, von Neumann and Quantum

David DiVincenzo

Abstract:

von Neumann went through two major phases in specifying computer architectures, his “First draft of a report on the EDVAC” in 1945, and his “Probabilistic logics and the synthesis of reliable organisms from unreliable components”, formulated in 1952. These show a remarkable evolution of thinking: the first is prescriptive, with a list of familiar criteria for the kind of machines we recognise today as digital computers; the second is visionary, considering how computing can be done in the presence of a very noisy environment. Both approaches are reflected in current efforts to devise quantum computer architectures. There is a clear set of prescriptions for what needs to be done (with analogous but distinct criteria from von Neumann’s), and the realization that very creative approaches are needed to circumvent faults — in the quantum case, decohering interactions — and still make computation reliable.

Arch and Scaffold: Jordan’s statistical transformation theory and von Neumann’s Hilbert space formalism*

Michel Janssen

School of Physics and Astronomy, University of Minnesota
Lichtenberg Group for History and Philosophy of Physics, University of Bonn

*Based on joint work with Anthony Duncan (University of Pittsburgh)

In early 1927, Paul Dirac and Pascual Jordan, independently of one another, published their versions of a general formalism tying the various forms of the new quantum theory together and giving the theory’s statistical interpretation in full generality. This formalism has come to be known as the Dirac-Jordan (statistical) transformation theory. A few months later, in response to these publications, John von Neumann published his Hilbert space formalism for quantum mechanics. The relation between these two formalisms can be captured in terms of a metaphor of arches and scaffolds that I have argued fits a number of instances of theory change in physics. What is unclear in this case is which formalism serves as the scaffold and which one as the arch. Did von Neumann build an arch on the scaffold built by Jordan? Or did von Neumann build a scaffold to prevent the arch built by Jordan from collapsing? Either way, a narrative for this episode in the history of quantum mechanics based on the arches-and-scaffolds metaphor illustrates the promise of borrowing ideas from the approach to evolutionary biology known as evodevo for reconstructing the evolution of theories rather than species.

From mathematization of games to mathematical programming: The significance of von Neumann's minimax theorem, duality and WWII

T. H. Kjeldsen[1]

[1]*Department of Mathematical Sciences, University of Copenhagen, Universitetsparken 5, DK-2100, Copenhagen, Denmark*

In this history of mathematics talk, we will discuss connections of various kinds between John von Neumann and his early work on game theory and the emergence and development of mathematical programming in the USA in the context of WWII. The focus will be on the significance of von Neumann's minimax theorem in two-person zero-sum games on the one hand and duality in mathematical programming on the other, as well as the conditions of WWII for this development.

References

[1] G. B. Dantzig, Reminiscences about the Origins of Linear Programming. *Operations Research Letters*, **1**, 43-48 (1982)

[2] D. Gale, H. W. Kuhn, A. W. Tucker, Linear programming and the theory of games. In *Activity Analysis of Production and Allocation*, T. C. Koopmans, Ed., Cowles Commission Monographs, New York: Wiley, **13**, 317–329 (1951)

[3] T. H. Kjeldsen, A Contextualized Historical Analysis of the Kuhn-Tucker Theorem in Nonlinear Programming: The Impact of World War II. *Historia Mathematica*, **27**, 331-361 (2000)

[4] T. H. Kjeldsen, John von Neumann's Conception of the Minimax Theorem: A Journey Through different Mathematical Contexts. *Archive for History of Exact Sciences*, **56**, 39-68 (2001)

[5] T. H. Kjeldsen, From duality in mathematical programming to Fenchel duality and convex analysis: Duality as a force of inspiration in the creation of new mathematics. In *Duality in 19th and 20th Century Mathematical Thinking*, R. Krömer, E. Haffner, K. Volkert, Eds., Springer, 733–758 (2024)

[6] H. W. Kuhn, A. W. Tucker, Nonlinear programming. In *Proceedings of the Second Berkeley Symposium on Mathematical Statistics and Probability*, J. Neyman, Ed., 481–492 (1951)

[7] M. S. Rees, Mathematics and the Government: The Post-War Years as Augury of the Future. In *The Bicentennial Tribute to American Mathematics, 1776-1976*, D. Tarwater, Ed, MAA, 101-116 (1977)

