Scientific Report: Cost MP1209 Thermodynamics in the Quantum Regime
3rd Quantum Thermodynamics Conference
Porquerolles (France)
11th – 16th October 2015

COST Action MP1209 held its third conference between, 11th – 16th October 2015 in Porquerolles, France

During this conference the three Working Groups of the COST Action met for the fifth time and a Management Committee meeting was held. A detailed summary of the Working Group discussions can be found in appendix 1.

The conference had 70 registered participants of which:

- 42 (60%) were also registered to the MP1209 network.
- Of those 42 participants, 76% were Early Stage Researchers and 14% were female.
- COST MP1209 supported 29 of these participants.

There were 13 invited talks and 22 contributed talks. The competition to have a contributed talk was high and those that were not accepted were offered the opportunity to present a poster. Presentation abstracts can be found on http://www.ifisc.uib-csic.es/qtd2/abstracts.html.

- 38% of invited talks were by Early Stage Researchers and 23% by women researchers.
- 36% of contributed talks were by Early Stage Researchers and 7% woman researchers.
- 2 of the 3 Working Group sessions were chaired by three Early Stage Researchers each.

This is the second conference organized by the COST MP1209 Action in which the option to use the provided childcare facilities was utilized. The actions taken by the conference's organizing committee to facilitate the use of the childcare facilities included:

- Publicizing babysitting facilities from the first conference announcement
- Information regarding the childcare facilities and possible children's activities were included on the conference web page.
- The cost of childcare was funded by the conference (from non-COST sources).
- The registration process asked participants about their possible use of the childcare facilities.
- Transport between the conference venue & hotel was carefully selected to ensure that it was suitable for parents with children.

Invited talks

- Janet Anders (Exeter, UK)
- Anne Anthore (Marcoussis, France)
- Jean-Philippe Brantut (Zurich, Switzerland)
- Göran Johansson (Chalmers, Sweden)
- Andrew Jordan (Rochester, USA)
- Nikolai Kiesel (Vienna, Austria)
- Jonne Koski (Aalto, Finland)
- Ahsan Nazir (Manchester, UK)
- Juan Parrondo (Madrid, Spain)
- Roberto Serra (Sao Carlos, Brazil)
- Janine Splettstoesser (Chalmers, Sweden)
- Tim Taminiau (Delft, NL)
- Masahito Ueda (Tokyo, Japan)

Tutorials

- Jens Eisert (Berlin, Germany)
- Alberto Imparato (Aarhus, Denmark)
- Eric Lutz (Erlangen, Germany)
- Jean-Michel Raimond (Paris, France)
- Killian Singer (Mainz, Germany)

Invited WG meeting Chairs

- WG1: Robert Whitney
- WG2: Marti Peranau, Nadja Bernardes & Philipp Kammerlander
- WG3: James Millen, Mischa Woods, & Marcus Huber

Local Organising Committee

- Benjamin Huard
- Alexia Auffeves
- Robert Whitney
- Sebastien Tanzilli
- Maxime Clusel

Scientific Committee

- Jukka Pekola (Aalto, Finland) -CHAIR-
- Alexia Auffeves (Grenoble, France)
- Benjamin Huard (Paris, France)
- Geraldine Haack (Grenoble, France)
- Mauro Paternostro (Belfast, UK)

Programme

Sunday, October 11, 2015

5:45 pm - 5:45 pm	Boat to Porquerolles - Departure from La Tour Fondue terminal to Porquerolles
6:30 pm - 6:30 pm	Boat to Porquerolles - Departure from La Tour Fondue terminal to Porquerolles
7:30 pm - 9:00 pm	Opening reception

Monday, October 12, 2015

8:45 am - 10:15 am	Classical and quantum trajectories
08:45 - 10:15	› Tutorial -- Fluctuation theorems in classical systems in contact with several baths: theory and experiments - *Alberto Imparato, University of Aarhus*
10:15 am - 10:45 am	Coffee break
10:45 am - 12:15 pm	Classical and quantum trajectories
10:45 - 11:15	› Stochastic path integral formalism for quantum trajectories of continuously measured systems - *Andrew Jordan, Department of Physics and Astronomy, University of Rochester*
11:15 - 11:45	› Coherence and measurement in quantum thermodynamics - *Janet Anders, University of Exeter*
11:55 - 12:15	› Nonclassical features in the distribution of work performed on a quantum system - *Paolo Solinas, Istituto SPIN-CNR*
12:15 pm - 1:15 pm	Lunch

