Quantum Thermodynamics for Young Scientists

713. WE-Heraeus-Seminar

02 Feb - 06 Feb 2020
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 713. WE-Heraeus-Seminar:

Quantum thermodynamics is an emergent research field, which combines ideas from statistical mechanics, open quantum system theory, quantum information and mesoscopic physics. Its goals are as diverse as the different fields involved, ranging from the desire to understand the emergence of the laws of thermodynamics from a microscopic picture to the need of designing useful quantum heat engines in a new era of increased nanotechnological abilities. While many different approaches have been put forward in the last years to understand thermodynamics in the quantum regime, a remaining future challenge is to bridge the gaps between different communities and to create a common understanding of the phenomena involved. The goal of this workshop is twofold:

On the one hand, it is crucial to permit young researchers to benefit from conferences in order to get acquainted with different visions of the field, as well as to communicate their own research. Therefore, this workshop will especially give early career researchers in quantum thermodynamics and related fields the opportunity to present their research, exchange ideas, and get exposed to different topics. With this step we will keep the field open for new ideas.

On the other hand, it is also important to connect the different fields and approaches involved. Therefore, the workshop will rest on four tutorial lectures given by recognised young researchers about 'equilibration in closed many-body systems' (Markus Müller), 'open quantum systems' (Javier Cerillo), 'quantum information theory and thermodynamics' (Nicole Yunger Halpern), and 'quantum transport and mesoscopic physics' (Geraldine Haack).

Furthermore, while the curiosity driving research remains essentially the same throughout all generations of physicists, the scientific environment in which we carry out our research has drastically changed in the last decades. Since the young generation will be the one which shapes the future of science, we will have a special non-physics talk by Ben Martin on the present and future of our universities and academic research.

Scientific Organizers:

Dr. Marti Perarnau-Llobet	MPI für Quantenoptik, Garching, Germany E-mail: marti.perarnau@mpq.mpg.de
Dr. Philipp Strasberg	Universitat Autònoma de Barcelona, Spain E-mail: philipp.strasberg@uab.cat

Program

Sunday, 2 February 2020

17:00 – 21:00	Registration	
from 18:30	*BUFFET SUPPER / Informal get together*	

Monday, 3 February 2020

08:00 – 09:00	*BREAKFAST*	
09:00 – 09:20	Philipp Strasberg Marti Perarnau-Llobet	**Welcome**
09:20 – 10:20	Géraldine Haack	**An efficient Aharonov-Bohm quantum heat engine: Fundamentals of thermoelectricity and applications**
10:20 – 10:50	*COFFEE BREAK*	

First slot Contributed Talks (Chair: Géraldine Haack)

10:50 – 11:15	Cecilia Chiaracane	**Quasiperiodic quantum heat engines with a mobility edge**
11:15 – 11:40	Paolo Andrea Erdman	**Maximum power and corresponding efficiency for two-level heat engines and refrigerators: optimality of fast cycles**
11:40 – 12:05	Patrice Camati	**Autonomous Maxwell's demon in a cavity QED system**
12:05 – 12:30	Armin Tavakoli	**Autonomous entanglement engines**
12:30 – 12:40	**Conference Photo** (in front of the Lecture Hall)	
12:40	*LUNCH*	

Program

Monday, 3 February 2020

(Chair: Gabriel Landi)

14:00 – 15:00	Javier Cerrillo	**Open Quantum Systems: Noise, Decoherence, Memory**
15:00 – 15:15	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
15:15 – 15:45	*COFFEE BREAK*	
15:45 – 18:45	Poster Session	
19:00	*DINNER*	

Program

Tuesday, 4 February 2020

08:00	*BREAKFAST*	

<u>(Chair: Philipp Strasberg)</u>

09:20 – 10:20	Henrik Wilming	**Equilibration and thermalization in many-body systems**
10:20 – 10:50	*COFFEE BREAK*	

<u>Second slot Contributed Talks (Chair: Henrik Wilming)</u>

10:50 – 11:15	Faraj Bakhshinezhad	**Thermodynamically optimal creation of correlations**
11:15 – 11:40	Krzysztof Ptaszynski	**Thermodynamics of Quantum Information Flows**
11:40 – 12:05	Camille Lombard Latune	**Negative contributions to entropy production induced by quantum coherences**
12:05 – 12:30	Luis Pedro Garcia-Pintos	**Speed limits to quantum thermodynamics**
12:30	*LUNCH*	
14:00 – 16:30	Excursion to the « Löwenburg »	
16:30 – 17:00	*COFFEE BREAK*	

<u>Third slot Contributed Talks (Chair: Philippe Faist)</u>

17:00 – 17:25	Daniel Reiche	**Quantum Thermodynamics of Atom-Surface Interactions in Nonequilibrium Steady-States**
17:25 – 17:50	Mohammad Mehboudi	**Bath-induced correlations lead to sub-shot-noise thermometry precision**
17:50 – 18:15	Mathias Jørgensen	**Tight bound on finite-resolution quantum thermometry at low temperatures**
18:30	*DINNER*	

Program

Wednesday, 5 February 2020

08:00	*BREAKFAST*	

(Chair: Javier Cerrillo)

09:20 – 10:20	Markus Müller	**Thermodynamics as a resource theory: versions of the second law(s)**
10:20 – 10:50	*COFFEE BREAK*	

Fourth slot Contributed Talks (Chair: Markus Müller)

10:50 – 11:15	Lennart Dabelow	**Relaxation theory for perturbed many-body quantum systems**
11:15 – 11:40	Carlos Alberto Parra Murillo	**On non-ergodic environments and ETH in open quantum systems**
11:40 – 12:05	Jonas Richter	**Impact of eigenstate thermalization on the route to equilibrium**
12:05 – 12:30	Carlo Sparaciari	**Bounding the resources for thermalizing many-body localized systems**
12:30	*LUNCH*	

Program

Wednesday, 5 February 2020

Fifth slot Contributed Talks (Chair: Mohammad Mehboudi)

14:00 – 14:25	Paul Menczel	**Thermodynamics of Cyclic Quantum Amplifiers**
14:25 – 14:50	Pierre Nazé	**Optimal protocols for quantum Ising model under weak driving**
14:50 – 15:15	Philippe Faist	**Asymptotic Reversibility of Thermal Operations for Interacting Quantum Spin Systems**
15:15 – 15:45	*COFFEE BREAK*	
15:45 – 17:00	Time for discussions	
17:00 – 18:30	Ben Martin	**What's Happening to Our Universities?**
18:30	*HERAEUS DINNER at the Physikzentrum (cold & warm buffet, with complimentary drinks)*	

Program

Thursday, 6 February 2020

08:30	*BREAKFAST*	

Sixth slot Contributed Talks (Chair: Patrice Camati)

09:30 – 09:55	Mark Mitchison	**A spin heat engine coupled to a harmonic oscillator flywheel**
09:55 – 10:20	Noufal Jaseem Poovakkattil	**Quantum Synchronization in Nano-scale Heat Engines**
10:20 – 10:50	*COFFEE BREAK*	

Seventh slot Contributed Talks (Chair: Mark Mitchison)

10:50 – 11:15	Gabriel Teixeira Landi	**Thermodynamic uncertainty relations from exchange fluctuation theorems**
11:15 – 11:40	Matteo Scandi	**Quantum work statistics close to equilibrium**
11:40 – 12:05	Ricardo Puebla	**Shortcuts-to-adiabaticity protocols for a robust generation of non-classical states in spin-boson systems**
12:05 – 12:15	Philipp Strasberg Marti Perarnau-Llobet	**Poster awards and closing remarks**
12:20	*LUNCH*	

End of the seminar and departure

Posters

1	Paolo Abiuso	**Optimal cycles for low-dissipation heat engines**
2	Björn Annby-Andersson	**Maxwell’s demon in double quantum dots with continuous charge detection**
3	Alhun Aydin	**Landauer's principle in a quantum Szilard engine in the absence of an explicit Maxwell's Demon**
4	Ádám Bácsi	**Optimizing quantum quenches in the Luttinger model**
5	Christian Bartsch	**Thermalisation properties of closed quantum systems in linear response**
6	Bettina Beverungen	**Evaluation of Casimir forces in complex geometries**
7	Léa Bresque	**Energetic aspects of implementing quantum gates**
8	Martina Costa Reis	**Passive states in classical and quantum thermodynamics**
9	Otavio Augusto Dantas Molitor	**Collisional model-based quantum heat engines**
10	Tobias Denzler	**Coefficient of performance and entropy production fluctuations in quantum Otto fridges**
11	Owen Diba	**Effect of Classical Gaussian Noise on Quantum Work Statistics**
12	Léonce Dupays	**Shortcuts in open quantum systems: Superadiabatic control of an open quantum oscillator**

