Thermodynamics as a Resource Theory: Foundational and Philosophical Implications

2018 ANNUAL PHILOSOPHY OF PHYSICS CONFERENCE

20 June 2018 - 22 June 2018

Conference Program

Day 1: Wednesday, June 20	
9:00–10:15	Wayne Myrvold The Maxwellian view of statistical mechanics and thermodynamics
10:15–10:30	Break
10:30–11:45	Joshua Luczak On the aims of statistical mechanics
12:00–13:30	Lunch break
13:30–14:45	Robert W. Spekkens The invasion of physics by information theory
14:45–15:00	Break
15:00–16:15	Tony Bartolotta Bayesian updating in thermodynamics
16:15–17:30	General discussion

Day 2: Thursday, June 21	
9:00–10:15	David Wallace Thermodynamics as control theory
10:15–10:30	Break
10:30–11:45	Jos Uffink Tatiana Ehrenfest-Afanassjewa and the foundations of thermodynamics
12:00–13:30	Lunch break
13:30–14:45	Owen Maroney Is there a unique thermal entropy? Fluctuations, non-extensivity, irreversibility and statistical mechanics
14:45–15:00	Break
15:00–16:15	Carina Prunkl Resource theories of thermodynamics and axiomatics: a comparison
16:15–17:30	General discussion

Day 3: Friday, June 22	
10:30–11:45	Carlo Sparaciari Multi-resource theories and the first law
12:00–13:30	Lunch break
13:30–14:45	Nelly Ng The fundamental limits of efficiency for quantum heat engines
14:45–15:00	Break
15:00–16:15	Markus Müller Exact operational interpretation of the free energy without the thermodynamic limit
16:15–17:30	General discussion

Abstracts

Tony Bartolotta: *Bayesian Updating in thermodynamics*

Measurements have been previously incorporated in thermodynamics, usually in the context of feedback control. These measurements provide information about the current state of the system allowing useful work to be extracted. Furthermore, they contain information about previous states of the system. Consequently, under a Bayesian framework, the distribution functions of the previous states must be updated. This updating changes the definitions of "initial" entropy and free energy. Several thermodynamic equalities and inequalities that incorporate the information-theoretic contributions of the Bayesian updating are derived. The role of Bayesian updating in systems with coarse-grained or unknown dynamics is also discussed.

Joshua Luczak: *On the aims of statistical mechanics*

I highlight that the aim of using statistical mechanics to underpin irreversible processes is, strictly speaking, ambiguous. Traditionally, however, the task of underpinning irreversible processes has been thought to be synonymous with underpinning the Second Law of thermodynamics. I claim that contributors to the foundational discussion are best interpreted as aiming to provide a microphysical justification of the Minus First Law, which says that an isolated system in an arbitrary initial state within a finite fixed volume will spontaneously attain a unique state of equilibrium. I suggest that contributors should aim at accounting for both the Minus First Law and Second Law.

Owen Maroney: *Is there a unique thermal entropy? Fluctuations, non-extensivity, irreversibility and statistical mechanics*

There has long been a debate between the Boltzmannian and Gibbsian views of statistical mechanics, and in particular their different views of entropy. Recently, however, it has been suggested that even with the Gibbsian framework, the Gibbs-von Neumann entropy is not the appropriate statistical mechanical entropy, with a revival of interest in non-extensive entropies. I will attempt to put this recent work into a broader context. First I will show that even with phenomenological thermodynamics, fluctuation phenomena and irreversibility can point to the non-uniqueness of entropy as a function of state. Then I will review an argument to uniquely identify the Gibbs-von Neumann entropy as the statistical mechanical entropy function. Finally I will show how relaxing assumptions in this argument leads to a wide family of entropy functions that naturally incorporates the non-extensive entropies and the Gibbs-von Neumann entropy as special cases.

Markus Müller: ***Exact operational interpretation of the free energy without the thermodynamic limit***
According to the resource-theoretic approach, thermodynamics at the nanoscale behaves quite differently from its familiar counterpart in the regime of the thermodynamic limit: for example, the standard formulation of the second law (non-increase of the Helmholtz free energy) is replaced by an infinite family of "second laws" (cf. Brandao et al., PNAS 112, 2015). However, this result has been obtained under an auxiliary assumption that can be lifted in some circumstances. Namely, here I show that microscopic thermal machines can exploit a strategy that is unavailable in the thermodynamic limit: they can substantially increase their efficiency by correlating themselves with their working medium in clever ways. I show that this allows them to overcome the infinite family of "second laws", and to extract (or invest) the Helmholtz free energy difference in arbitrary state transitions exactly and basically without any fluctuations.

This restores the standard formulation of the second law at the nanoscale. Moreover, it gives the standard free energy (and the von Neumann entropy) an operational interpretation that is valid without averaging and for *single* instances of a quantum system (not just, as usual, for many weakly interacting identical copies).

Based on arXiv:1707.03451

Wayne C. Myrvold: ***The Maxwellian view of thermodynamics and statistical mechanics***
One of the pioneers of statistical mechanics, James Clerk Maxwell, was also a pioneer of the view that thermodynamics should be thought of as a resource theory. For Maxwell, the distinction between energy transfer as heat and energy transfer as work is a distinction relative to an agent's ability to keep track of, and manipulate a system to direct its energy to do useful work. The second law of thermodynamics, as Maxwell was the first to clearly articulate, becomes a statistical truth. I discuss the implications of this for the project of recovering thermodynamical laws from statistical mechanics.

