Suggestions for seminar topics

1 Maxwell's demon and the Szilard engine

Maxwell's demon is an imagined being that can rectify thermal energy into work, thus violating the second law of thermodynamics. This idea has been a source of inspiration for research over many years. One particular version of Maxwell's demon is the Szilard engine.

There is an almost endless literature on Maxwell's demon and its history. Here are only a few examples (the two last references give an overview from a rather critical perspective).

- C. H. Bennett, *Demons, Engines and the Second Law*, Scientific American, **257**, 108 (1987).
- L. Szilard, *Über die Entropieverminderung in einem thermodynamischen System bei Eingriffen intelligenter Wesen*, Zeitschrift für Physik, **53**, 840 (1929).
- H. S. Leff and A. F. Rex, *Maxwell's Demon: Entropy, Information, Computing* (Taylor and Francis, 1990).
- H. S. Leff and A. F. Rex, *Maxwell's Demon 2: Entropy, Classical and Quantum Information, Computing* (Taylor and Francis, 2002).

2 The thermodynamics of computation and Landauer's erasure principle

There has been a long history of attempts to explain why Maxwell's demon does not work, where the current understanding is that the extracted work is payed for by increasing the entropy of the demon's memory. This turns out to be closely related to the question of how much work we need to spend in order to erase a memory, which often is referred to as Landauer's principle.

- R. Landauer, *Irreversibility and heat generation in the computing process*, IBM Journal of research and development, **5**, 183 (1961).
- C. H. Bennett, *Notes on Landauer's principle, reversible computation, and Maxwell's Demon*, Studies in history and philosophy of modern physics, **34**, 501 (2003).
- M. B. Plenio, V. Vitelli, *The physics of forgetting: Landauer's erasure principle and information theory*

3 More concrete models of information erasure

Since Landauer's and Bennet's discussion of the work cost of information erasure, people have studied this in various more explicit models.

- B. Piechocinska, *Information erasure*, Physical Review A, **61**, 062314 (2000).

4 The Brownian ratchet

There are several thought experiments that, like Maxwell's demon and the Szilard engine, appear to violate the second law. One example is the Brownian ratchet, or Feynman ratchet, which at first sight seems to to rectify thermal fluctuations into work. These types of ideas are closely related to the notion of Brownian motors (which are not about challenging the second law).

- R. P. Feynman, chapter 46 in *The Feynman lectures on Physics*, Volume 1 (Addison-Wesley, Massachusetts, 1963).
- J. M. Parrondo and P. Español, *Criticism of Feynman's analysis of the ratchet as an engine*, American Journal of Physics, **64**, 1125 (1996).
- R. D. Astumian and P. Hänggi, *Brownian Motors*, Physics Today, November, 33 (2002).

5 Work extraction

In 'work extraction' we are given a system in a non-equilibrium state and wish to extract as much useful energy as possible by equilibrating it with respect to a heat bath of a given temperature.

- A. E. Allahverdyan, R. Balian, and Th. M. Nieuwenhuizen, *Maximal work extraction from finite quantum systems*, Europhysics Letter, **67**, 565 (2004).
- R. Alicki, M. Horodecki, P. Horodecki, and R. Horodecki, *Thermodynamics of quantum information systems - Hamiltonian description*, Open Systems and Information Dynamics **11**, 205 (2004).

6 Single shot entropies and work extraction

The standard approaches to work extraction and information erasure suggest that the work yield or work cost can be characterized in terms of measures based on the Shannon or von Neumann entropy. However, there are situations that may require more general types of entropy measures.

- O. C. O. Dahlsten, R. Renner, E. Rieper, V. Vedral, *Inadequacy of von Neumann entropy for characterizing extractable work*, New Journal of Physics, **13**, 053015 (2011).

7 Correlations and work

What happens when we wish to extract work from systems that are shared between two or several parties? How much work can be stored in correlations? In the quantum regime one can investigate the difference between classical and quantum correlations from a thermodynamic perspective.

- J. Oppenheim, M. Horodecki, P. Horodecki, and R: Horodecki, *Thermodynamical approach to quantifying quantum correlations*, Physical Review Letters, **89**, 180402 (2002).
- M. Perarnau-Llobet, K. V. Hovhannisyan, M. Huber, P. Skrzypczyk, N. Brunner, and A. Acín, *Extractable work from correlations*, Physical Review X, **5**, 041011 (2015).