Posters

13	Eric Gomes Arrais	**Work statistics for sudden quenches in interacting quantum many-body systems**
14	Tamal Guha	**How Quantum Theory Restricts Thermodynamics**
15	JungYun Han	**Quantum cooling induced by hyper parametric oscillation.**
16	Pedro Harunari	**Time asymmetric reciprocity relations for an arbitrarily long single-particle stochastic pump and its exact solution**
17	Mattes Heerwagen	**Work statistics for classical and quantum, periodical driven, anharmonic oscillator**
18	Simon Hermann	**The role of magnetic fluctuations in nonequilibrium atom-surface dispersion forces**
19	Santiago Hernández Gómez	**Experimental test of quantum fluctuation theorems with a diamond NV center**
20	Adam Hewgill	**Three-qubit refrigerator with two-body interactions**
21	Lilo Höcker	**A new Na-K apparatus to study quantum thermodynamics**
22	Michael Konopik	**Differences between local and global master equations**
23	Patryk Lipka-Bartosik	**Second law of thermodynamics for batteries with vacuum state**
24	Nathan Myers	**Bosons Outperform Fermions – The Thermodynamic Advantage of Symmetry**

Posters

25	Zakaria Mzaouali	**Irreversibility and information scrambling in critical quantum spin models**
26	Marcelo Pereira	**Rectification and out-of-time-order correlators**
27	Maria Popovic	**Quantum thermodynamics in non-Markovian settings using the TEMPO algorithm**
28	Andreu Riera-Campeny	**Dynamically induced heat rectification in quantum systems**
29	Franklin Luis Rodrigues	**Thermodynamics of Weakly Coherent Collisional Models**
30	Ricardo Román-Ancheyta	**Spectral signatures of non-thermal baths in quantum thermalization**
31	Connor Sait	**An open quantum system approach to the dynamics of magnetic spin systems**
32	Stefano Scali	**Probing the geometry of open-system dynamics**
33	Nazish Shahid	**Green's Function Method to Approximate Spectral Function and Quasi-particles' Energy in a Quantum Fermi System**
34	Varinder Singh	**Three-Level Laser Heat Engine at Optimal Performance with Ecological Function**
35	Nicolas Staudenmaier	**Experimental Investigation of Quantum Fluctuation Relations with a Solid-State Based Quantum Heat Engine**
36	Akram Touil	**The thermodynamics of quantum information scrambling—A dynamical perspective**
37	Bhavesh Valecha	**Optimising Mesoscopic Heat Engines**

Posters

38	Alexander van Meegen	**On the path integral approach to random neural networks**
39	Maria Violaris	**Purifying the Demon: Does Quantum Erasure Cost More Than You Remember?**
40	Mugdha Zadkar	**Classical counterparts to fully quantum fluctuation theorems**
41	Giorgio Zicari	**Initial correlations and entropy production rate in a system of non-Markovian harmonic oscillators.**

Abstracts of Lectures

(in chronological order)

An efficient Aharonov-Bohm quantum heat engine: Fundamentals of thermoelectricity and applications

Géraldine Haack

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When discussing quantum heat engines, researchers often mention well-known figures of merit like the ZT coefficient and transport and thermo-electric coefficients characterizing the electrical and thermal responses of the devices (Onsager coefficients). I will take the opportunity of this talk to introduce those concepts and quantities from a more fundamental perspective, explaining the origin of the ZT figure of merit or deriving the implications of the micro-reversibility principle in the quantum regime on the Onsager coefficients. As an illustration, I will consider a recent quantum thermal machine proposed in Ref. [1], based on one of the most emblematic mesoscopic devices for quantum transport, the Aharonov-Bohm ring. Remarkably, transport and thermo-electric responses of this device rely on electronic single-particle interference effect, a genuine quantum effect. Hence, this proposal is of particular interest for motivating realizations of thermal machines operating in the quantum regime.

References

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Quasiperiodic quantum heat engines with a mobility edge

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Steady-state thermoelectric machines convert heat into work by driving a thermally generated charge current against a voltage gradient. In this work, we propose a new class of steady-state heat engines operating in the quantum regime, where a quasiperiodic tight-binding model that features a mobility edge forms the working medium. In particular, we focus on a generalization of the paradigmatic Aubry-André-Harper (AAH) model, known to display a single-particle mobility edge that separates the energy spectrum into regions of completely delocalized and localized eigenstates. Remarkably, these two regions can be exploited in the context of steady-state heat engines as they correspond to ballistic and insulating transport regimes [1]. This model also presents the advantage that the position of the mobility edge can be controlled via a single parameter in the Hamiltonian [2]. We exploit this highly tunable energy filter, along with the peculiar spectral structure of quasiperiodic systems, to demonstrate large thermoelectric effects, exceeding existing predictions by several orders of magnitude. This opens the route to a new class of highly efficient and versatile quasiperiodic steady-state heat engines, with a possible implementation using ultracold neutral atoms in bichromatic optical lattices

References

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Maximum power and corresponding efficiency for two-level heat engines and refrigerators: optimality of fast cycles

P. A. Erdman[1], **V. Cavina**[1], **R. Fazio**[2,1], **F. Taddei**[3], **and V. Giovannetti**[1]

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We study how to achieve the ultimate power in the simplest, yet non-trivial, model of a thermal machine, namely a two-level quantum system coupled to two thermal baths [1]. Without making any prior assumption on the protocol, via optimal control we show that, regardless of the microscopic details and of the operating mode of the thermal machine, the maximum power is universally achieved by a fast Otto-cycle like structure in which the controls are rapidly switched between two extremal values. A closed formula for the maximum power is derived, and finite-speed effects are discussed. We also analyze the associated efficiency at maximum power (EMP) showing that, contrary to universal results derived in the slow-driving regime [2], it can approach Carnot's efficiency, no other universal bounds being allowed.

References

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Autonomous Maxwell's demon in a cavity QED system

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Maxwell's demon is a key historical example of how information and thermodynamics are connected to one another. This relationship arises from the feedback control implemented by the demon on the thermodynamic system, which extracts information through some measurement and feeds it back into the system through a conditioned evolution. As realized by Maxwell himself, such protocols may lead to situations that defy the second law of thermodynamics [1–3]. Over the last 150 years, a number of contributions, both at the classical and at the quantum realm, pointed out that the information extracted by the demon has to be explicitly accounted for in the entropy balance so as to retain the validity of the second law [4–6]. The majority of experimental works in the quantum setting addressed a Maxwell's demon in a work-extraction protocol [7–15]. Among those, a few reported a Maxwell's demon operating in an autonomous way [8, 12], where the information extraction and feedback steps are automatically implemented. On the other hand, we present a thermodynamic analysis, both at the average and at the quantum trajectory level, of a Maxwell's demon that controls the heat exchanged between two systems [16]. We obtained an integral and a detailed fluctuation relation as well as an expression for the entropy production and its relation to the system-demon correlations consumed during the feedback. Our results can be experimentally investigated with current quantum technologies and, in particular, our protocol has been implemented in a cavity QED setup.

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Autonomous entanglement engines

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The generation of entangled states is a paradigmatic task in quantum information theory. Here we explore whether it is possible to generate entanglement in autonomous systems that use only incoherent couplings to thermal baths and time-independent interactions (in particular, they have no work input). We present a general architecture for such autonomous entanglement engines. It enables the generation of the strongest forms of both genuine multipartite entanglement and high-dimensional entanglement in a heralded manner. We exemplify this by developing the robust generation of paradigmatic states in quantum information theory; namely maximally entangled states, Greenberger-Horne-Zeilinger states, Dicke states and cluster states. More generally, given a target multiple-qubit state, we give a sufficient condition ensuring that it can be generated by our machine. These results demonstrate the fundamental potential of purely thermal resources for creating multipartite entangled states useful for quantum information processing.

References

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Open Quantum Systems: Noise, Decoherence, Memory

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The interaction of a quantum system with a noisy environment can produce not only decohering and dissipative effects, but also memory effects [1] that may result advantageous for certain tasks. Mathematically, their dynamics are only rigorously formalized in terms of superoperators that present a Kraus map structure [2]. Nevertheless, comprehensive simulation methods of general open quantum systems involving strong-coupling and non-Markovian effects tend to be numerically demanding. In this tutorial talk, I present a partial review of existing simulation methods especially suited for that regime with special emphasis in their shortcomings.

Later, I introduce the transfer tensor formalism (TTM) [3] that transforms the Kraus map representation of the dynamics of open quantum system into a compact multiplicative propagator in the form a memory kernel. This method has been shown to provide extraordinary acceleration of non-Markovian open quantum system simulations. The method relies on the theory of projection operators. TTM is a general and flexible approach that does not depend on the form of the environment or the interaction and has generated widespread interest.

I finalize with a discussion of the effects of initial correlations between the system and the environment. Although such situations are difficult to capture with the Kraus formalism, I will show how to apply TTM in this context.

References

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Equilibration and thermalization in many-body systems

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In statistical mechanics and thermodynamics we commonly use statistical ensembles like the canonical or microcanonical ensemble to obtain predictions. For this to be possible a system has to equilibrate to a stationary state in the first place. In the last decade the problem of understanding how complex quantum systems equilibrate, while evolving unitarily according to the Schrödinger equation has received renewed interest, with applications and contributions ranging form condensed matter physics, quantum information theory to research in quantum gravity. I will give an introduction to the problem and explain some recent results and open problems.