1:15 pm - 2:45 pm	Quantum equilibration
13:15 - 14:45	› Tutorial: All you ever wanted to know about equilibration and thermalization - *Jens Eisert, Freie University Berlin*
2:45 pm - 4:15 pm	Working Group 1
4:15 pm - 4:45 pm	Coffee break
4:45 pm - 5:55 pm	Quantum detectors of heat and work
16:45 - 17:15	› TBA - *Nikolai Kiesel, Vienna Center for Quantum Science and Technology (Faculty of Physics, University of Vienna)*
17:15 - 17:35	› Irreversible Entropy Production in Quantum Systems Out of Equilibrium - *Matteo Brunelli, Centre for Theoretical Atomic and Molecular Physics (Queen's University Belfast)*
17:35 - 17:55	› Reversible work extraction in a hybrid opto-mechanical system - *Cyril Elouard, Institut Néel*
5:55 pm - 6:15 pm	Classical and quantum trajectories
17:55 - 18:15	› Thermodynamics of trajectories of a network of quantum harmonic oscillators - *Simon PIGEON, Queen's University of Belfast*
7:15 pm - 8:15 pm	Dinner
8:15 pm - 10:00 pm	Poster session 1
20:15 - 22:00	› A small quantum absorption refrigerator with reversed couplings - *Paul Skrzypczyk, ICFO – The Institute of Photonic Sciences,*
20:15 - 22:00	› A Spin Chain Quantum Refrigerator - *Yasser Omar, Universidade de Lisboa, Instituto de Telecomunicações*
20:15 - 22:00	› Efficiency bounds for quantum engines powered by non-thermal baths - *Wolfgang Niedenzu, Weizmann Institute of Science*
20:15 - 22:00	› Fluctuation Limited Free Energy - *Jonathan Richens, Quantum Optics and Laser Science, Blackett Laboratory*
20:15 - 22:00	› Single-ion heat engine - *Johannes Roßnagel, QUANTUM, University of Mainz*
20:15 - 22:00	› Transient effects due to lead-dot coupling modulation in thermoelectric transport through a quantum dot - *Anne-Marie Daré, Institut des Matériaux, de Microélectronique et des Nanosciences de*

Provence

Tuesday, October 13, 2015

Time	Event
8:45 am - 10:15 am	Thermodynamics and classical information
08:45 - 10:15	› Tutorial -- The physics of information: from Maxwell's demon to Landauer - *Eric Lutz, Friedrich-Alexander University of Erlangen-Nuremberg*
10:15 am - 10:45 am	Coffee break
10:45 am - 12:15 pm	Thermodynamics and classical information
10:45 - 11:15	› Information to energy conversion with electronic Maxwell's demons - *Jonne Koski, Aalto University*
11:15 - 11:45	› Time asymmetric driving and entropy production - *Juan Parrondo, Departamento de Física Atómica, Molecular y Nuclear and GISC, Universidad Complutense de Madrid*
11:45 - 12:05	› Measurement of the equilibrium free energy and the tunnel dynamics of a confined electron driven out of equilibrium - *Andrea Hofmann, Solid State Physics Laboratory, ETH Zürich*
12:15 pm - 1:15 pm	Lunch
1:15 pm - 2:45 pm	Working Group 2
2:45 pm - 4:15 pm	Experiments in the quantum world
14:45 - 15:15	› Quantum physics and information with spins in diamond - *Tim Taminiau, Delft University of Technology*
15:15 - 15:45	› Experimental implementation of a quantum heat engine and its optimization - *Roberto Serra, University of York, Federal University of ABC*
15:45 - 16:05	› Experimental demonstration of information to energy conversion in a quantum system at the Landauer Limit - *Lucas Céleri, Universidade Federal de Goiás*
4:15 pm - 4:45 pm	Coffee break
4:45 pm - 5:25 pm	Thermodynamics and classical information
16:45 - 17:05	› Extracting work from absence of correlations - *Markus Mueller, Heidelberg University, Germany*