[8] J. von Neumann, Zur Theorie der Gesellschaftsspiele, *Mathematische Annalen*, **100**, 295–320 (1928)

[9] J. von Neumann, O. Morgenstern, *Theory of Games and Economic Behavior*. Princeton, NJ: Princeton Univ. Press (1944)

Quantum Logic

- a short survey -

Pekka Lahti
University of Turku

Quantum logic, as a search for an axiomatic basis of quantum mechanics, arose with the 1936 paper of Garrett Birkhoff and John von Neumann entitled *The Logic of Quantum Mechanics*. After briefly summarizing the main results of this paper, we will revisit the fundamental common proposition-state structures of quantum logic as obtained from various approaches to probabilistic physical theories and the representation of these structures through orthomodular spaces. Subsequently, we will explore three different scenarios to delineate the orthomodular space representation as a classical Hilbert space representation, paying most attention to Solèr's theorem and the symmetry arguments supporting the application of this result. Additionally, we will discuss some arguments that necessitate the Hilbert space to be complex. Finally, we will briefly address some of the axiomatizations of quantum mechanics derived from the perspective of quantum information theory.

von Neumann algebras over the years

Roberto Longo

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The subject of Operator Algebras was originally designed by John von Nuemann as a framework for the description of Quantum Mechanics. The monumental work by Murray and von Neumann put the basis of the theory and already showed connections with different mathematical subjects as Group Representations, Ergodic Theory, and other. Initially, several years were needed to understand the great relevance of their work. Today we know that von Neumann algebras have a crucial interplay with several other subjects as Knot Theory, Index Theorems, Quantum Groups, etc... However, the interplay with Quantum Physics has remained constant over the time.

I will talk on some highlights about von Neumann Algebras over the years, with focus on the relation with Quantum Field Theory. The fundamental Modular Theory of Tomita-Takesaki in the early `70s has been deeply applied in the community of Local Quantum Field Theory and provided a new light. Presently, Modular Theory is a central topic in Theoretical Physics and gives new perspectives and language, with notions and results that are not otherwise attainable.

Optimal Quantum Computing Architecture through Deep Co-Design

Abhi Rajagopala[1], Akel Hashim[1], Akhil Francis[1], Anastasiia Butko[1], Gang Huang[1], Irfan Siddiqi[1], Katherine Klymko[1], Neel Vora[1], Neelay Fruitwala[1], Ravi Naik[1], Yilun Xu[1], Kasra Nowrouzi[1]

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Much like classical computers, quantum computers follow an abstraction model for their architecture (e.g. Figure 3 in [1]). The performance of a quantum computer is dependent on both the performance of each layer of this abstraction model, as well as the optimality of the abstraction model itself. In this talk, I will first set the context by describing our full-stack superconducting quantum computers at the Advanced Quantum Testbed [2] at Lawrence Berkeley National Laboratory. I will then motivate our strategy in addressing the quantum architecture problem and discuss a few examples of significant performance improvements as a result of deep co-design across the abstraction layers (e.g. [3], [4]). Based on these, I will make technical and organizational suggestions for continuous advancement of optimal quantum architecture going forward.

References

[1] Fu, X., Riesebos, L., Lao, L., Almudever, C.G., Sebastiano, F., Versluis, R., Charbon, E. and Bertels, K. A heterogeneous quantum computer architecture. *Proceedings of the ACM International Conference on Computing Frontiers*, pp. 323-330, (2016)

[2] https://aqt.lbl.gov/

[3] Fruitwala, N., Hashim, A., Rajagopala, A.D., Xu, Y., Hines, J., Naik, R.K., Siddiqi, I., Klymko, K., Huang, G. and Nowrouzi, K. Hardware-efficient randomized compiling. *arXiv preprint arXiv:2406.13967*. (2024)

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Moving the cut: von Neumann's measurement

Ladina Hausmann and Renato Renner

Institute for Theoretical Physics, ETH Zurich, Switzerland

In his study of the quantum measurement process, von Neumann pointed out the need to subdivide the world into two parts: the observed system and the observer. However, the subdivision — known as the "cut" — is motile, i.e., no physical law determines its location. As a consequence, different placements of the cut might lead to different predictions, thus rendering the use of quantum theory ambiguous. But, fortunately, in standard situations with only one single observer, the predictions for the outcomes of measurements remain independent of the cut, as von Neumann famously demonstrated.