Thermodynamically optimal creation of correlations

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Correlations lie at the heart of almost all scientific predictions. It is therefore of interest to ask whether there exist general limitations to the amount of correlations that can be created at a finite amount of invested energy. Within quantum thermodynamics such limitations can be derived from first principles. In particular, it can be shown that establishing correlations between initially uncorrelated systems in a thermal background has an energetic cost. This cost, which depends on the system dimension and the details of the energy-level structure, can be bounded from below but whether these bounds are achievable is an open question. Here, we put forward a framework for studying the process of optimally correlating identical (thermal) quantum systems. The framework is based on decompositions into subspaces that each support only states with diagonal (classical) marginals. Using methods from stochastic majorisation theory, we show that the creation of correlations at minimal energy cost is possible for all pairs of three- and four-dimensional quantum systems. For higher dimensions we provide sufficient conditions for the existence of such optimally correlating operations, which we conjecture to exist in all dimensions.

References

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Thermodynamics of Quantum Information Flows

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We report [1] two results complementing the second law of thermodynamics for Markovian open quantum systems coupled to multiple reservoirs with different temperatures and chemical potentials. First, we derive a nonequilibrium free energy inequality providing an upper bound for a maximum power output, which for systems with inhomogeneous temperature is not equivalent to the Clausius inequality. Second, we derive local Clausius and free energy inequalities for subsystems of a composite system, generalizing the result previously derived for classical stochastic systems [2]. These inequalities differ from the total system one by the presence of an information-related contribution and build the ground for thermodynamics of quantum information processing. Our theory is used to study the recently proposed autonomous quantum Maxwell demon based on two exchange-coupled quantum dots [3].

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Negative contributions to entropy production induced by quantum coherences

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It was recently pointed out in [1] that quantum systems going through dissipative processes present two sources of irreversibility: one from populations and one from coherences. We show [2] that for degenerate (or near-degenerate) systems, additional contributions to the entropy production (irreversibility) emerge. Interestingly, under some particular conditions to be detailed (including for instance collective couplings), such additional contributions can become negative, marking the departure from usual (classical) thermodynamics through two distinct phenomena. The first one is the reversal of the natural convergence of the populations: instead of converging towards the thermal equilibrium distribution, the populations go away from it. This can also be related in some specific situations to heat flow reversals [3]. The second phenomenon is the generation of coherences between degenerate energy levels. Furthermore, these two phenomena exhibit an insightful complementary relation: the consumption of one fuels the other, and reciprocally.

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Speed limits to quantum thermodynamics

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We study the connection between the charging power of a quantum battery and the fluctuations of the extractable work stored in the battery. We show that in order to have a non-zero rate of change of the extractable work, the work fluctuations must be non-zero. This is presented in terms of an uncertainty relationship that bounds the speed of the charging process of any quantum system. Our findings also identify quantum coherence in the battery as a resource in the charging process, which we illustrate on a toy model of a heat engine.

Quantum Thermodynamics of Atom-Surface Interactions in Nonequilibrium Steady-States

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Fluctuations have profound impact on physical reality. For instance, in the presence of materials, a fluctuating vacuum leads to measurable forces between electrically neutral objects. Such fluctuation-induced forces are well-understood phenomena in the framework of open quantum systems at equilibrium and have become an experimental tool for the manipulation of nano- and micro-scale devices.

However, sometimes equilibrium can only be considered as an approximation of reality. To this day, theoretical investigations of nonequilibrium situations often rely on equilibrium techniques. This considerably simplifies the statistical properties of the interaction and may not be appropriate. We argue that a thermodynamically consistent description of nonequilibrium interactions inevitably requires to go beyond the commonly used equilibrium-based approaches.

In the context of an atom moving with respect to a planar and dissipative material interface, we explicitly discuss a more careful treatment [1]. Focusing on the dynamics at late times, where the system can reach a steady-state, we fully incorporate the back-action of the environment on the particle and highlight the importance of long-time correlations in the system; a contribution that is often neglected [2].

Our findings provide a step towards a theoretical basis for experimentally probing nonequilibrium fluctuation-dissipation relations and introduce a fundamental consistency condition for numerical simulations of nonequilibrium systems.

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Bath-induced correlations lead to sub-shot-noise thermometry precision

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We study the role of bath induced correlations in temperature estimation of cold bosonic baths. Our protocol includes multiple probes, that are not interacting, nor are they initially correlated to each other. It is well known that after being placed in the same bath, such probes get correlated to each other and even they might get entangled, especially at very low temperature. We examine the usefulness of these correlations for metrology, namely thermometry of the bath. Our results show that at low enough temperatures, the error in estimation scales below the shot-noise-limit, and even in some cases it might obey a Heisenberg-like scaling. We further study whether the described enhancement might be achieved by local measurements performed on individual probes. We find out that, by local Homodyne detection it is not possible to achieve the said precision, and to our knowledge, a global measurement, which might even be non-Gaussian is needed.

Tight bound on finite-resolution quantum thermometry at low temperatures

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Precise thermometry is of wide importance in science and technology in general and in quantum systems in particular. I will present a theoretical study of the fundamental precision limits for thermometry on cold quantum systems, taking into account limitation imposed by finite measurement resolution. I will present a tight bound on the optimal precision scaling with temperature as the temperature approaches zero, and illustrate that the bound is tight and can be saturated by monitoring the non-equilibrium dynamics of a single-qubit probe. Modeling the non-equilibrium dynamics of open quantum systems at low temperatures is technically challenging, and I will discuss one approach to the problem based on tensor-network techniques. The results presented here are relevant both fundamentally, as they illuminate the ultimate limits to quantum thermometry, and practically, in guiding the development of sensitive thermometric techniques applicable at very low temperatures.

Thermodynamics as a resource theory: versions of the second law(s)

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In this tutorial, I will give an introduction to the resource-theoretic formulation of (quantum) thermodynamics, with an emphasis on the repeatable use of resources and versions of the second law. After describing fundamental results like the difference between extractable work and work of formation (see Ref. 1), I will illustrate how the possible state transitions are determined by "many second laws" (see Ref. 2). I will then introduce a slightly different picture, in which the thermal machine is allowed to build up correlations with the physical systems on which it acts while exactly preserving its own state. It turns out that, surprisingly, the original form of the unique second law is exactly restored in this setting (see Ref. 3), which gives the nonequilibrium free energy an exact operational meaning without thermodynamic limit or averaging.
Finally, I will briefly explain how the presence of quantum coherence leads naturally to questions about the repeatable use of quantum references frames, in particular clocks, and describe a recent no-broadcasting result that tells us that clocks must necessarily degrade upon repeated use (see Ref. 4). In particular, this shows that Åberg's "catalytic coherence" (see Ref. 5) is only possible in the presence of an infinite-dimensional catalyst.

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Relaxation theory for perturbed many-body quantum systems

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We develop an analytic prediction for the relaxation of isolated many-body quantum systems subject to weak-to-moderate perturbations. Provided that the unperturbed behavior is known, we employ a typicality approach modeling the essential characteristics of the perturbation operator to describe the time evolution of expectation values in the perturbed system. Our theory provides a unified framework for such diverse phenomena as prethermalization, quantum quenches, or the relaxation of system-bath compounds. We demonstrate its wide applicability by comparison with various experimental and numerical results from the literature.

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On non-ergodic environments and ETH in open quantum systems

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The dynamics of an open system crucially depends on the correlation function of its environment, $C(t)$. We show that for thermal non-Harmonic environments $C(t)$ may not decay to zero but to an offset, $Co>0$. The presence of such offset is determined by the environment eigenstate structure, and whether it fulfills or not the eigenstate thermalization hypothesis. Moreover, we show that a $Co>0$ could render the weak coupling approximation inaccurate and prevent the open system to thermalize. Finally, for a realistic environment of dye molecules, we show the emergence of the offset by using matrix product states (MPS), and discuss its link to a 1/f noise spectrum that, in contrast to previous models, extends to zero frequencies. Thus, our results may be relevant in describing dissipation in quantum technological devices like superconducting qubits, which are known to be affected by such noise.

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Impact of eigenstate thermalization on the route to equilibrium

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The eigenstate thermalization hypothesis (ETH) and the theory of linear response (LRT) are celebrated cornerstones of our understanding of the physics of many-body quantum systems out of equilibrium. While the ETH provides a generic mechanism of thermalization for states arbitrarily far from equilibrium, LRT extends the successful concepts of statistical mechanics to situations close to equilibrium. In our work, we connect these cornerstones to shed light on the route to equilibrium for a class of properly prepared states. We unveil that, if the off-diagonal part of the ETH applies, then the relaxation process can become independent of whether or not a state is close to equilibrium. Moreover, in this case, the dynamics is generated by a single correlation function, i.e., the relaxation function in the context of LRT. Our analytical arguments are illustrated by numerical results for idealized models of random-matrix type and more realistic models of interacting spins on a lattice. Remarkably, our arguments also apply to integrable quantum systems where the diagonal part of the ETH may break down.

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Bounding the resources for thermalizing many-body localized systems

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Understanding the conditions under which physical systems thermalize is one of the long-standing questions in many-body physics. While it has been observed that generically quantum systems do thermalize, little is known about the underlying mechanism. Furthermore, instances where thermalization is hindered for many-body systems have been uncovered, now known as many-body localization, bringing promising insights into the mechanisms that underlie thermalization. In this work, we derive upper and lower bounds on the size of the heat bath required to thermalize a many-body localized system, for a broad class of collision models. To obtain these bounds, we employ a recently developed tool from quantum information theory known as the *convex split lemma*. We apply our results to the disordered Heisenberg chain, which we study numerically, and we characterize the robustness of the MBL phase in this system for the family of thermalization processes considered.