Time	Event
17:05 - 17:25	› Thermodynamic meaning and power of non-Markovianity - *Bogna Bylicka, The Institute of Photonic Sciences, Institute of Physics, Faculty of Physics, Astronomy and Inf ormatics, Nicolaus Copernicus University*
5:25 pm - 5:45 pm	Quantum Engines
17:25 - 17:45	› A magnetic thermal switch for heat management at the nanoscale - *Francesco Mazza, Scuola Normale Superiore di Pisa, NEST Istituto Nanoscienze-CNR*
5:45 pm - 6:05 pm	Experiments in the quantum world
17:45 - 18:05	› Fluctuation-dissipation relations of a tunnel Junction driven by a quantum circuit - *Carles Altimiras, Service de Physique de l'Etat Condensé*
7:15 pm - 8:15 pm	Dinner
8:15 pm - 10:00 pm	Poster session 2
20:15 - 22:00	› Adiabatic and Non-adiabatic entropy production in quantum evolutions - *Gonzalo Manzano, Institute for Cross-Disciplinary Physics and Complex Systems, Departamento de Física Atómica, Molecular y Nuclear and GISC, Universidad Complutense de Madrid*
20:15 - 22:00	› Energy fluctuations in electron quantum optics - *Pascal Degiovanni, Laboratoire de Physique de l'ENS Lyon*
20:15 - 22:00	› Entanglement of a quantum dipolar gas loaded in optical lattices - *Laurent Vernac, Laboratoire de Physique des Lasers*
20:15 - 22:00	› Fluctuation relations in a superconducting circuit QED system - *Yuta Masuyama, The University of Tokyo*
20:15 - 22:00	› Measuring Work and Heat Statistics in Superconducting Quantum Circuits - *Quentin FICHEUX, ENS*
20:15 - 22:00	› Thermoelectricity without absorbing energy from the heat sources - *Robert Whitney, Laboratoire de Physique et Modélisation des Milieux Condensés*
20:15 - 22:00	› V-shape artificial atom based on superconducting quantum circuit - *remy dassonneville, Univ. Grenoble Alpes, Inst NEEL*

Wednesday, October 14, 2015

Time	Event
8:45 am - 10:15 am	Quantum Engines
08:45 - 10:15	› Tutorial -- TBA - *Kilian Singer, Institut für Physik [Mainz]*
10:15 am - 10:45 am	Coffee break
11:00 am - 5:00 pm	Boat tour - Visit of Port Cros Island
5:30 pm - 7:00 pm	Quantum Engines
17:30 - 17:50	› Steady-state entanglement in an autonomous quantum thermal machine - *Jonatan Bohr Brask, Institute for Theoretical Physics, Geneve*
17:50 - 18:10	› Coherence-assisted single-shot cooling by quantum absorption refrigerators - *Mark Mitchison, Quantum Optics and Laser Science, Blackett Laboratory*
18:10 - 18:30	› Quantum machines coupled to nonequilibrium reservoirs - *Obinna Abah, Friedrich-Alexander University of Erlangen-Nuremberg*
18:30 - 18:50	› Realization of a quantum Maxwell demon using superconducting circuits - *Nathanael Cottet, Laboratoire Pierre Aigrain*
7:15 pm - 8:15 pm	Dinner

Thursday, October 15, 2015

8:45 am - 10:15 am	Experiments in the quantum world
08:45 - 10:15	› Tutorial -- Cavity Quantum Electrodynamics: quantum trajectories, feedback and reservoir engineering - *Jean-Michel Raimond, Laboratoire Kastler Brossel*
10:15 am - 10:45 am	Coffee break
10:45 am - 11:45 am	MC - Management committee meeting
11:45 am - 12:15 pm	Quantum equilibration
11:45 - 12:15	› System-environment correlations in open quantum systems - *Ahsan Nazir, The University of Manchester [Manchester]*
12:15 pm -	Lunch

1:15 pm	
1:15 pm - 2:45 pm	Working Group 3
2:45 pm - 3:25 pm	Quantum equilibration
14:45 - 15:05	› Thermalisation of a quantum system from first principle - *Gregoire Ithier, Department of Physics, Royal Holloway, University of London*
15:05 - 15:25	› Energy and temperature fluctuations in the single electron box - *Tineke Van den Berg, Lund University, Department of Physics*
3:25 pm - 4:15 pm	Experiments in the quantum world
15:25 - 15:55	› Mesoscopic transport with cold atoms - *Jean-Philippe Brantut, Department of physics, ETH Zurich, 8093 Zurich, Switzerland*
4:15 pm - 4:45 pm	Coffee break
4:45 pm - 6:15 pm	Quantum Engines
16:45 - 18:15	› TBA - *Masahito Ueda, Department of Physics [Tokyo]*
7:15 pm - 9:00 pm	Conference dinner at "Villa Sainte Anne"