8 Entanglement and the foundations of statistical mechanics

An approach where the randomness of the thermal state is not due to our ignorance, but rather due to entanglement with the environment.

- S. Lloyd, *Excuse our ignorance*, Nature Physics **2**, 727 (2006).
- S. Popescu, A. J. Short, A. Winter, *Entanglement and the foundations of statistical mechanics*, **2**, 754 (2006).
- S. Popescu, A. J. Short, A. Winter,*The foundations of statistical mechanics from entanglement: Individual states vs. averages*, arXiv: quant-ph/0511225 (2006).

9 How small can a fridge be?

An absorption refrigerator uses two different heat baths with different temperature to drive the cooling of a third system. It turns out that this type of refrigerator in principle can be as small as two qubits or a single qutrit.

- N. Linden, S. Popescu, and P. Skrzypczyk, *How small can thermal machines be? The smallest possible refrigerator*, Physical Review Letters, **105**, 130401 (2010).

10 The eigenstate thermalization hypothesis

An approach to understand how thermalization may occur in closed quantum systems.

- J. M. Deutsch, *Quantum statistical mechanics in a closed system*, Physical Review A, **43**, 2046 (1991).
- M. Srednicki, *Chaos and quantum thermalization*, Physical Review E, **50**, 888 (1994).
- M. Rigol, V. Dunjko, and M. Olshanii, *Thermalization and its mechanism for generic isolated quantum systems*, Nature, **452**, 854 (2008).

11 Negative entropy in quantum information theory

As opposed to the classical case, the conditional von Neumann entropy can become negative (which typically happens for sufficiently entangled states). It turns out that this has an interpretation in terms of “state merging”, which is process where a quantum state shared by several parties is transfered to one party.

- M. Horodecki, J. Oppenheim, A. Winter, *Partial quantum information*, Nature, **436**, 673 (2005).
- M. Horodecki, J. Oppenheim, A. Winter, *Quantum state merging and negative information*, Communications in mathematical physics, **269**, 107 (2007).
- P. Hayden, *Putting certainty in the bank*, Nature, **436**, 633 (2005).

12 Negative entropy in quantum thermodynamics

From Landauer’s erasure principle we know that it typically costs work to erase a memory. However, in the quantum case it turns out the there are situations when the erasure cost can become negative, i.e., we erase the memory and gain useful energy.

- L. del Rio, J. Åberg, R. Renner, O. Dahlsten, and V. Vedral, *The thermodynamic meaning of negative entropy*, Nature, **474**, 61 (2011).
- P. Hayden, *Entanglement as elbow grease*, Nature, **474**, 41 (2011).

13 Noisy operations and thermal operations

Inspired by notions from quantum information theory, and in particular entanglement transformations, one can construct resource theories for non-equilibrium states. (This topic is closely related to topic 20.)

- M. Horodecki, P. Horodecki, and J. Oppenheim, *Reversible transformations from pure to mixed states and the unique measure of information*, Physical Review A, **67**, 062104 (2003).
- M. Horodecki, J. Oppenheim, *Fundamental limitations for quantum and nanoscale thermodynamics*, Nature Communications, **4**, 2059 (2013).
- F. G. S. L. Brandão, M. Horodecki, J. Oppenheim, J. M. Renes, and R. W. Spekkens, *Resource theory of quantum states out of thermal equilibrium*, Physical Review Letters, **111**, 250404

14 Fluctuation theorems (classical)

Imagine that you push a spoon through a bowl of syrup. On a sufficiently small scale, the friction will resolve into random molecular collisions, and hence result in random energy dissipation each time we perform the given process. Fluctuation theorems characterize the nature of these random fluctuations. One can say that the fluctuation theorems provide a refined formulation of the second law of thermodynamics that is valid also in a microscopic regime.

- C. Jarzynski, *Nonequilibrium equality for free energy differences*, Physical Review Letter, **78**, 2690 (1997).
- G. E. Crooks, *Entropy production fluctuation theorem and the nonequilibrium work relation for free energy differences*, Physical Review E, **60**, 2721 (1999).
- C. Bustamante, J. Liphardt, and F. Ritort, *The nonequilibrium thermodynamics of small systems*, Physics Today, **58**, 43 (2005).
- C. Jarzynski, *Equalities and Inequalities: Irreversibility and the second law of thermodynamics at the nanoscale*, Annual review of condense matter physics, **2**, 329 (2011).