Thermodynamics of Cyclic Quantum Amplifiers

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We develop a generic model for a cyclic quantum heat engine that makes it possible to coherently amplify a periodically modulated input signal without the need to couple the working medium to multiple reservoirs at the same time. Instead, we suggest an operation principle that is based on the spontaneous creation of population inversion in incomplete relaxation processes induced by periodic temperature variations. Focusing on Lindblad dynamics and systems with equally spaced energy levels, e.g. qubits or quantum harmonic oscillators, we derive a general working criterion for such cyclic quantum amplifiers. This criterion defines a class of candidates for suitable working media and applies to arbitrary control protocols. For the minimal case of a cyclic three-level amplifier, we show that our criterion is tight and explore the conditions for optimal performance.

Optimal protocols for quantum Ising model under weak driving

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Quantum annealing appears as one of the most promising strategies to implement quantum computing nowadays. In this paradigm, the system, controlled by an external parameter, is adiabatically driven from an initial ground state, in such a manner that it stays in that particular state along the whole process. However, in practice, annealing is always compromised by two fundamental types of error: The first one arises from the environmental noise the system is always subjected to; the second one occurs due to the excitations of the non-equilibrium dynamics of the process. Although a successful strategy involving energy penalties has been found to correct the first type of error, strategies to correct the second one are still a challenge. In the present work, we minimize the thermodynamic work performed on a quantum Ising model, weakly perturbed by a transverse magnetic field. Particular attention is given at the region near the critical point of the second-order phase transition, thereby elucidating the relation of linear-response theory and Kibble-Zurek mechanism.

Asymptotic Reversibility of Thermal Operations for Interacting Quantum Spin Systems

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The resource theory of thermal operations, an established model for small-scale thermodynamics, provides an extension of equilibrium thermodynamics to nonequilibrium situations. On a translation-invariant lattice with local interactions, we show that ergodic states (i.e. states that have sharp statistics for any translation-invariant observable) can be reversibly converted to and from the thermal state with thermal operations and a small amount of coherence. This proves the emergence of an operationally well-justified thermodynamic potential for this class of states, which includes states that are not in equilibrium. As an intermediate result of independent interest, we show that the gap between the min- and max-relative entropies controls the amount of coherence that is present in the state and that if this gap is small, the state can be approximately reversibly converted to and from the thermal state with a small reference frame. Our results provide a strong link between the abstract resource theory of thermodynamics and more realistic physical systems that go beyond the i.i.d. setting.

What's Happening to Our Universities?

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In recent decades, many universities have been moving in the direction of a more hierarchical and centralised structure, with top-down planning and reduced local autonomy for departments. Yet the management literature over this period has stressed the numerous benefits of flatter organisational structures, decentralisation and local autonomy for sections or departments. What might explain this paradox? And why have academics remained strangely quiet about this, meekly accepting their fate? The paper critically examines the dangers of centralised top-down management, increasingly bureaucratic procedures, teaching to a prescribed formula, and research driven by assessment and performance targets, illustrating these with a number of specific examples. It discusses a number of possible driving forces of these worrying developments, and concludes by asking whether academics may be in danger of suffering the fate of the boiled frog.

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A spin heat engine coupled to a harmonic oscillator flywheel

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I will describe a recent experimental realisation of a heat engine comprising a single trapped ion, which performs work on a quantum load. The ion's internal spin constitutes the working medium, while the ion's quantised vibrations act as the load, or "flywheel", that captures the output work. I will explain an intuitive theoretical model of the flywheel dynamics in terms of a random walk in phase space. Characterising the flywheel's Husimi Q function allows us to measure the work output of a heat engine with single-quantum resolution. By inferring the ergotropy of the flywheel's quantum state, we distinguish between useful work and useless thermal energy, thus elucidating how fluctuations fundamentally limit engine performance at the nanoscale.

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Quantum Synchronization in Nano-scale Heat Engines

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Nature is replete with examples of classical synchronization(1) and it has been observed both in natural and artificial systems at all scales. This has led to two questions in the quantum regime, namely (a) can genuine quantum synchronization(2) be observed experimentally? and (b) can it be put to use in a technology application?

In our paper (*arXiv:1812.10082*), we answer both of these questions in the affirmative. In doing so, we provide a universal mechanism for creating quantum synchronization by linking it to quantum coherence. This is done by using a resource theoretic measure of coherence, and clarify how such a coherence can be put to use to produce coherent quantum technologies powered by synchronization in the quantum regime. The example we consider is a three-level thermal maser(3,4), which makes experimental observation of quantum synchronization much easier, given that masers are a mature quantum technology. Following standard literature in quantum optics, we analyze the maser as a thermal engine, but connect thermal performance to synchronization and show how the engine power is related to synchronization. This displays the connections between the fields of quantum synchronization and quantum thermodynamics.

Quantum thermal machines are an emerging branch of quantum thermodynamics. Improving the understanding of such thermal machines by understanding the underlying synchronization dynamics will aid in designing new and better machines. Furthermore, the intersection of thermodynamics and non-linear dynamics will surely bear fruit by promoting the cross-pollination of ideas.

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Thermodynamic uncertainty relations from exchange fluctuation theorems

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Thermodynamic uncertainty relations (TURs) place strict bounds on the fluctuations of thermodynamic quantities in terms of the associated entropy production. In this work we identify the tightest (and saturable) matrixvalued TUR that can be derived from the exchange fluctuation theorems describing the statistics of heat and particle flow between multiple systems of arbitrary dimensions. Our result holds for both quantum and classical systems, undergoing general finite-time, non-stationary processes. Moreover, it provides bounds not only for the variances, but also for the correlations between thermodynamic quantities. To demonstrate the relevance of TURs to the design of nanoscale machines, we consider the operation of a two-qubit SWAP engine undergoing an Otto cycle and show how our results can be used to place strict bounds on the correlations between heat and work [1, 2].

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Quantum work statistics close to equilibrium

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We study the statistics of work, dissipation, and entropy production of a quantum quasi-isothermal process, where the system remains close to the thermal equilibrium along the transformation. We derive a general analytic expression for the work distribution and the cumulant generating function. All work cumulants split into a classical (non-coherent) and quantum (coherent) term, implying that close to equilibrium there are two independent channels of dissipation at all levels of the statistics. For non-coherent or commuting protocols, only the first two cumulants survive, leading to a Gaussian distribution with its first two moments related through the classical fluctuation dissipation relation. On the other hand, quantum coherence leads to positive skewness and excess kurtosis in the distribution, and we demonstrate that these non-Gaussian effects are a manifestation of asymmetry in relation to the resource theory of thermodynamics. Furthermore, we also show that the non-coherent and coherent contributions to dissipation satisfy independently the Evans-Searles fluctuation theorem, which sets strong bounds on the fluctuations in dissipation, with negative values exponentially suppressed.

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Shortcuts-to-adiabaticity protocols for a robust generation of non-classical states in spin-boson systems

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A time-dependent Hamiltonian evolution leads to non-equilibrium state transformations, that are in general different from its corresponding adiabatic evolution unless performed sufficiently slow. Yet, such adiabatic evolution can be sped-up arbitrarily by resorting to specific protocols dubbed as shortcuts to adiabaticity [1], which require an additional energetic cost [2]. These protocols are therefore of great interest for quantum state preparation. Here we show that, by applying shortcut-to-adiabaticity protocols in a time-dependent Jaynes-Cummings model, one can obtain interesting non-classical states in short evolution times, such as individual Fock states and superpositions thereof, as Schroedinger cat states [3]. In addition, these protocols allow for the preparation of photon-shifted states, akin to photon-added/subtracted states but displaying more non-classicality [3]. This scheme is naturally robust against decoherence effects, and to small variations in the time-dependent pulses. Thanks to the ubiquity of the Jaynes-Cummings interaction mechanism, our scheme may be realized in a variety of experimental setups.

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Abstracts of Posters

(in alphabetical order)

Optimal cycles for low-dissipation heat engines

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We consider the optimization of a finite-time Carnot engine characterized by small dissipation. We bound the power with a simple inequality and show that the optimal strategy is to perform small cycles around a given working point, which can be thus chosen optimally. Remarkably, this optimal point is independent of the figure of merit combining power and efficiency that is being maximized. Furthermore, for a general class of dynamics the power output becomes proportional to the heat capacity of the working substance. Since the heat capacity can scale supra-extensively with the number of constituents of the engine, this enables us to design optimal many-body Carnot engines reaching maximum efficiency at finite power per constituent in the thermodynamic limit.

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Maxwell's demon in double quantum dots with continuous charge detection

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Maxwell's demon converting information into work has during the last decade gained renewed interest as it gives insight into the relation between information theory and thermodynamics. Here we investigate an implementation of Maxwell's demon in a double quantum dot and theoretically demonstrate how heat can be converted into work using only information. This is accomplished by continuously monitoring the charge state of the quantum dots and transferring electrons against a voltage bias using a feedback scheme. We investigate the electrical work produced by the demon, and find a non-Gaussian work distribution. To illustrate the effect of a realistic charge detection scheme, we develop a model taking into account noise as well as a finite delay time, and show that an experimental realization is feasible with present day technology. Depending on the accuracy of the measurement, the system is operated as a Maxwell demon or a single-electron pump.