Nelly Ng: ***The fundamental limits of efficiency for quantum heat engines***
Abstract: Sadi Carnot's theorem regarding the maximum efficiency of heat engines famously states that the maximum efficiency depends only on the temperature of the heat baths used by the engine – but not the specific details on how these baths are actually realized. Carnot's results can be derived as a consequence of the second law of thermodynamics. However, in the quantum nanoscale regime, we show that these results demand revision, in particular, more information about the bath other than its temperature is required to decide whether maximum (Carnot) efficiency can be achieved. Moreover, for qualitatively different characterizations of

the energy/work extracted, the maximum achievable efficiency of quantum heat engines can be either sub-Carnot, or even exceed Carnot efficiency. This highlights the importance of carefully distinguishing work and heat, especially for a heat engine that operates in the nanoscale quantum regime.

Carina Prunkl: ***Resource theories of thermodynamics and axiomatics: a comparison***
The resource theory of non-thermal states provides a lean and powerful framework to calculate the thermal behavior of quantum systems. Some scientists even claim that it has "advanced our understanding of fundamental physical principles, such as the second law of thermodynamics" (del Rio et al., 2015, p.1). It is furthermore said that thermodynamics itself can be derived from resource theoretic considerations, since "the free energy of thermodynamics emerges naturally from the resource theory of energy-preserving transformations" (Brandão et al., 2013, p.1).

Here I want to probe the claim that resource theories provide us with a deeper understanding of thermodynamics. I will do so by comparing them to the axiomatic approaches developed by Carathéodory and by Lieb and Yngvason. At the center of such axiomatic formulations is the concept of adiabatic accessibility. A state is said to be adiabatically accessible from another if the thermodynamic system in question can evolve into it without exchanging heat or matter with the environment. This notion of adiabatic accessibility has a striking resemblance to the order relations encountered in the resource theory of nonuniformity and the resource theory of non-thermal states, each of which define at least one measure on the resource states that is monotonically non-decreasing under the set of allowed transformation. In my talk I will explore similarities and differences between the two approaches and discuss whether resource theories indeed provide us with a deeper insight into thermodynamics.

Carlo Sparaciari: ***Multi-resource theories and the first law***
We derive conditions for the interconversion of resources, that is, for the existence of a `first law of thermodynamics' within arbitrary quantum resource theories. Resource theories are versatile tools that characterise several aspects of quantum physics, from entanglement to thermodynamics. Usually one identifies a single quantity as the resource associated with the theory: in studying non-locality the resource is entanglement, while for thermodynamics it can be work. In reality, we often need more than a single resource in order to perform a given task: for instance, the power of quantum computation relies on both purity (of the input qubits), and coherence (created by the gates).
Here we introduce a general framework to describe tasks requiring multiple resources in quantum settings. We study reversibility conditions for multi-resource theories, and find that the relative entropy distances from the invariant sets of the theory plays a fundamental role in the quantification of the resources. Finally, we analyse the interconversion of resources, introducing a first law for general multi-resource theories – a single relation which links the change in the properties of the system during a state transformation and the weighted sum of the resources exchanged. We apply these results to thermodynamics with multiple conserved charges, and to the theory of local control under energetic restrictions.

Robert Spekkens: *The invasion of physics by information theory*

Historically, many revolutions in physics have been preceded by the discovery of a novel perspective on an existing physical theory. The discovery of least-action principles, symmetry principles, and thermodynamic principles are good historical examples. Information-theoretic principles may well play a similar role in physics today. To make the case for this idea, I will discuss some of the highlights of two resource theories: the resource theory of asymmetry, which characterizes the relations among quantum states that break a symmetry; and the resource theory of athermality, which characterizes the relations among quantum states that deviate from thermal equilibrium. In particular, I will discuss how Noether's theorem does not capture all of the consequences of symmetries of the dynamics, and how the second law of thermodynamics does not capture all of the constraints on thermodynamic transitions. Finally, I will show that both asymmetry and athermality are informational resources, and that rehabilitated versions of Noether's theorem and the second law can both be understood as constraints on data processing. Considerations such as these—as well as evidence from other fronts of the invasion—make a compelling case for the usefulness of reconceiving physics from an information-theoretic perspective.

Jos Uffink: *Tatiana Ehrenfest-Afanassjewa and the foundations of thermodynamics.*

I will consider Afanassjewa's work on the foundations of thermodynamics. In particular I consider her response to Caratkhédory's (1909) axiomatization, her view on the definition of a "reversible process" in the context of Norton's recent claim that this notion is paradoxical, her discussion of negative absolute temperatures, 30 years before Ramsey introduced this notion into statistical mechanics, her view on the question whether thermodynamics is a dynamical theory at all, and, if time permits, on the distinction between thermal contact and "pressure contact" (as mediated, say, by a piston) between thermodynamical systems.

David Wallace: *Thermodynamics as control theory*

I explore the reduction of thermodynamics to statistical mechanics by treating the former as a control theory: a theory of which transitions between states can be induced on a system (assumed to obey some known underlying dynamics) by means of operations from a fixed list. I recover the results of standard thermodynamics in this framework on the assumption that the available operations do not include measurements which affect subsequent choices of operations. I then relax this assumption and use the framework to consider the vexed questions of Maxwell's demon and Landauer's principle. Throughout I assume rather than prove the basic irreversibility features of statistical mechanics, taking care to distinguish them from the conceptually distinct assumptions of thermodynamics proper.