Friday, October 16, 2015

8:45 am - 9:45 am	Quantum detectors of heat and work
08:45 - 09:15	› Heat transport in quantum conductors - *Anne Anthore, Laboratoire de photonique et de nanostructures*
09:15 - 09:45	› Counting propagating microwave photons and generating single phonons - *Göran Johansson, Chalmers University of Technology*
9:45 am - 10:15 am	Quantum Engines
09:45 - 10:15	› Fermion-parity duality and energy relaxation in interacting open systems - *Janine Splettstoesser, RWTH Aachen University*
10:15 am - 10:30 am	Conclusions
10:45 am -	Boat to La Tour Fondue - Departure from Porquerolles

10:45 am	
11:30 am - 11:30 am	Boat to La Tour Fondue - Departure from Porquerolles

Appendix 1

Summary Of Working Group Discussions

Working Group 1 : Thermalization
Discussion subject "Open questions in thermalization"

Chaired by Rob Whitney

1) What are the timescales? Open versus closed, thermalized versus pre-thermalized, etc

Proving absence of system-environment coupling in experimental system:

If we wish to study experimentally the thermalization of a closed system. We need to be sure it does not interact with the environment. Easiest way is to simulate closed system and compare. But most interesting situations are those in which system is too big, or the dynamics are on too long timescales for even super computers. This is case for relatively small systems (exponential dependence of computing difficulty on system size).

E.G. Ion trap experimentalist believe environment coupling becomes relevant on scales of 100microseccond,
so they try to do their experiments on timescale of 1-10 microsecond.

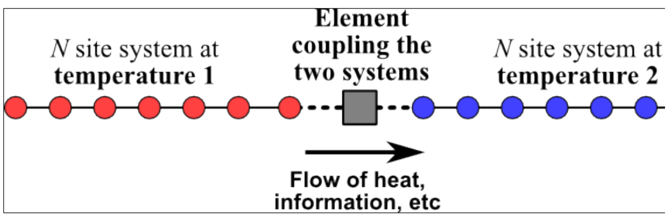
Open question: how to prove experimental system which is too big to simulate is really isolated from its environment?

Work in progress on this (J. Eisert) theoretical calculations that do not require simulating the system, but which could be compared with experimental results to prove that experiment is isolated.

Open question: Ssuperconducting circuit experiments work with systems states with special symmetries special states which couple more weakly to environment modes that an arbitrary system state. Will this useful for other experiments? Can theorists find ntn-trival thermalization problems involving *only* states with this special symmetries (so the environment's effect on this thermalization is negligible) .

Prethermalization connection to transport measurements:

Take two finite but large reservoirs at different temperatures, Turn on coupling between two reservoirs, and watch the thermalization process. On intermediate timescales a quasi -steady state will form. This state is closely related to what happens in transport theory



Open questions: What does transport theory tell us about pre-thermalization?
What does pre-thermalization tell us about transport theory?

Time scales for which nearly ideal experiment feels environment is difference between an “equilibrium state”, “thermal state”, and “pre-thermal state”?

2) Definitions of temperature and entropy for non thermal states

For temperature of thermalized in isolated systems - need proof of Eigenstate Thermalization Hypothesis (ETH)

ETH believed to work for ``middle of band''; i.e. not for low-lying energy states (ground state, etc). Need proof of what “middle” means.
ETH believed to gives reasonable effective temperature (temperatures higher for eigenstates with higher energy,
no negative temperatures, etc). Can this be proved?
ETH can be shown not to work for many-body localization. What other systems does it fail for?

Global entropy for closed system gives us no information about system's evolution

Global entropy is conserved in closed system - does not change in time. So it does not distinguish initial state and “thermalized” state. Thus we should use local definitions of entropy to get a handle on the thermalization.

What is known about fundamental limits on measuring temperature in experiments?

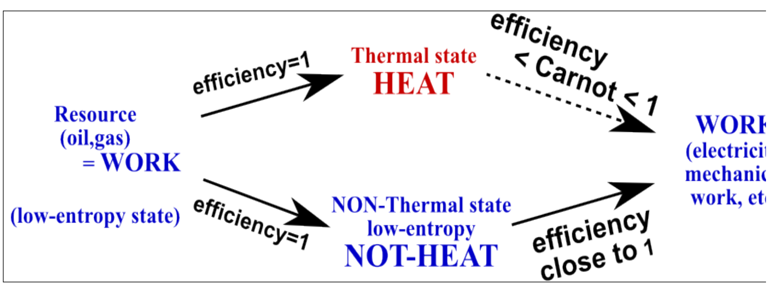
a) Temperature fluctuations mean errors are $(k_B T)^2/C$ where C is heat capacitance of thermometer.
b) As temperature is closely related to energy, expect Hesienberg uncertainty to limit measurements on short time.

3) What potential engineering applications for non-thermal states?