Landauer's principle in a quantum Szilard engine in the absence of an explicit Maxwell's Demon

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Szilard engines are in general operated by a Maxwell's Demon where Landauer's principle resolves the apparent paradoxes. Here we propose a Szilard engine setup without featuring an explicit Maxwell's demon. In a demonless Szilard engine, the acquisition of which-side information is not required, but erasure and the related heat dissipation still take place implicitly by the very nature of the work extraction process. We see that the insertion of the partition in a quantum Szilard engine does not localize the particle to one side, instead it creates a superposition state of the particle being in both sides. To be able to extract work from the system, particle has to be localized at one side. The localization occurs as a result of quantum measurement on the particle, which shows the importance of the measurement process regardless of whether one uses the acquired information or not. In accordance with the Landauer's principle, localization by quantum measurement corresponds to a logically irreversible operation and for this reason it has to be accompanied by the corresponding heat dissipation. This shows the validity of the Landauer's principle even in quantum Szilard engines without Maxwell's demon.

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Optimizing quantum quenches in the Luttinger model

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Reaching a target quantum state from an initial state within a finite temporal window is a challenging problem due to non-adiabaticity. The optimal protocol is studied for switching on interactions to reach the ground state of a weakly interacting Luttinger liquid within a finite time, starting from the non-interacting ground state. The protocol is optimized by minimizing the excess energy at the end of the quench, or by maximizing the overlap with the interacting ground state.

It is found that the optimal protocol can be expressed as a functional of the occupation numbers of the bosonic modes in the final state. For short quench durations, the optimal protocol exhibits fast oscillation and excites high energy modes. In the limit of long quenches, however, minimizing the excess energy requires a smooth protocol (analytic expression is provided on the poster) while maximizing overlap requires a linear quench protocol. In this limit, the minimal energy and maximal overlap are both universal functions of the system size and the duration of the protocol.

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Thermalisation properties of closed quantum systems in linear response

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Linear response theory provides a useful tool to describe non-equilibrium dynamics not too far away from equilibrium. We are able to identify different long time behaviour for certain types of non-equilibrium initial conditions also with respect to the eigenstate thermalisation hypothesis (ETH). Additionally, we investigate the stability of long time dynamics in driven quantum systems and its dependence on, e.g., the driving frequency. Along these lines we analyse the average energy input per driving period.

Evaluation of Casimir forces in complex geometries

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In a system in thermal equilibrium, fluctuations and dissipation into the environment are self-consistently intertwined via the fluctuation-dissipation theorem. This result holds even in the limit of zero temperature due to the irreducible nature of quantum fluctuations. A notable manifestation of this behavior, emerging from the quantum thermodynamical properties of light-matter interaction, is the Casimir effect, which is essentially a force between nonmagnetic neutral objects. This interaction has received increasing attention from both theoretical and experimental side, in particular for its relevance in the design of small-scale devices like nano- or micro electro-mechanical systems and atom-chips.

New generations of experiments have created new challenges for researchers to increase the predictive and interpretative power of the theoretical description. One major obstacle to overcome is the evaluation of Casimir forces for non-trivial geometries and materials. Here, we discuss a finite-element-based numerical method, employing state-of-the-art techniques, that enables high-precision calculations. Our scheme allows for the accurate encoding of the quantum thermodynamical properties of the system and permits the evaluation of the force for in principle arbitrary complex geometries and material models.

Energetic aspects of implementing quantum gates

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The field of quantum computing has attracted increased attention in recent years because of theoretical demonstrations that quantum computers could perform some specific tasks much faster than classical computers and with similar amounts of noise. Yet, to implement such tasks, these computers would need a large number of logical qubits and thus scalability[2]. However, adding more qubits also means adding more quantum gates, and thus more noise. Indeed, for each gate, the manipulation of a qubit with a quantized control eletromagnetic field will induce correlations between them. In turn, this will imply that instead of implementing a perfect unitary transformation on the qubit, a completely positive trace preserving map (CPTP) is performed. Thus, tracing over the field state, the amount of noise introduced by the correlations will depend on how classical the field is [1]. For large-scale quantum computers, the overal energy needed to implement an algorithm, which is linked to the number of photons in each gate, can be very large. Hence, implementation energy is a key feature to be analyzed and has been slightly addressed so far in this context[3–5].

Our main question in this study is the following: What is the best way to use a given amount of energy (i.e., number of photons) to implement different numbers of gates with the best fidelity possible? Here, we considered N uncorrelated register qubits in each of which the same gate is performed and we characterize the overall fidelity in an way that is independent of the register qubits using the Choi matrix. Thanks to this formalism, we demonstrate for instance that, given two cavities, it is always more energetically efficient to split the energy of each field evenly than otherwise. These results could allow experimentalists to reduce the energy needed to implement gates when building large-scale quantum computer without losing in terms of fidelity.

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Passive states in classical and quantum thermodynamics

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Since the emergence of the first thermodynamic theories by mid-19th century, scientists have devoted great attention to the stability of thermodynamic systems and particularly how the Clausius inequality imposes constraints on the fluxes of heat and mass. However, in the first half of the 20th century, Meixner [1] and Day [2] proposed independently to replace the formulation of the second law of thermodynamics based on the Clausius inequality by a weaker one based on the concept of passivity.

Thus, in this work we revisit the concept of passivity in classical and quantum thermodynamics. To this end, we show that the global passivity inequality [3] proposed for quantum systems is coherent with the dissipation inequality introduced by Meixner and Day.

Moreover, we also show how the dissipation inequality can be exploited to investigate the stability of thermodynamic states [4]. For classical systems, we illustrate the relation passivity-stability by analyzing the behavior of viscoelastic materials, whereas for quantum systems we discuss the behavior of quantum batteries and exotic quantum machines.

The theoretical definitions and cases presented in this work are the starting point to the development of new approaches that help to better understand how perturbations can affect the unitary evolution of quantum systems.

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Collisional model-based quantum heat engines

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In the context of quantum thermodynamics, the study of quantum heat engines is of utmost importance [1]. A recent and interesting approach is to study such engines in the framework of collisional models, where each environment is made of an ensemble of identically prepared auxiliary systems, which interact sequentially with an individual subsystem for an infinitesimally small time, giving rise to a local master equation (LME), for whatever internal interactions the subsystems might have [2]. In this work we study a quantum heat engine composed of two qubits, each coupled to a heat bath. These heat baths are at different temperatures and can be seen as flywheels of thermal state units (Fig. 1). Then, by means of the time evolution of the mean energy of the system at each stroke, a stroboscopic (discrete time) operation of the heat engine is obtained and a limit-cycle is achieved. In this scenario, one can compute the heat exchange with the baths, the work extracted (injected) from (into) the system, the entropy production and other thermodynamical-informatic quantities. This quantum heat engine model is simple and powerful, as it enables the conception of new engines using genuine quantum features (e.g. entanglement, coherence [3]) in a straightforward way.

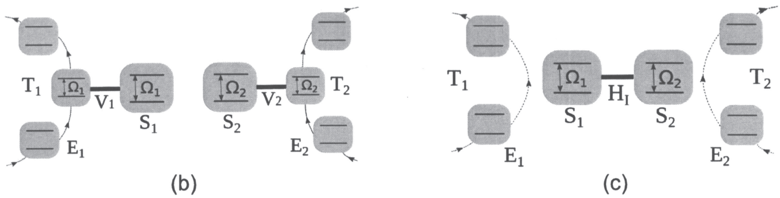

Fig 1. Model of the quantum heat engine to be studied. We have two different strokes: heat stroke (a) and work stroke (b).

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Coefficient of performance and entropy production fluctuations in quantum Otto fridges

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We treated the coefficient of performance and entropy production of a quantum Otto fridge as stochastic quantities and analyzed their corresponding distributions and moments in the adiabatic and non-adiabatic regime. We focused specifically on the case of a qubit system. We discovered that the mean of both quantities differ from the known results due to the presence of correlations between heat and work. Finally we analyzed the transitition from the quantum to the classical regime.

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Effect of Classical Gaussian Noise on Quantum Work Statistics

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Noise is an inconvenience which is present to some extent in all quantum systems. With recent successful experiments in measuring quantum work statistics it is an interesting and relevant question to ask what the effect is of classical noise on these statistics. We look at driven quantum systems with classical fluctuations in the control parameters of their time-dependent Hamiltonians. We define a work distribution averaged over an ensemble of noise realizations in the system. Using the properties of Gaussian noise we find expressions for the moments of this distribution. Some simple examples are considered: a spin 1/2 system and a harmonic oscillator driven with *shortcut to adiabaticity* protocols. Their work statistics are compared to systems driven with less sophisticated protocols. Finally, we look at the implementation of these protocols in quantum heat engines and the effect of the noise on the engine performance.

