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# Taming catalysts in quantum thermodynamics

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## Abstract
Auxiliary quantum systems which can be borrowed to help facilitate thermodynamic processes but must be returned almost undisturbed—i.e. catalysts—are very powerful objects in quantum thermodynamics. In fact, they appear almost too powerful, since they allow for any state transformation to be carried out while being disturbed by an arbitrarily small amount. In their recent paper Ng *et al* (2015 *New J. Phys.* **17** 085004) show how to tame catalysts in quantum thermodynamics by placing additional physical constraints on them, in terms of dimension and energy.

Normally when thinking about catalysts, one has in mind chemical reactions, where an additional agent allows for a reaction to take place that otherwise would not occur, or to substantially speed it up. Crucially, the agent is returned at the end of the reaction in an unaltered state, and can thus be re-used in further reactions. One can however think more generally about catalysts, outside the context of chemical reactions. Anything that can be borrowed to allow for some otherwise-impossible (or very difficult) task to take place, as long as it is afterwards returned in perfect condition, can be considered a catalyst. In this sense, a tin-opener, which facilitates the easy opening of a tin of beans, can also be thought of as a catalyst.

In quantum thermodynamics, it turns out that there are situations where catalysts also play a fundamental role. In particular, one basic question is which state transformations are possible at the level of a single system, in the presence of a thermal bath at temperature $T$? (With no other external sources of energy or entropy allowed.) This question was recently studied [1] using the resource theory of quantum thermodynamics [2]. There it was shown that the answer changes dramatically if at the same time one is given access to an auxiliary quantum state —the catalyst—which must be returned perfectly after being used [3].

Care however must be taken—it is clear that the requirement of being returned perfectly is an idealization which will never be met in reality. What we really want is that the catalyst is returned almost perfectly undisturbed. This is especially pertinent in the case of quantum catalysts, where one intuitively expects that 'back-action' during use cannot be ignored. Here an interesting effect occurs, analogous to an effect from entanglement theory known as 'embezzlement' [4]. Even arbitrarily small disturbances in the returned catalyst (i.e. even if the state after return is almost perfectly indistinguishable from the original state) allow for all state transformations to become possible. Thus it seem that in the presence of catalysts we are lead to a trivial resource theory of quantum thermodynamics.

However, all is not lost. The question that remains is how do catalysts achieve this amazing embezzling feat? Could it be that while mathematically possible, if one makes additional physically reasonable restrictions on the catalyst that this feat becomes impossible? This is exactly the question studied in this article by Ng and co-authors [5], and the short answer is yes, physical restrictions rule out the possibility of all-powerful catalysts. One can recover a sensible resource theory of quantum thermodynamics.

In more detail, the authors provide two main results, depending upon the Hamiltonian of the system under consideration. They start with the simpler but more tractable case of a system with trivial Hamiltonian (i.e. fully degenerate), which amounts to restricting to the resource theory of nonuniformity [6]. Here they answer the question of what is the minimal disturbance in the returned catalyst (as measured in terms of the trace distance) that allows for the most difficult state transformation to take place—the transformation taking the maximally mixed state to a pure state. Since a catalyst which facilitates this most difficult transformation also facilitates every other 'easier transformation', the authors solve the problem of when a universal embezzling catalyst exists;

if the disturbance in the final catalyst is smaller than the bound they give then there is no universal catalyst which can facilitate the transformation; if the disturbance is bigger they give an explicit construction for a catalyst which does the job.

One interesting aspect of their result is the minimal disturbance itself which marks the border of universal embezzling. Imagine that the catalyst is made up of a number of constituents (i.e. particles), all of the same dimension as the system which undergoes the transformation. Then the minimal disturbance scales asymptotically with the number of constituents in the catalyst. This shows that the physical requirement is that the disturbance per catalyst particle be small enough, rather than the total disturbance be small, thus taming large catalysts.

The second main result concerns the general case of arbitrary system Hamiltonians. The question now is whether, after placing additional restrictions on the catalyst, there is a minimal disturbance below which no catalyst can facilitate the most difficult diagonal transformation (now between the thermal state, and the maximally energetic eigenstate). The authors consider two physical restrictions, first that the dimension of the catalyst is bounded, and second that the average energy of the catalyst is finite (while allowing for unbounded dimension and maximum energy level). In both cases they show that sufficiently large disturbances must occur in the catalyst in order for it to facilitate the transformation. Thus, even in this more general scenario, the power of catalysts can again be tamed by restricting either their dimension (similarly to the previous case) or by restricting how much energy they can store on average.

We thus now have a much better understanding of what catalysts can and cannot do in the resource theory of quantum thermodynamics. Nevertheless there remain many exciting avenues to explore, for example tailoring catalysts to specific transformations, or concerning when the system or the catalyst contain coherences between energy eigenstates. One thing though is already for sure, that unlike a catalyst, thanks to the work of Ng *et al*, our state of understanding will definitely not be returning to what it was before.

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