Non-thermal states are abolutely essential for all quantum information applications (qubits, quantum simulators, quantum communication, quantum computers).

May be good for Bolometers, etc.

Equilibrium system cannot act as amplifier.



Most resources for power generation (oil, gas, etc) are in low-entropy states (energy in chemical bonds).

It is BAD to burn them to create a hot thermal state, since converting HEAT into WORK always has a limited efficiency (Carnot efficiency). Converting resource work (chemical bonds) into another form of non-thermal state, and then into desired work (electricity, etc) could be done with efficiency of one (or close to one. Thus power production is much *more efficient* if one uses non-thermal states.

Working Group 2: Information in thermodynamics
Discussion "Standardizing the definition for WORK"

Proposed and chaired by three ESRs: Marti Peranau, Nadja Bernardes & Philipp Kammerlander

Three definitions of WORK suggested for quantum systems.

Non-equilibrium free-energy
Two projective measurement scheme
Resource theory approach
What are the positive and negative points with each definition.

I) Non-equilibrium free-energy

intial state : $r_{SB} = r_S \times \exp[-bH_B]/Z_B$ where S =system and B=bath

Inequality for average work : « Wext (r_{SB} to s_{SB}) » $\leq$ $F_{non\text{-}eq}(r_S) - F_{non\text{-}eq}(s_S)$

with free-energy $F_{non\text{-}eq}(r_{SB}) = \mathrm{Tr}\,[r_S H_S] - T\,S(r_S)$ for initial bath temperature $T = 1/b$,
and state r_S has von Neumann entropy $S(r_S)$.

GOOD	BAD
Not restricted to weak coupling	Not for fluctuations about average
Valid for all states, r_S and s_S	Not fully quantum (since driving is classical field)
including superpositions	**Response:** can probably treat driving quantum mechanically using quantum ancillary states and quantum clock.
	Hard to fit with experiments. Because hard to extract free energy in expts.
	Scheme makes sense if experimentalist can manipulate and measure system+environment, but most experiment only manipulate/measure system (and at most a few average properties of environment).
	Gives inequality rather than equality
	Question of whether it is free energy in thermodynamic sense, and whether it is free-energy (i.e. available energy) for a given real experiment.

Discussion about whether it is a free-energy in the thermodynamic sense:
In thermodynamics the free-energy is the energy one can extract by thermodynamic (macroscopic) operations.
Here we assume arbitrary global unitary (operation on S and B) is possible. However the number of relevant operations seems to scale with the size of the

system, so it seems that this energy is only extractable by someone who can perform microscopic operations on the system. So it does not tell us how much energy one can extract if one can only perform macroscopic operations.

2) Two-projective measurement scheme

projection 1 evolution projection 2

r_{SB} -----------------> $|E_i\rangle\langle E_i|$ ------------------------> U $|E_i\rangle\langle E_i|$ $U^{\dagger}$ ---------------------> $|E_j\rangle\langle Ej|$

This scheme gives us information about "evolution+ projection2" not about "evolution" alone.

GOOD	**BAD**
Has fluctuations as well as average	Projection 2 is invasive measurement, it change the system. The thermodynamics of this projection process is unclear. It destroys coherences in the system, is this doing work on system, is it changing the system entropy?
Correspondence with classical physics :reproduces second law of thermodyn,and classical fluctuation theorems	Boring : no modification of thermodynamic relations in quantum limit (always reproduces 2n law of thermodyn, and classical fluctuation theorems with no hbar-dependent corrections)
The scheme fits with most natural experimental protocols. Scheme only requires measuring system, not system+env.	Cost of projection 1 is unclear Discussion: It is probably natural to treat this cos separately from the process. So maybe this is nc a problem.

3)Resource theory definition of work

Consider Hamiltonian for system + reservoirs + *work-storage device*

Then work storage device is treated in a fully quantum manner.

GOOD	**BAD**
Work in storage device really looks like useful work (but see "BAD" comment)	Too general : Gibb's state in work-storage devic would here be defined as WORK, when there strong argument that this is HEAT not WORK.
Can treat coherences	To restrictive : fails to capture many situatior that we perceive as thermodynamic – such a heat engines
Single shot : therefore fluctuations as well as averages	Strange situation

General conclusion (due to Raam Uzdin): Maybe the problem of choosing which definition is best is not clear because the experimental tasks are not yet clear.

Classical thermodynamics was built *after* many different types of machines (mostly steam-engines) existed, so the "universal" aspects of machine properties and "universal" nature of the tasks could be used to build the theory. At present, we only have a few examples of experimental machines, so there not yet a clear distinction between "universal" and "system specific" aspects. As more experiments become available in the near future, the most natural definition of quantities like work should become clearer.

