Quantum information and thermodynamics: a resource-theoretic approach

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Fundamental laws of Nature often take the form of restrictions: nothing can move faster than light in vacuum, energy cannot be created from nothing, there are no perpetuum mobiles. It is due to these limitations that we can ascribe value to different objects and phenomena, e.g., energy would not be treated as a resource if we could create it for free. The mathematical framework developed to study the influence of such constraints on the possible transformations of quantum states is known under the collective name of resource theories.

The first and second laws of thermodynamics are such fundamental constraints that force thermodynamic processes to conserve the overall energy and forbid free conversion of thermal energy into work. Thus, a natural question to ask is: what amounts to a resource when we are restricted by these laws? It has been recently identified that apart from *athermality* (the property of a state of having a distribution over energy levels that is not thermal), also *coherence* can be viewed as a second, independent resource in thermodynamics [1]. This stems from the fact that energy conservation implied by the first law restricts processing of coherence, and so possessing a state with coherence allows for otherwise impossible transformations. It also enforces a modification of the traditional Szilard argument: both athermality and coherence contribute to the free energy, however coherence remains "locked" and cannot be extracted as work.

Since coherence is a thermodynamic resource, an open question is what kind of coherence processing is allowed by thermodynamic means. The aim of this presentation is to address this problem and ask: what are the allowed transformations of quantum states that are consistent with the first and second laws of thermodynamics? Our approach employs the underlying energy-conservation within thermodynamics that constrains all thermodynamic evolutions to be "symmetric" under time translations. This in turn allows us to make use of harmonic analysis techniques, developed in [2], to track the evolution of coherence under thermodynamic transformations in terms of the "mode components" of the system. This constitutes a natural framework to understand coherence and allows us to separate out the constraints that stem solely from symmetry arguments from those particular to thermodynamics. This approach also implies that the existing single-shot results applicable to block-diagonal results, constrained by thermo-majorization [3], can be viewed as particular cases of our analysis when only the zero-mode is present. Beyond this regime, every non-zero mode obeys *independent* constraints, and displays thermodynamic irreversibility similar to the zero-mode.

Exploiting these tools we arrive at the upper bounds on final coherences in the energy eigenbasis for quantum states undergoing time-translation symmetric and thermodynamic processing [4]. A rich dynamics is allowed, in which coherence can be transferred among different energy levels within each mode. We show that similarly to heat flows, coherence flows show directionality due to the limitations imposed by the second law. This new kind of irreversibility adds up to the ones identified in work extraction [3] and coherence distillation [1]. Finally, we analyse the process of converting quantum coherence to work, emphasizing the need of an external source of coherence and connecting its quality with the efficiency of the conversion process [5].

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[1] M. Lostaglio, D. Jennings, and T. Rudolph, Nat. Commun. **6**, 6383 (2015).
[2] I. Marvian and R. W. Spekkens, Phys. Rev. A **90**, 062110 (2014).
[3] M. Horodecki and J. Oppenheim, Nat. Commun. **4**, 2059 (2013).
[4] M. Lostaglio, K. Korzekwa, D. Jennings, and T. Rudolph, Phys. Rev. X **5**, 021001 (2015).
[5] K. Korzekwa, M. Lostaglio, J. Oppenheim, and D. Jennings, arXiv:1506.07875 (2015).