In this talk, I will explore the role of the cut in situations that go beyond the one considered by von Neumann. A key idea entering the analysis is that an observer requires background information to access and measure a system. While this information is often implicit, I will show that insights from quantum gravity yield bounds on its size. Specifically, the amount of background information that an observer — who can themself be considered a system — must possess to measure another system depends on the boundaries between these systems.

To illustrate the consequences of this idea, I will revisit a variant of the Wigner's friend thought experiment. The experiment involves multiple observers, some capable of manipulating entire laboratories, inside which other observers perform measurements. It has recently been discovered that shifting the cut in such situations can lead to contradictions. However, by taking into account the background information required for measurements, these contradictions can be resolved.

Retrodiction and irreversibility

Valerio Scarani

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More than half a century ago, Watanabe contended that irreversibility should be understood as “irretrodictability”: knowing the output of a process (“future”), one can only make probabilistic statements about the input (“past”). Classically, this type of inference uses Bayes rule. Quantum analogs of Bayes rule have been proposed some time ago, but are still a topic of investigation.

In this talk, I shall start by proving that the density matrix, which is sufficient for all predictions, is not sufficient for retrodiction: in the latter case, the belief on the preparation plays also a role [LGS25; see also PM25 for related ideas]. Then I shall present quantitative definitions of irreversibility as dependence of the retrodictive map on the reference prior [LAS25]. If there is time, I shall quickly discuss why the extension of Watanabe’s idea to thermodynamical dissipation, conjectured in [BS21,ABS21] is still open.

[LBS25] M. Liu, G. Bai, V. Scarani, https://arxiv.org/abs/2502.10030

[PM25] J. Pinske, K. Molmer, https://arxiv.org/abs/2504.16170

[LAS25] L. Liu, C.C. Aw, V. Scarani, https://arxiv.org/abs/2503.12112

[BS21] F. Buscemi, V. Scarani, Phys. Rev. E 103, 052111 (2021) https://arxiv.org/abs/2009.02849

[ABS21] C.C. Aw, F. Buscemi, V. Scarani, AVS Quantum Sci. 3, 045601 (2021) https://arxiv.org/abs/2106.08589

Von Neumann algebraic Quantum information Theory

<u>L. van Luijk</u>, A. Stottmeister, R. F. Werner and H. Wilming

Leibniz Universität Hannover, Hanover, Germany

I will present basics of von Neumann algebraic quantum information theory with an emphasis on entanglement theory.

We will consider agents with partial access to a quantum system, typically with infinitely many degrees of freedom. For instance, an agent might be able to implement all operations that act solely on some subsystem. Under suitable assumptions, the operations and measurements that are accessible to the agent described by a von Neumann algebra on the system's Hilbert space.

Following the pioneering work [1], we are interested in the interplay between algebraic properties of the von Neumann algebra and operational tasks that can (or cannot) be performed by the agent.

The main result is that the classification of von Neumann factors in terms of type and sub-type can be completely recovered from operational tasks in entanglement theory [2, 3, 4].

References

1. Summers, Werner. *On Bell's inequalities and algebraic invariants*. Lett Math Phys 33, 321–334 (1995). DOI: 10.1007/BF00749686
2. Van Luijk, Stottmeister, Werner, Wilming. *Relativistic Quantum Fields Are Universal Entanglement Embezzlers*. Phys. Rev. Lett. 133.26 (2024). DOI: 10.1103/PhysRevLett.133.261602.
3. Van Luijk, Stottmeister, Werner, Wilming. *Pure state entanglement and von Neumann algebras* (2024). arXiv:2409.17739
4. Van Luijk, Stottmeister, Werner, Wilming. *Embezzlement of entanglement, quantum fields, and the classification of von Neumann algebras* (2024). arXiv: 2401.07299

John von Neumann, Game Theory, and Computing

Bernhard von Stengel

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In this talk, directed at a general audience with interest in mathematics, we give an overview of von Neumann's role and contributions in the development of game theory and computing [1, 2]. In game theory, active randomization, long known to be important, is essential for von Neumann's minimax theorem for zero-sum games [3, 4]. It was later extended by John Nash [5, 6] (and dismissed by von Neumann) to include games with win-win (non-zero-sum) outcomes. Nash equilibrium proved more successful in economic theory than the "cooperative games" created by von Neumann and Oskar Morgenstern in their monumental "Theory of Games and Economic Behavior" [6]. The minimax randomization probabilities are related to optimization variables in linear programming, which as a field blossomed with the advent of the software-driven electronic computers that von Neumann co-invented [7].