Shortcuts in open quantum systems:
Superadiabatic control of an open quantum oscillator

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The dynamical control of quantum systems is a necessity to advance quantum sciences and technology. Techniques known as shortcuts to adiabaticity (STA) provide an alternative to adiabatic driving, and have proven useful in a wide diversity of applications. However, they are currently restricted to the control of closed systems[1, 2]. We introduce STA in open quantum systems, and develop a technique to control the thermalization of a single particle in a driven harmonic trap. We provide the control trap frequency and dephasing strength to allow for the transformation of an initial state to a final thermal state in a finite time. Thereby, the super-adiabatic control of Gaussian states in non-unitary processes is demonstrated. Experimental implementation in the laboratory relies on stochastic parametric driving, which is readily accessible in current platforms. The possibility to control cooling and heating of thermal states finds applications in finite-time thermodynamics[3].

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Work statistics for sudden quenches in interacting quantum many-body systems

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Work in isolated quantum systems is a random variable and its probability distribution function obeys the celebrated fluctuation theorems of Crooks and Jarzynski. In this study, we provide a simple way to describe the work probability distribution function for sudden quench processes in quantum systems with large Hilbert spaces. This description can be constructed from two elements: the level density of the initial Hamiltonian, and a smoothed strength function that provides information about the influence of the perturbation over the eigenvectors in the quench process, and is especially suited to describe quantum many-body interacting systems. We also show how random models can be used to find such smoothed work probability distribution and apply this approach to different one-dimensional spin-$1/2$ chain models. Our findings provide an accurate description of the work distribution of such systems in the cases of intermediate and high temperatures in both chaotic and integrable regimes.

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How Quantum Theory Restricts Thermodynamics

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Quantum theory (QT) is the most acceptable description of the microscopic world, while, thermodynamics dictates the occurrence of many natural processes. Here, we have tried to characterize two different issues in quantum thermodynamics, where, quantum theory restricts seemingly allowed operations of thermodynamics. Firstly in [1], we have studied how the structure of QT prohibits cloning or masking of the amount of work stored in a quantum state. However, another important thermodynamic quantity, namely, energy of a quantum state can be cloned perfectly. Furthermore, we have also shown that there is no universal work masker, which can mask the work content of a quantum state in the correlation shared among the constituents of its bipartite extension. However, for a restricted class of states along with a blanck ancilla, under the action of energy preserving unitary opertaion, it is possible to prepare a joint state which is locally passive in nature. In the second part [2], we have characterized several classes of classically correlated and entangled bipartite correlations whose preparation from two thermal qubits is forbidden due to the inherent structure of QT and not because of the disagreement in their correlation content and the amount of energy supplied. We have also characterized the most general class of entangled states which can be prepared from any two arbitrarily given thermal qubits. A dimension dependent upper-bound on the temperature is derived, below which two copies of any d−dimensional thermal state can be entangled in $2\times d$ dimension.

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Quantum cooling induced by hyper parametric oscillation

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We explore the nonequilibrium thermodynamics of a nonlinear photonic system in the presence of hyper-parametric oscillation, using spontaneous four-wave mixing (SFWM) [1-3]. The specific form of the interaction causes the photonic system to cool down, an atypical behavior for generic nonlinear interactions, e.g., Bose-Hubbard type interaction induced via cross-phase modulation (XPM). We propose a feasible physical model composed of two ring resonators depicted in Fig. 1(a) to emulate this nonlinear system through the dissipative ring resonator setup without frequency conversion between pump and signals [4,5]. Presuming centro-symmetry of the system, the Hamiltonian,

$$\hat{H}_S = \omega_a \hat{a}^\dagger \hat{a} + \omega_b \hat{b}^\dagger \hat{b} + J\left(\hat{a}^\dagger \hat{b} + \text{h.c.}\right) + Y_1\left(\hat{a}^\dagger \hat{a}^\dagger \hat{b}\hat{b} + \text{h.c.}\right) + Y_2 \hat{a}^\dagger \hat{a} \hat{b}^\dagger \hat{b}, \tag{1}$$

where $\omega_{a,b}$ are detuning frequencies for each site, J quantifies the linear hopping induced by direct coupling between resonators, and Y_1, Y_2 are coefficients with respect to 3rd order nonlinear susceptibility on SFWM and XPM respectively. Now, we connect the bosonic bath at temperature T induced by the thermal state through probe waveguide to each ring resonator. What we explore is the response of the system concerning the work done by the coupling. The dissipative description is governed by a Lindblad master equation and in the weak coupling limit and the response gives rise to time-dependent heat current $\dot{Q}(t) = \text{Tr}_S\left[\hat{H}_S \frac{d\rho_S}{dt}(t)\right]$, where ρ_S is the reduced density matrix obtained via the Lindblad equation [6,7]. Positive current $\dot{Q}(t) > 0$ indicates that bath pumps energy into the system inducing excited states to be occupied more while negative $\dot{Q}(t) < 0$ leads to extracting the heat from the system.

We simulate two feasible initial states, (i) vacuum, (ii) superposition of three lowest eigenstates. We observe that depending on the initial state and the environment temperature, the XPM interaction strongly heats the system immediately after it is coupled to the environment and the system cools down slowly to equilibriate with it's environment [Fig. 1(b)]. However, in the presence of SFWM, the result is quite the opposite [Fig. 1(c)]. In this case the system looses heat (cools) continuously to the environment $\dot{Q}(t) < 0$ until it equilibriates.

The robust cooling provided by the SFWM depends on the nonlinear interaction strength Y_1. Below a critical value of Y_1 for the fixed detuning the nonequilibrium ground-state population governed by the Lindblad equation decreases with time causing the excited states to populate and hence heat the system. Surprisingly, above the critical value the nonequilibrium dynamics pushes the system into the ground state, i.e., ground state population increases, leading to cooling of the system. This phenomenon persists even though the bath is at a high temperature causing the system to cool down. Such a behavior is not observed in XPM which causes the system to heat.

Overall, we propose an experimentally realizable ring resonator based photonics system within which we can achieve cooling if the interaction between the cavities is modulated by spontaneous four-wave mixing between the resonator modes. Other interactions between the photons, nonlinear or disorder, mainly cause the resonator setup to heat and we hope our findings could help cool these systems using SFWM.

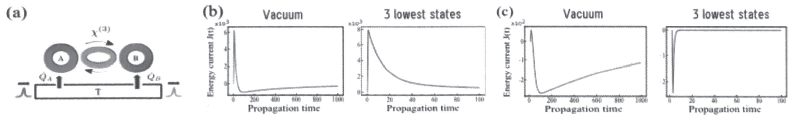

Fig. 1 (a) Schematic of system. (b) Heat current when $\omega_a = \omega_b = 0$, $\hbar\omega/k_BT = 2.0$, and $Y_2 = 1.0J$ (XPM) for vacuum (left) and superposition of 3 lowest eigenstates (right). Both initial conditions show heating. (c) Heat current when $Y_1 = 1.0J$ (SFWM) with the same setup. Here we observe cooling.

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Time asymmetric reciprocity relations for an arbitrarily long single-particle stochastic pump and its exact solution

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A single-particle stochastic pump consists of a two level system, the quantum dot, interacting with particle and heat reservoirs, one at a time, time-periodically. We present an exact solution irrespective of the number of reservoirs involved. Consequently, we discuss exact expressions for flux, entropy production, affinities, heat, work and chemical work, valid arbitrarily far from equilibrium. Near equilibrium the Onsager (kinetic) coefficients and its symmetries are relevant, so we derived reciprocity relations for this kind of pump.

Work statistics for classical and quantum, periodical driven, anharmonic oscillator

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When extending the laws of thermodynamics to nanoscopic systems, quantum effects may dominate the dynamics and have to incorporated these in a thermodynamic prescription. The definition of work in small quantum systems plays a pivotal role. Defining quantum work by a double measurement of energy is a possible approach. We use the two projective measurement (TPM) method to compare the quantum work and the traditional notion of work used for classical systems.

Therefore, we consider an anharmonic oscillator initially at equilibrium with a bath. Then the heat bath is removed and a periodic driving with slowly increasing envelope function is switched on. After reaching a maximum the driving is smoothly reduced again such that the final Hamiltonian coincides with the initial one. By the first law of thermodynamics, the classical work of the external driving equals the energy change of the system during the process. We determine the probability density $P(E_f|E_i)$ for transitions from initial energy E_i to final energy E_f and deduce from it the work statistics for the periodically driven anharmonic oscillator.

Numerical results for quantum case are compared to classical numerical results and analytical estimates resulting from the pendulum approximation for periodic orbits.

The role of magnetic fluctuations in nonequilibrium atom-surface dispersion forces

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Driving a microscopic object above a planar medium induces a force opposing the direction of motion even if both the object and the material are non-magnetic and electrically neutral. The interaction stems from the fluctuations within the microscopic object and the medium and occurs even if the temperature goes to zero, rendering the effect a purely quantum phenomenon. The mechanical motion drives the full system out of thermal equilibrium, making its description rather difficult.
In order to circumvent this problem previous authors often applied the so-called local thermal equilibrium (LTE) approximation, where both the microscopic object and the planar surface are considered to be separately in thermal equilibrium with their immediate surroundings. A more careful analysis shows, however, that the frictional interaction heavily relies on long correlation times rendering the LTE approximation inadequate and the interaction intrinsically non-Markovian [1,2]. In addition, due to the mathematical complexity of the problem, most of the earlier descriptions focused on the electric contribution to the interaction. Here, we present a more complete treatment that also takes into account the contribution arising from the nonequilibrium magnetic fluctuations of the system and offer a more consistent perspective of the underlying physical processes affecting the frictional interaction.