15 Lieb-Yngvason's axiomatic thermodynamics

In 'standard' thermodynamics (as opposed to statistical mechanics) we only deal with macroscopic quantities without any reference to any underlying microscopic theory. There have been various attempts to axiomatize thermodynamics, and a relatively recent contribution in this direction is by Lieb and Yngvason.

- E. H. Lieb and J. Yngvason, *A fresh look at entropy and the second law of thermodynamics*, Physics Today, April, 32 (2000).
- E. H. Lieb and J. Yngvason, *The physics and mathematics of the second law of thermodynamics*, Physics Reports, **310**, 1 (1999).

16 Quantum fluctuation theorems

It is not entirely clear how one should generalize the idea of fluctuation theorems to the quantum setting. Several different ideas have been proposed (it is a bit of a jungle).

- P. Hänggi and P. Talkner, *The other QFT*, Nature Physics, **11**, 108 (2015).
- M. Campisi, P. Hänggi, and P. Talkner, Colloquium: Quantum fluctuation relations: Foundations and applications, Reviews of Modern Physics, **83**, 771 (2011).
- Á. M. Alhambra, L. Masanes, J. Oppenheim, and C. Perry, Fluctuating Work: From quantum thermodynamical identities to a second law equality, Physical Review X, **6**, 041017 (2016).

17 Thermal systems with several conserved quantities

More than energy can be conserved in a system (for example, angular momentum, or particle number), and in quantum mechanics it may happen that these conserved quantities do not commute.

- M. Lostaglio, D. Jennings, and T. Rudolph, *Thermodynamic resource theories, non-commutativity and maximum entropy principles*, New Journal of Physics, **19**, 043008 (2017).
- Y. Guryanova, S. Popescu, A. J. Short, R. Silva, P. Skrzypczyk, *Thermodynamics of quantum systems with multiple conserved quantities*, Nature Communications, **7**, 12049 (2016).
- N. Yunger Halpern, P. Faist, J. Oppenheim, A. Winter, *Microcanonical and resource-theoretic derivations of th thermal state of a quantum system with noncommuting charges*, Nature Communications, **10**, 1038 (2016).
- M. Perarnau-Llobet, A. Riera, R. Gallego, H. Wilming, J. Eisert, *Work and entropy production in generalized Gibbs ensembles*, New Journal of Physics, **18**, 123035 (2016).

18 Passivity

The Gibbs state describes thermal equilibrium, and one may wonder why the equilibrium state takes this particular form. One approach to answer this is via the notion of passivity, which singles out the type of states from which we cannot extract work.

- A. Lenard, *Thermodynamical proof of the Gibbs formula for elementary quantum systems*, Journal of Statistical Physics, **19**, 575 (1978).
- W. Pusz, S. L. Woronowicz, *Passive states and KMS states for general quantum systems*, Communications in Mathematical Physics, **58**, 273 (1978).
- C. Sparaciari, D. Jennings, J. Oppenheim, *Energetic instability of passive states in thermodynamics*, Nature Communications, **8**, 1895 (2017).

19 Work and coherence

Quantum systems can be in superpositions between different energy eigenstates. For analyzing systems in these types of states, it turns out that work is not the only relevant quantity, but that coherence emerges as a second independent resource.

- K. Korzekwa, M. Lostaglio, J. Oppenheim, D. Jennings, *The extraction of work form quantum coherence*, New Journal of Physics, **18**, 023045 (2016).
- M. Lostaglio, K. Korzekwa, D. Jennings, T. Rudolph, *Quantum coherence, time-translation symmetry, and thermodynamics*, Physical Review X, **5**, 021001 (2015).

20 The second laws of quantum thermodynamics

The second law constrains what kind of thermal transformations are possible. Within a model referred to as catalytic thermal operations it can be shown that the standard condition generalizes to a whole family of second laws. (This topic is closely related to topic 13.)

- F. Brandão, M. Horodecki, N. Ng, J. Oppenheim, S. Wehner, *The second laws of quantum thermodynamics*, Proceedings of the National Academy of Sciences, **112**, 3279 (2015).