References

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[2] P. R. Halmos, The legend of John von Neumann. *The American Mathematical Monthly* 80(4), 382–394 (1973)

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[4] B. von Stengel, *Game Theory Basics*. Cambridge University Press (2022)

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[7] J. von Neumann and O. Morgenstern, *Theory of Games and Economic Behavior*, 2nd ed. Princeton University Press, Princeton, NJ (1947)

[8] G. Dyson, *Turing's Cathedral: The Origins of the Digital Universe.* Pantheon Books (2012)

Von Neumann, projections and the functional calculus

R.F. Werner[1]

[1]QI Group, Leibniz Universität Hannover, Germany
[2] another Institute, another town, another country

One key feature of von Neumann’s mathematical framework that has effectively been abandoned in quantum information theory, is the role of projection operators as the sole representatives of yes/no measurements. Instead, we nowadays allow any positive operator less than the identity, and more generally positive operator valued measures rather than projection valued ones to represent observables. In this talk I retrace von Neumann's approach, based on a vector space of observables with a functional calculus. This may serve as a prelude to some of the later talks, specifically measurement theory, von Neumann algebras, and quantum logic. I will then discuss some of the criticism against this approach. The tension between taking sums of observables as an obvious operation with products of observables a more dubious one, versus taking products and the functional calculus as obvious and finding sums problematic, helps to understand what John Bell missed, when he called von Neumann's proof against hidden variables "silly".

References

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[2] JvN, Wahrscheinlichkeitstheoretischer Aufbau der Quantenmechanik, Gött.Nach. 245-272, (1927)
[3] JvN, Allgemeine Eigenwerttheorie Hermitescher Funktionaloperatoren, Math.Ann. 102:49-131 (1929)
[4] Workshop talks of Lahti, van Luijk, Longo, Bruß

Quantum thermodynamics with cold atoms

Artur Widera[1]

[1] RPTU Kaiserslautern-Landau and State Research Center OPTIMAS,
Kaiserslautern, Germany

With the growing interest in nonequilibrium phenomena and the control of dynamic quantum processes, quantum thermodynamics is moving into the spotlight of quantum technologies. Cold atomic systems provide a powerful platform for investigating thermodynamic behavior at the quantum level with unprecedented precision. Their versatility enables the study of both individual atoms and strongly correlated many-body systems, thereby bridging the gap between microscopic quantum dynamics and macroscopic thermodynamic laws. In particular, cold atoms allow for the resolution of energy exchanges in nonequilibrium processes at the level of single quanta, granting access to full counting statistics of energy and work distributions. This capability opens up new avenues for understanding fundamental thermodynamic concepts in the quantum regime. In my talk, I will present a range of experimental examples demonstrating how single-atom control and many-body quantum physics contribute to our understanding of thermodynamic processes and measurements in complex quantum systems.

Abstracts of Posters

(in alphabetical order)

Toward Realization of Scalable Packaging and Wiring for Coaxmon Superconducting Quantum Circuits

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Realizing large-scale superconducting quantum circuits with individually addressable, high-coherence qubits remains a significant hardware challenge on the path toward utility-scale quantum computing. Scaling these systems is hindered by technical obstacles such as Josephson junction fabrication yield, precise frequency targeting, and quantum crosstalk. As the number of qubits increases, spurious modes and residual inter-qubit interactions degrade performance and reduce the fidelity of quantum operations. Overcoming these limitations requires scalable architectures that minimize parasitic couplings while maintaining robust connectivity. In this talk, I will present our Oxford effort[1-4] in developing engineered solutions for multiplexed and low-crosstalk operation across a 16-qubit device.

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Enhancing Quantum Imaging Precision: Squeezed Light and Phase Distillation Techniques

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Non-linear interferometers (NLIs) enable quantum-enhanced bicolour imaging without direct probe interaction, achieving phase sensitivity comparable to Heisenberg scaling [1]. While peak sensitivity occurs at specific operational phases [2], it remains vulnerable to noise. Currently used phase-shifting algorithms mitigate noise but are fundamentally limited by shot-noise scaling [3].