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Experimental test of quantum fluctuation theorems with a diamond NV center

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Fluctuation relations enable the extraction of equilibrium quantities from the statistical analysis of an ensemble of out of equilibrium quantities [1,2]. The application to quantum systems, has recently attracted much interest [3,4]. Although proven for closed systems, its verification for open quantum systems has shown to be conceptually difficult.

Here [5], we investigate the exchange fluctuation theorem (EFT) in the presence of a controlled dissipation channel, using a Nitrogen-vacancy (NV) center spin qubit in diamond, a prominent platform for quantum technologies [6,7]. For this purpose, we used the NV center ground spin state, to form a qubit that can be coherently controlled with MW radiation, optically initialized and read out. Besides driving it with a unitary evolution, the system is intermittently connected to a tunable dissipation channel and subject to repeated quantum projective measurements. To verify the EFT, we measure the energy dissipated during the process by using a two-point measurement protocol, using as initial state a thermal state. Furthermore, we found an analytical solution that describes the dynamics of the system.

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Three-qubit refrigerator with two-body interactions

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We propose a three-qubit setup for the implementation of a variety of quantum thermal machines where all heat fluxes and work production can be controlled. An important configuration that can be designed is that of an absorption refrigerator, extracting heat from the coldest reservoir without the need of external work supply. Remarkably, we achieve this regime by using only two-body interactions instead of the widely employed three-body interactions. We look at the effect that modelling the open system dynamics with a global or local approach has on the behaviour of the system. Finally, we look at the system from a thermal control perspective, seeing how this setup can be used as a thermal valve, using one qubit to control the heat flow between the other two.

A new Na-K apparatus to study quantum thermodynamics

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Ultracold atomic gases present a high control over experimental parameters which makes them an ideal candidate to simulate a wide variety of physical systems. Ultracold atomic mixtures expand these horizons by covering an even greater range of quantum many body phenomena like dynamical gauge fields, effect of spin impurity presence in a lattice (Kondo effect) etc.
Furthermore, ultracold atoms are a promising candidate for the implementation of a quantum heat engine.
In this poster, we present the new Na-K experiment at Heidelberg, which we are setting up as a platform to study some of those problems.

Differences between local and global master equations

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For modeling open quantum systems, Lindblad master equations are highly used [1]. A proper derivation of the Lindblad master equation demands the diagonalization of the Hamiltonian. Therefore, the more complex the Hamiltonian becomes, the harder it is to find the correct master equation. For coupled composite systems one can use a local approach and solely add dissipators locally, ignoring any inter subsystem coupling. Compared to the full master equation, the global approach, there are differences expected [2]. We will consider for a model of two coupled harmonic oscillators the differences that can occur for these different approaches.

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Second law of thermodynamics for batteries with vacuum state

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In the standard formulation of thermodynamics work is a random variable whose average is bounded by the change in free energy of the system. In most treatments, however, work reservoir that absorbs the change in energy is either tacitly assumed or modelled using unphysical systems with unbounded Hamiltonians. In this work [1] we describe the consequences of introducing the ground state of the battery into thermodynamic considerations and thus breaking translational symmetry of the battery. Using the framework of thermal operations we obtain corrections to the second law of thermodynamics which vanish when battery is initialized far from the bottom of its spectrum. Furthermore, by studying a paradigmatic example of Landauer erasure we show that the ability to break translational symmetry can provide a well-defined advantage over ideal batteries. In particular, breaking translational symmetry allows to effectively reduce fluctuations of thermodynamic work, while still satisfying the second law of thermodynamics. Surprisingly, this effect remains true even when battery operates far from its bottom. This leads to far reaching practical consequences as fluctuations of thermodynamic quantities are one of largest obstacles in constructing nanoscale devices.

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Bosons Outperform Fermions – The Thermodynamic Advantage of Symmetry

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The recent miniaturization of heat engines to the nanoscale introduces the possibility of engines that harness quantum resources. The analysis of quantum engines provides important insight into how their efficiency compares to classical analogues and deepens our understanding of thermodynamic mechanisms at the quantum scale. We examine a quantum Otto engine with a harmonic working medium consisting of two non-interacting particles to explore the use of wave function symmetry as an accessible quantum resource. The efficiency, power output, and trade-off between efficiency and power are compared based on whether the medium consists of bosons or fermions. We show that the bosonic system displays enhanced performance when compared to two single particle engines, while the fermionic system displays reduced performance. We also examine the parameter regimes under which the system functions as engine, refrigerator, or heater and demonstrate that the bosonic system operates under a wider parameter space both when operating as an engine and as a refrigerator.

Irreversibility and information scrambling in critical quantum spin models.

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We study quantum work statistics of quenched critical spin models. We find that the average work is only sensitive to some quantum phase transitions. We show that long and short ranged models exhibits different revival dynamics using the Loschmidt echo. Furthermore, we assess the role of the long and short range interaction of spin models in the scrambling of information. Finally, we investigate irreversibility in critical spin models from a phase space picture using the Wigner entropy production rate.

Rectification and out-of-time-order correlators

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When a conductor is subject to a potential difference, a current of electrons will flow in the same direction as the electric gradient. If the sign of the gradient is inverted, then usually so is the current. However, that does not have to be so. In diodes, for instance, the current is asymmetric with respect to changes in the sign of the voltage difference. Materials of this form are said to be rectified. Currently there is a large interest from the scientific community in one-dimensional quantum materials that exhibit large rectification effects. In this project we propose to contribute to this search by studying rectification from the perspective of the underlying commutation relations of quantum mechanical operators. To accomplish that, we shall use the concept of out-of-time-order correlators, which have recently been introduced as a measure of how the Hilbert space support of operators grows with system interactions.

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Quantum thermodynamics in non-Markovian settings using the TEMPO algorithm

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Dynamically induced heat rectification in quantum systems

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Heat rectifiers are systems that conduct heat asymmetrically for forward and reversed temperature gradients. We present an analytical study of heat rectification in linear quantum systems. We demonstrate that asymmetric heat currents can be induced in a linear system only if it is dynamically driven. The rectification can be further enhanced, even achieving maximal performance, by detuning the oscillators of the driven network. Finally, we demonstrate the feasibility of such driven harmonic network to work as a thermal transistor, quantifying its efficiency through the dynamical amplification factor.

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Thermodynamics of Weakly Coherent Collisional Models

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We introduce the idea of weakly coherent collisional models, where the elements of an environment interacting with a system of interest are prepared in states that are approximately thermal but have an amount of coherence proportional to a short system-environment interaction time in a scenario akin to well-known collisional models. We show that, in the continuous-time limit, the model allows for a clear formulation of the first and second laws of thermodynamics, which are modified to include a nontrivial contribution related to quantum coherence. Remarkably, we derive a bound showing that the degree of such coherence in the state of the elements of the environment represents a resource, which can be consumed to convert heat into an ordered (unitarylike) energy term in the system, even though no work is performed in the global dynamics. Our results therefore represent an instance where thermodynamics can be extended beyond thermal systems, opening the way for combining classical and quantum resources.

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Spectral signatures of non-thermal baths in quantum thermalization

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We show that certain coherences, termed as heat-exchange coherences, which contribute to the thermalization process of a quantum probe in a repeated interactions scheme, can modify the spectral response of the probe system. We suggest to use the power spectrum as a way to experimentally assess the apparent temperature of non-thermal atomic clusters carrying such coherences and also prove that it is useful to measure the corresponding thermalization time of the probe, assuming some information is provided on the nature of the bath. We explore this idea in two examples in which the probe is assumed to be a single-qubit and a single-cavity field mode. Moreover, for the single-qubit case, we show how it is possible to perform a robust quantum simulation of resonance fluorescence using such repeated interactions scheme with clusters carrying different class of coherences.

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An open quantum system approach to the dynamics of magnetic spin systems.

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Motivated by the failure of the phenomenological Landau-Lifschitz-Gilbert (LLG) equation in explaining dynamic and equilibrium properties of ferromagnets [1], we here set up an open quantum systems treatment of Heisenberg spins by including coupling to an environmental (quantum) field. We show that it is possible to derive the LLG equation for the spin dynamics under certain assumptions, uncovering the physical principles that determine the validity range of the LLG equation. The open systems approach allows us to examine the nature of magnetic damping and thermal noise more closely than was previously possible. Moreover, we show that dynamical equations for the spins that deviate from the LLG equation are possible, which automatically fulfil the fluctuation-dissipation relation and which may explain experimental magnetisation curves that deviate from those expected when working with the LLG equation.

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Probing the geometry of open-system dynamics

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Exceptional points are a crucial manifestation of the peculiarity of non-Hermitian dynamics emerging from the introduction of loss in the system. In this scenario, we can find square-root singularities in parameter space known as exceptional points whose footprint is the *degeneracy* of eigenvalues together with the coalescence of the corresponding eigenvectors. The immediate consequence is the loss of degrees of freedom in the system and not enough eigenstates to span the space we started with. This lies at the origin of surprising behaviours such as topological chirality [1] and laser-mode selectivity [2].