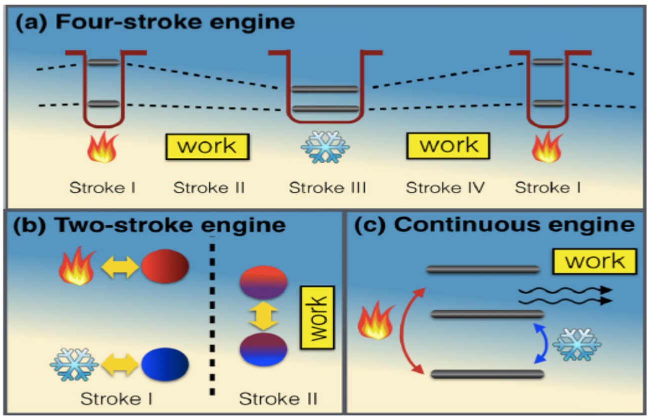
Working Group 3: Implementations
Discussion "Quantum engines : where are we, and what is quantum?"

Proposed and chaired by three ESRs: James Millen, Mischa Woods, & Marcus Huber

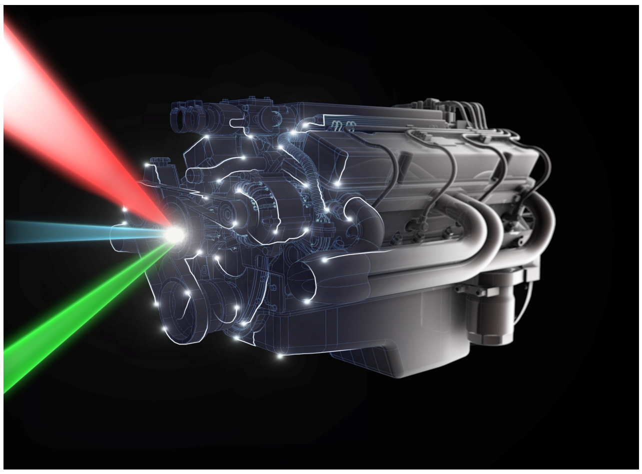
PART 1 : Where are we (experimental engines to date) slides compiled of James Millen

Continuous verses "stroke-based" engines

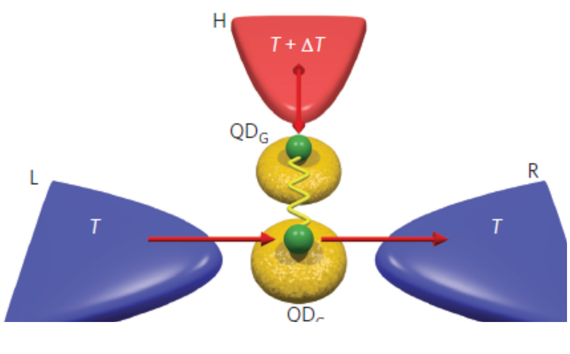
Profound connection between the two
Uzdin, Levy, Kosloff PRX 5, 031044 (2015)



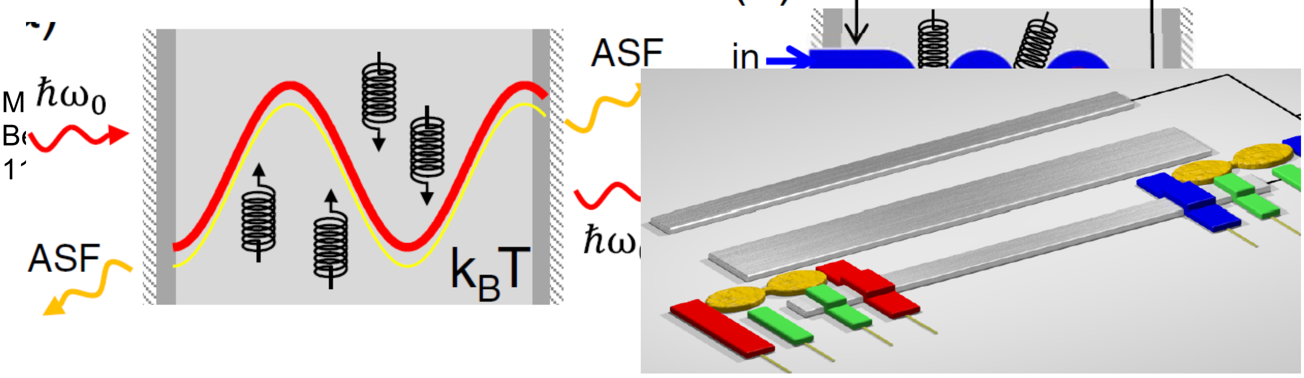
Artist impression of "quantum engines"