Our theoretical analysis explores NLIs in both the spontaneous and high-gain regime [4]. In the spontaneous regime NLIs show no fundamental difference to traditional linear interferometers. However, this drastically changes in the high-gain regime when operating the NLI at the optimal working point. In this operational mode NLIs allow in the presence of noise phase sensitivity scaling better than shot noise – a result tied to the photon statistics of squeezed vacuum.

This strategy enables bicolour imaging with phase uncertainties surpassing shot noise by leveraging near-optimal working conditions. Our findings advance quantum imaging distillation into high-gain regimes, combining supersensitive phase detection with bicolour techniques for quantum-enhanced sensing.

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An Introduction to Self-adjointness in Quantum Theory

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Quantum mechanics describes nature at atomic and subatomic scales, where particles exhibit wave-like properties characterized by a wave function. The fundamental equation governing this behaviour is called the Schrödinger equation, it dictates how quantum states evolve in space and time. Beyond its physical significance, this differential equation reveals deep mathematical structures that are essential for understanding quantum systems.

We studied how solutions of the Schrödinger equation can be expressed in terms of the unitary time evolution group, uniquely determined by its self-adjoint generator. Establishing the existence and uniqueness of such solutions requires tools from functional analysis, which provides a rigorous framework for quantum dynamics.

This builds upon von Neumann's foundational contributions to operator theory and Hilbert spaces and remains central to modern approaches in quantum mechanics.

Optimising measurement of correlators for fermionic quantum simulators

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Quantum simulators are powerful tools designed to replicate the behaviour of complex quantum systems, and they provide insights into phenomena that are difficult to study experimentally or computationally. Commonly, quantum simulators are based on qubits, enabling universal computation through digital quantum simulation. However, simulating many-body fermionic systems on conventional quantum computers poses significant challenges due to the overheads associated with the encoding of fermionic statistics in qubits, leading to the proposal of native fermionic simulators as an alternative [1, 2]. This raises the question of characterising the state of a fermionic simulator, which often boils down to measuring certain overlapping sets of few-point correlators from the output of the quantum simulation. We present a systematic framework for optimising the measurement of two- and four-point correlators in fermionic simulators based on their native fermionic gates. Our methodology of optimising the measurement settings involves constructing a graph representation of the correlators to be measured and another graph capturing the constraints imposed by the native gates, which are then combined to reformulate the measurement optimisation problem as a graph-theoretical framework solvable with various algorithms. We demonstrate the utility of this approach with applications to recent proposal of a fermionic simulator [2], showcasing its effectiveness in optimising the measurement settings for various sets of two- and four-point correlators and highlighting its potential for advancing fermionic quantum simulations.

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Overlap Gap Property limits limit swapping in QAOA

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Abstract

The Quantum Approximate Optimization Algorithm (QAOA) is a quantum algorithm designed for Combinatorial Optimization Problem (COP). We show that if a local algorithm is limited in performance at logarithmic depth for a spin glass type COP with an underlying Erdös–Rényi hypergraph, then a random regular hypergraph exhibits it as well. As such, we re-derived the fact that the average-case value obtained by QAOA for the Max-q-XORSAT for even $q \geq 4$ is bounded away from optimality even when the algorithm runs indefinitely if optimised using the so-called tree parameters due to the presence of the Overlap Gap Property (OGP). While this result was proven before, the proof is rather technical compared to ours. In addition, we show that the earlier result implicitly also implies limitation at logarithmic depth $p \leq \epsilon \log n$ providing an improvement over limitation at constant depth.

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Wigner meets von Neumann in a black hole

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The von Neumann measurement scheme shows that the placement of the Heisenberg cut is a choice. In particular, different observers may choose different placements of their cut. An observer may even choose to place another observer on the quantum side of her cut — this is known as a Wigner's friend experiment. Recent versions of such experiments have shown that combining the conclusions of observers with different Heisenberg cuts leads to paradoxes. Here, we argue that this conclusion is relevant for paradoxes in quantum gravity, like the firewall paradox of a black hole, as their structure is similar to a Wigner's friend experiment: they feature multiple observers with different Heisenberg cuts who combine their conclusions. Conversely, this similarity between paradoxes in quantum gravity and Wigner's friend experiments allows us to view the latter through a new lens.