In the context of quantum technologies, superconducting qubits coupled to resonators with tunable dissipation allow for the most efficient cooling at the exceptional points [3]. To describe these systems, the theory of open quantum systems has to be taken into account. However, in the field of multi-partite open quantum systems, determining the dynamics of the system can take different directions. To date, the most common problem addressed has been deciding which, between local and global master equations, has to be used in order to obtain a faithful dynamics in different regimes, but what if different choices come into play? What if an even more fundamental judgement has to be made? And in what manner the exceptional points are affected by our selections?

To give an answer to this questions, we will consider the case of a quantum wire thoroughly analysed by Gonzalez et al. in [4] and we will compare our work with the results obtained by Partanen et al. in [3].

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Green's Function Method to Approximate Spectral Function and Quasi-particles' Energy in a Quantum Fermi System

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The Kadanoff-Baym (KB) version of Green's function formalism has been adopted to study the transport properties of neutral-fermi liquid and electron liquid of normal metals. The validity of Landau-Silin (LS) kinetic equations for quickly varying disturbances has been established at low temperature up to the linear terms in the width of one-particle energy levels. The possibility of validity of LS equations for quasi-particle distribution at low temperature up to the quadratic terms in the width of one-particle energy levels has been discussed. For separable model of energy levels, such approximations of spectral function are sought that verify the equation of spectral function, obtained from generalized quantum kinetic equation.

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Three-Level Laser Heat Engine at Optimal Performance with Ecological Function

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Although classical and quantum heat engines work on entirely different fundamental principles, there is an underlying similarity. For instance, the form of efficiency at optimal performance may be similar for both types of engines. In this work, we study a three-level laser quantum heat engine operating at maximum ecological function which represents a compromise between the power output and the loss of power due to entropy production. We present numerical as well as analytic results for the global and local optimization of our laser engine in different operational regimes. Particularly, we observe that in low temperature regime, three-level laser heat engine can be mapped to Feynman's ratchet and pawl model, a steady state classical heat engine. Then, we derive analytic expressions for efficiency under the assumptions of strong matter-field coupling and high bath temperatures. Upper and lower bounds on the efficiency exist in case of extreme asymmetric dissipation when the ratio of system-bath coupling constants at the hot and the cold contacts respectively approaches, zero or infinity. These bounds have been established previously for various classical models of Carnot-like engines. Further, for weak (or intermediate) matter-field coupling, we derive some new bounds on the efficiency of the engine.

Experimental Investigation of Quantum Fluctuation Relations with a Solid-State Based Quantum Heat Engine

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When scaling down heat engines one will arrive at a level where fluctuations in the work output and absorbed heat become relevant. In thermodynamics these fluctuations are statistically connected to the equilibrium properties of the system via fundamental equalities [1], which hold in the same form regardless whether the system is classical or quantum.
The statistics of work and transferred heat of a miniaturized (quantum) heat engine are described by the quantum heat engine fluctuation relation (QHEFR) [2]. Here, we want to experimentally investigate a quantum heat engine made by a single nitrogen-vacancy (NV) center in diamond. The ground state spin of the NV center is used as a coherently controllable two-level system that forms the working medium. A dissipative channel, that is opened under illumination with laser light, is used to externally simulate coupling to the thermal reservoirs [3]. The validity of the QHEFR in the two cases of infinite bath temperature and vanishing work extraction is shown and operation in a four-stroke Otto cycle is presented.

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The thermodynamics of quantum information scrambling—A dynamical perspective

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Understanding what happens to a qubit thrown into a black hole is not an easy task; is the information lost to any outside observer or can it still be retrieved by local measurements? This problem boils down to studying the scrambling of information over the event horizon, which draws attention to a general class of problems: scrambling of quantum information. In our work, we study the scrambling properties of quantum systems through the mutual information (MI). To this end, we lower bound the MI by the Out-of-Time-Order Correlators (OTOC) and determine its dynamical properties, relating the MI to thermodynamic quantities such as irreversible entropy production. We then illustrate, through examples, the thermodynamic significance of the MI for quantum information scrambling. Thus, as a main result, we establish a clear link between the MI and the OTOC, which enables us to probe the thermodynamics of quantum information scrambling and opens the door for further studies of the thermodynamics of quantum chaotic systems (such as black holes).

Optimising Mesoscopic Heat Engines

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Heat engines have been one of the most extensively studied topics in thermodynamics and statistical physics. This research has been mostly focused on getting finite power at Carnot efficiency i.e. optimising the power-efficiency trade-off. This trade-off gets more complicated when one goes to small scales because the fluctuations involved become significant. Recent works([1]-[3]) have shown that a third factor enters the trade-off, the fluctuations in the power output, called the constancy of the engine. In particular, it has been proven([4]), for a large class of thermal engines, that these three parameters complement each other such that none can be improved at the expense of at least one other parameter. We studied this universal trade-off between the three desiderata: power output, efficiency, and constancy; using the trajectory approach of Stochastic Thermodynamics([5]) and Large Deviation Theory to determine these quantities. In particular, we studied the nanoscale model system where work is extracted by applying forces on a Brownian particle in a potential. This trade-off was optimised using a multi-objective optimisation technique, the Pareto front which is commonly used in economics to optimise trade-offs.

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On the path integral approach to random neural networks

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Inferring the macroscopic behavior of a system from the underlying microscopic dynamics is a pertinent problem in various fields of research. Intriguingly, the mathematical approaches, as well as the major obstacles, are often very similar. However, this is easily overlooked due to scarce communication between the fields. Coming from a background in Theoretical Neuroscience, we would like to contribute to this workshop with a review of a mathematical approach that recently gained substantial traction in our field. Our main goal is to ignite a dialogue about common approaches, problems, and solutions.

We focus on path integral techniques that have proven to be useful in both Quantum Thermodynamics [1] and Theoretical Neuroscience [2-4,7]. We start with a brief introduction to the path integral approach to dynamics in random neural networks (networks with a random connectivity matrix) [2]. Next, we present two analytically tractable models of random neural networks [2-4] and more involved spiking neural network models that account for the pulse-based coupling via action potentials [5-7]. As an outlook, we discuss recent progress on the relation between the path integral approach and an alternative (mathematically well defined) approach based on large deviation theory [8].

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Purifying the Demon: Does Quantum Erasure Cost More Than You Remember?

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The scale-dependence of statistical mechanics remains an unsolved problem. Theories of information apply to any scale, yet are connected to scale-dependent thermodynamic notions directly by Landauer's principle. How far the second law applies for microscopic systems, and whether irreversibility is truly fundamental, are troublingly open questions.

Constructor Theory takes a new approach to this problem, providing a framework to reconcile exact statements about irreversibility with time-reversal symmetric dynamical laws. Recently a task was discovered that demonstrates these properties. Using the constructor-theoretic definition of possibility, it was found that transforming a pure state to a mixed state using the 'quantum homogenisation' machine is possible, while the reverse need not be. This machine approximates the non-unitary process of quantum information erasure using unitary dynamics.

My research investigates the consequences of giving the demon in Szilard's Engine a quantum homogenisation machine to erase its memory qubit from a mixed state to a pure state, allowing the engine to work in a cycle. Constructor Theory implies an added cost to using the homogeniser in a cycle for the demon's memory erasure, in addition to that from Landauer's principle. This could have implications for cosmological models and efficient quantum computation, and ultimately inform the search for a scale-independent formulation of irreversibility – connecting entropy, quantum mechanics and information.

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Classical counterparts to fully quantum fluctuation theorems

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Fully quantum fluctuation relations incorporate coherence and quantum correlations, but typically require explicit modeling of components that more traditional approaches (both classical and quantum) only treat implicitly. Such components include the system that delivers the work, as well as the system that imposes the external control. In this project, we strive to mimic the general machinery of fully quantum fluctuation relations in a purely classical phase space setting, and within this construction derive classical counterparts to various fully quantum fluctuation relations. One goal is to understand the effects of introducing explicit batteries and external controls in the classical scenario, and how this relates to standard classical approaches. A further aim is to enable a comparison between fully quantum fluctuation relations and classical fluctuation relations on a more equal footing.

Initial correlations and entropy production rate in a system of non-Markovian harmonic oscillators.

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Entropy production plays a fundamental role in both classical and quantum thermodynamics: by being related to the second law at a fundamental level, it enables to identify and quantify the irreversibility of physical phenomena. This issue is of great interest in the case of an open quantum system, where we study the reduced dynamics of a system interacting with its environment.

The theoretical description of this scenario is challenging, especially if one goes beyond the standard Born-Markov approximation and considers the possibility of a back-flow of information from the environment to the system.

In our work, we focus on an open quantum system composed by two uncoupled harmonic oscillators undergoing non-Markovian dynamics. This minimal, yet insightful, setting allows us to investigate – both numerically and analytically – how different preparations of the initial state (separable, entangled, quantum correlated without being entangled) can affect the entropy production rate and assess the conditions under which the latter is maximised. This sheds light on the interplay between initial correlations and thermodynamic irreversibility in a scenario of strong experimental relevance.

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