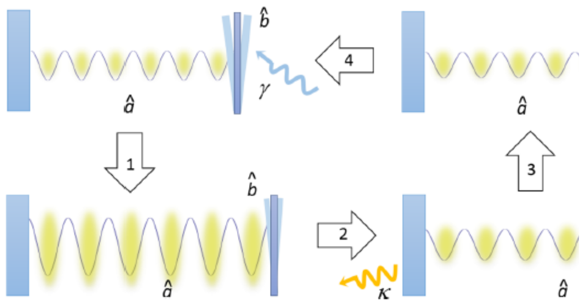
Quantum dot heat pump
Thierschmann et al. Nature Nano 10, 854 (2015)



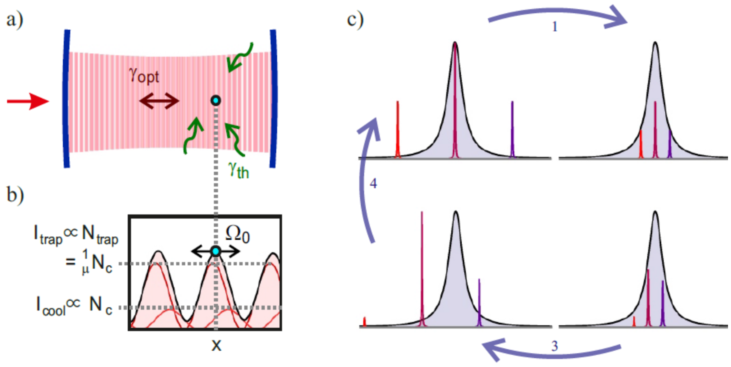
Polariton heat engine
Klembt et al. Phys. Rev. Lett. 114, 186403 (2015)



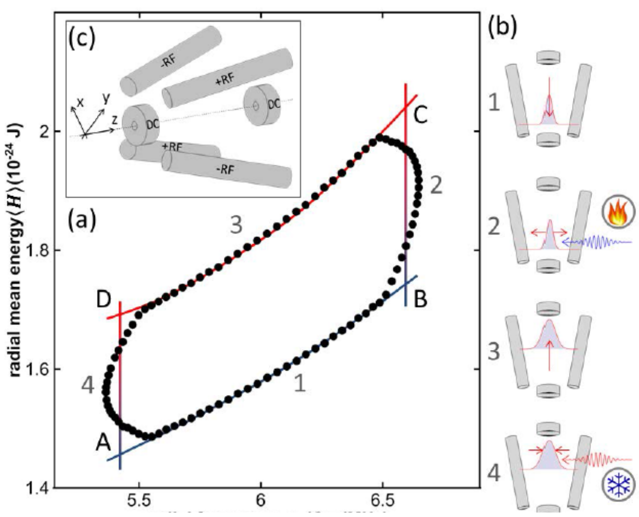
Quantum optomechanical heat-engine (not realized)
Zhang, Bariani, Meystre Phys, Rev. Lett. 112, 150602 (2014)



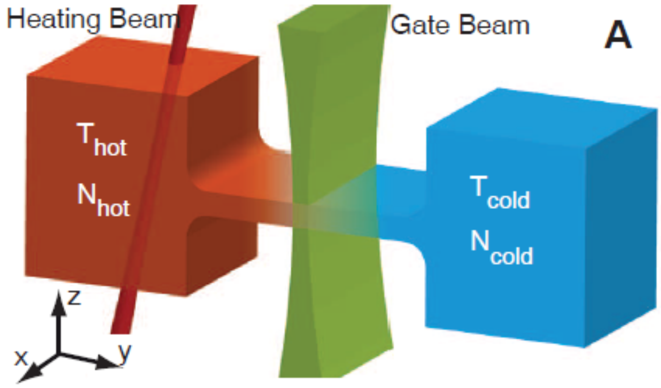
Single particle heat engine (not realized)
Dechant, Kiesel, Lutz Phys, Rev. Lett. 114, 183602 (2015)



Single ion heat engine (being realized)
Abah et al. PRL 109, 203006 (2012),
Roβnagel et al. PRL 112 030602 (2014)



Brantut et al. Science 342, 713 (2013)