A Weak Measurement Based Toy Model to Probe Quantum Properties in a Cosmological Setting

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Probing quantum properties in cosmology could offer profound insights into the fundamental nature of the universe. Given the great success of quantum theory, one can ask if the universe can be regarded as a quantum system. Here, we present a novel perspective on the detectability of quantum properties in cosmology. Firstly, we motivate a set of fundamental limitations inherent to observational cosmology, which defines the abstract notion of a *cosmological setting*. We then translate the cosmological limitations into operational constraints for a general quantum system. We propose a toy model, based on quantum weak measurements, and show how the limitations can be successfully circumvented by studying weakly coupled pointer degrees of freedom. Using quantum information techniques, we find that the non-commutativity of observables can be inferred by comparing measurement statistics, even though limited by the weakness of the measurements. The significance can be improved by assuming a decomposition of the system into identical subsystems. This result can provide a hint but not conclusive evidence, for the quantum nature of the system. Finally, we investigate Leggett-Garg inequalities [1], which separate classical from non-classical temporal correlations. We demonstrate that generalised Leggett-Garg inequalities [2] cannot be violated using three consecutive weak measurements while remaining agnostic about the underlying interactions. The notion of a cosmological setting for a quantum system, as well as the proposed toy model, may serve as a starting point for future investigations.

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Applying Optimal Control to circularize Rydberg Atoms

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Atoms in circular Rydberg states offer a promising platform for quantum simulation or sensing. Their preparation involves a multi-state transfer driven by radio-frequency pulses. Optimal pulse shapes that enable a fast and accurate state preparation have been found for single atoms using optimal quantum control techniques [1]. However, these pulses do not account for interatomic interactions that can perturb the intended dynamics. We generalize these previous efforts and develop pulses that accurately prepare two interacting atoms in a simultaneous circular state. Further, we identify a shift of transition frequencies as the crucial effect by which the interactions perturb the performance of pulses optimized for single atoms. Based on this, we propose a pulse parameterization that enables an adaption of optimal single atom pulses to atom pairs by optimizing at most four parameters. This approach can be used in a closed-loop optimization where the optimizer is directly connected to the experiment.

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The Quantum Optical Master Equation is of the same order of approximation as the Redfield Equation

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Quantum master equations are widely used to describe the dynamics of open quantum systems. All these different master equations rely on specific approximations that may or may not be justified. Starting from a microscopic model, applying the justified approximations only may not result in the desired Lindblad form preserving positivity. The recently proposed Universal Lindblad Equation [1], is in Lindblad form and still retains the same order of approximation as the Redfield master equation. In this work, we prove that the well-known Quantum Optical Master Equation is also in the same equivalence class of approximations. We furthermore compare the Quantum Optical Master Equation and the Universal Lindblad Equation numerically and show numerical evidence that the Quantum Optical Master Equation yields more accurate results.

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Gradient evaluation of analytic controls for large Hilbert space

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Open loop optimization of a quantum system involves computing gradients of propagators with respect to control parameters. One of the most commonly used optimal control methods is GRAPE, which assumes a piece-wise constant (PWC) pulse ansatz. While GRAPE allows for an easy evaluation of the gradients, it is harder to implement in experiments due to deviation from the ideal pulse shape. These pulses are also susceptible to be problem specific and hard to interpret. Analytic controls on the other hand have fewer parameters, making it easier to implement, and provide interpretable results.

In this work, we construct a general framework for computing analytical gradients of quantum dynamics for both open and closed system, for any general pulse shape. These are derived from the analytic solution to gradients, and can be evaluated in parallel using only a few state propagation. Additionally, by analysing locality and the speed of operator growth, we present cases where the computation of the gradients can be done by propagating only a single state, hence making it useful for systems with large Hilbert space. Finally, we extend these ideas to discuss robustness and simulability of quantum systems from an quantum optimal control perspective.

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

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

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Hyperinvariant Spin Network States - An AdS/CFT Model from First Principles

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We study existence and limitations for hyperinvariant tensor networks incorporating a local SU(2) Gauss constraint (HITs). As discrete implementations of the celebrated anti de-Sitter/conformal field theory (AdS/CFT) correspondence, holographic states and codes have created methodological and conceptual bridges between the fields of quantum information, entanglement theory and quantum gravity. Adding SU(2) symmetry onto the tensor network allows for a direct connection to spin network states, a basis of the kinematic Hilbert space of loop quantum gravity (LQG). We show that important aspects of the AdS/CFT correspondence are realized in certain quantum states of the gravitational field in LQG, thus justifying, from first principles, a class of models introduced in [1] . An approximate duality of bipartite entanglement on the boundary and a geodesic path length in the bulk is given on HITs, as the expectation value of the path length operator of LQG exactly matches the graph length previously used to show this duality. We provide examples of HITs and show clear boundaries for their existence in the form of no-go theorems that exclude absolutely maximally entangled (AME) states as well as general holographic codes from local SU(2)-invariance.

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All incompatible measurements on qubits lead to multiparticle Bell nonlocality

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Bell nonlocality is a fundamental phenomenon of quantum physics as well as an essential resource for various tasks in quantum information processing. It is known that for the observation of nonlocality the measurements on a quantum system have to be incompatible, but the question which incompatible measurements are useful, remained open. Here we prove that any set of incompatible measurements on qubits leads to a violation of a suitable Bell inequality in a multiparticle scenario, where all parties perform the same set of measurements. Since there exists incompatible measurements on qubits which do not lead to Bell nonlocality for two particles, our results as depicted in Fig. 1 demonstrate a fundamental difference between two-particle and multi-particle nonlocality, pointing at the superactivation of measurement incompatibility as a resource. In addition, our results imply that measurement incompatibility for qubits can always be certified in a device-independent manner.

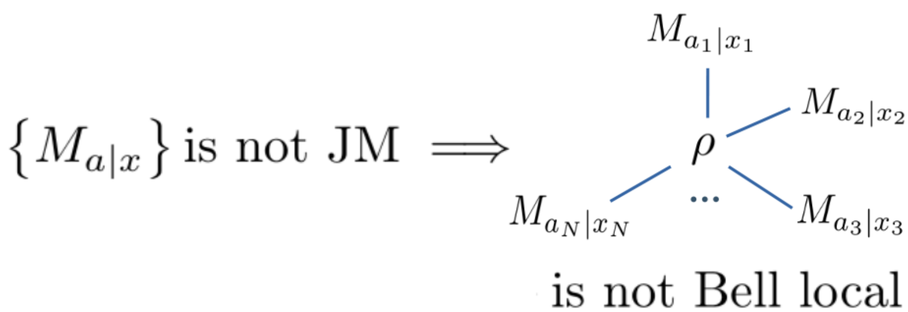

Figure 1. In this paper we show that, if $\{M_{a|x}\}$ is a set of qubit measurements (so-called POVMs where a and x label the inputs and outputs, respectively) which is incompatible, then there exist a number of parties $N \in \mathbb{N}$ and a quantum state $\rho \in \mathcal{D}(\mathbb{C}_2^{\otimes N})$ such that the behaviour $p(a_1 \dots a_N | x_1 \dots x_N) = \mathrm{Tr}[\rho(M_{a_1|x_1} \otimes \dots \otimes M_{a_N|x_N})]$ is Bell nonlocal, i.e., it violates some Bell inequality.

Lie Meets von Neumann for Symmetry Characterisation of Compact Lie Algebras

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Abstract: Von Neumann's celebrated double-centraliser theorem completely characterises an operator algebra by its symmetries/commutant. How can this idea be taken over to symmetry-characterise all simple compact Lie algebras (i.e. subalgs of $\mathfrak{u}(N)$) given a finite dimension N?

Von Neumann's own early contributions (*inter alia* inspired by Noether, Artin, van-der-Waerden) see group algebras to regular representations of finite groups as first incarnations of von Neumann algebras—still in finite dimensions. — Turning to compact Lie groups and their Lie algebras, we follow this spirit and elucidate the add-ons to central isotypic projections (via the commutant to the adjoint representation) that allow for a full symmetry characterisation. Avoiding to calculate an explicit Lie closure, we thus give a general algorithm that identifies a compact simple Lie algebra just from a given set of generators based on their joint symmetries thus substantially driving our earlier work [1-3] into a full classification.