OTHERS:
Optical, encoded in photon polarization. Z
17, 075007 (2015)

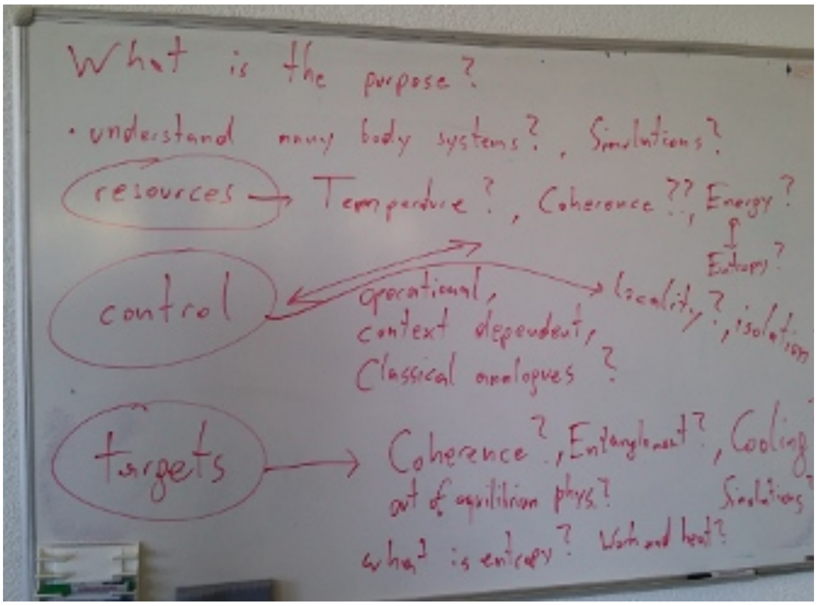
Molecular, NMR type schemes Hübner et a
Batalhão et al. Phys. Rev. Lett. 113, 14060

Internal states of an ion An et al. Nature Ph

PART 2 : What is "quantum" in quantum thermodynamics?

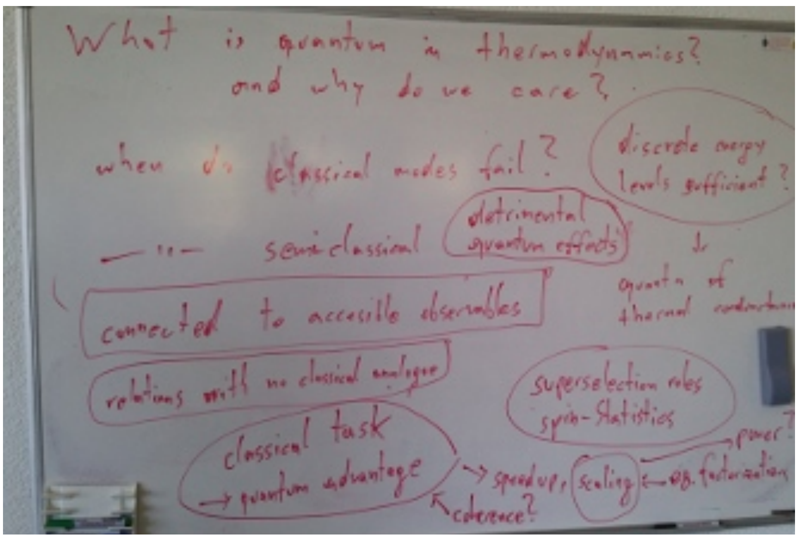
Question what is purpose of quantum thermodynamics?

Conclusion of discussion summarized by Marcus Huber:
We have identified that the theory we are interested in is conditioned upon different operational targets (cooling many body systems, creation of entanglement, probing quantum scale dynamics, waste-heat recycling). Together with this context dependent target, we also implicitly assume various levels of control (locality of operations, access to thermal baths, etc) and the ultimate aim is to identify the limitations of reaching this target, and which resources (thermal baths gradients, coherence, etc) allow us to overcome such limitations and to what extent.



Concerning the quantumness of quantum thermodynamics?

Conclusion of discussion summarized by Marcus Huber:
While various, potentially contradictory, notions of what constitutes genuine quantumness were voiced in the room, ultimately there seems to be an agreement that this is not the most relevant question. More important to the



participants it seemed to the respective targets and whether this can be called "quantum" ultimately boils down to semantics. Various interesting proposals and analogues were articulated, such as scalability of quantum advantages (reminiscent of quantum computation), and while the vast majority of suggestions concerned quantum engines outperforming classical ones (e.g. in power), detrimental quantum influences have also been mentioned (see white board photo).