Our algorithmic approach can be applied to problems in various fields such as measurement-based quantum computing, stabiliser design via Clifford algebras, phases of many-body systems—and last but not least quantum control.

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Work, Heat and Internal Energy in Autonomous Quantum Systems

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We compare definitions of the internal energy of an open quantum system and strategies to split the internal energy into work and heat contributions as given by four different approaches from the autonomous system framework. Our discussion focuses on methods that allow for arbitrary environments (not just heat baths) and driving by a quantum mechanical system. As a simple application we consider an atom as the system of interest and an oscillator field mode as the environment. Three different types of coupling are analyzed. We discuss ambiguities in the definitions and highlight differences that appear if one aims at constructing environments that act as pure heat or work reservoirs. Further, we identify different sources of work (e.g. coherence, correlations, or frequency offset), depending on the underlying framework. Finally, we give arguments to favour the approach based on minimal dissipation.

Seegebrecht, A., Schilling, T. Work, Heat and Internal Energy in Open Quantum Systems: A Comparison of Four Approaches from the Autonomous System Framework. *J Stat Phys* **191**, 34 (2024). https://doi.org/10.1007/s10955-024-03249-0

Non-Markovian Ensemble Propagation

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Open quantum systems are ubiquitous in nature and central to quantum technologies. A common description of their dynamics is given by the celebrated Lindblad master equation, which can be generalized to the non-Markovian scenario. In this work, we introduce the Non-Markovian Ensemble Propagation (NMEP) method, which extends the Monte Carlo Wave-Function (MCWF) method to the non-Markovian case in a simple and general manner. We demonstrate its accuracy and effectiveness in a selection of examples, and compare the results with either analytic expressions or direct numerical integration of the master equation.

Relative entropy in lattice CFT

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The multi-interval mutual information associated with 1+1-dimensional free fermions is exactly known in the continuum and has recently been rigorously computed by Longo and Xu. Using operator-algebraic renormalization, we prove that this quantity is convergent in scaling limit procedures via finite-dimensional approximations based on soft-inductive limits. This result can be understood as a generalization of the martingale property of the relative entropy, and it entails that standard lattice-fermion regularizations of the multi-interval mutual information are convergent.

Spectral Compatibility and Analytical Constraints in Quantum Marginal Problems

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The compatibility of quantum marginals, or reduced density matrices, is a cornerstone of quantum mechanics, underlying phenomena like entanglement and non-locality. A fundamental variant of this problem concerns the compatibility of spectra, rather than the reduced density matrices themselves. Specifically, given eigenvalues $\vec{\lambda}_{AB}$ and $\vec{\lambda}_{BC}$ for subsystems AB and BC, the task is to determine whether there exists a joint quantum state ρ_{ABC} such that its reduced density matrices $\rho_{AB} = tr_C(\rho_{ABC})$ and $\rho_{BC} = tr_A(\rho_{ABC})$ exhibit these spectra. If such a state exists, the spectra are deemed compatible; otherwise, they are incompatible.
Recently, a hierarchy of semidefinite programs (SDP) was developed to address this challenge [1]. This hierarchy is complete and provides dimension-free certificates of incompatibility for all local dimensions. The poster introduces a new constraint on incompatibility by solving the second hierarchy level for multipartite qudit systems and highlights key incompatibility cases across different hierarchy levels.

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Co-designing Transmon devices for control with simple pulses

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In the current NISQ era, there is demand for functional quantum devices to solve relevant computational problems, which motivates a utilitarian perspective on device design: The goal is to create a device that is able to run a given algorithm with state-of-the-art performance. In this work, we use optimal control tools to derive the gate set required by a toy algorithm and, in tandem, explore the model space of superconducting quantum computer design, from dispersively coupled to stronger interacting qubits, to maximize gate fidelity. We employ a Cartan decomposition to provide flexibility in the search for a perfect entangler in the Weyl chamber. This way, we compare designs with different entangling mechanisms, e.g., `CPHASE` and $\sqrt{\texttt{iSWAP}}$. To ensure the applicability of our investigation, we limit ourselves to "simple" (i.e., sparse parametrization) pulses and quantify, where results differ from using the full complexity of piecewise constant controls.

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