Quantum indistinguishability as a resource for purification

Samyak Pratyush Prasad,[1,2] Kiarn T. Laverick,[1,2] Maria Maffei,[3] and Alexia Auffèves[1,2]

[1] *MajuLab, CNRS-UCA-SU-NUS-NTU International Joint Research Laboratory*

[2] *Centre for Quantum Technologies, National University of Singapore, 117543 Singapore, Singapore*

[3] *Université de Lorraine, CNRS, Laboratoire de Physique et Chimie Théoriques, 54500 Vandoeuvre-les-Nancy, France*

Most quantum technologies and protocols rely on the use of pure quantum states. One approach to increase the purity of a quantum state is to apply purification protocols, which aim to reduce the entropy of an initially mixed state. Generally these protocols rely on measurements and feedback in order to reduce entropy. Even though multiple protocols [1–4] and bounds [5, 6] have been proposed for quantum state purification, the fundamental mechanisms underlying these processes have yet to be uncovered. In this work, we identify two fundamental mechanisms underlying a purification process. The first, that we dub classical purification, alters the probability distribution of the mixed state in order to reduce its entropy [2, 3]. A prime example of a process solely using classical purification is the Maxwell's demon experiment [7], where the demon sorts out high energy gas particles from lower energy ones, thereby reducing the entropy of the gas. The second, that we dub quantum purification, generates quantum indistinguishability between the quantum states which make up the mixture. This is as if the demon was to superpose the gas particles making them partially indistinguishable rather than sorting them. This process decreases the entropy of the gas solely using quantum purification. Concretely, we consider the purification of optical systems via a qubit (counterpart of the demon) where we illustrate our ideas on experimentally viable processes such as the preparation of Schrödinger cats, where both quantum and classical purification can be observed and SNAP [8] operations where solely quantum purification can be observed. Finally, we provide a pathway towards quantum cooling processes where both the entropy and energy of a state is lowered by generation of quantum indistinguishability.

[1] J. I. Cirac, A. K. Ekert, and C. Macchiavello, Optimal purification of single qubits, Phys. Rev. Lett. **82**, 4344 (1999).

[2] C. H. Bennett, G. Brassard, S. Popescu, B. Schumacher, J. A. Smolin, and W. K. Wootters, Purification of noisy entanglement and faithful teleportation via noisy channels, Phys. Rev. Lett. **76**, 722 (1996).

[3] A. M. Alhambra, M. Lostaglio, and C. Perry, Heat-bath algorithmic cooling with optimal thermalization strategies, Quantum **3**, 188 (2019).

[4] A. V. Lebedev, D. Oehri, G. B. Lesovik, and G. Blatter, Trading coherence and entropy by a quantum maxwell demon, Phys. Rev. A **94**, 052133 (2016).

[5] M. A. Nielsen, Characterizing mixing and measurement in quantum mechanics, Phys. Rev. A **63**, 022114 (2001).

[6] K. Jacobs, Efficient measurements, purification, and bounds on the mutual information, Phys. Rev. A **68**, 054302 (2003).

[7] J. C. Maxwell, *Theory of Heat*, Cambridge Library Collection - Physical Sciences (Cambridge University Press, 2011).

[8] R. W. Heeres, B. Vlastakis, E. Holland, S. Krastanov, V. V. Albert, L. Frunzio, L. Jiang, and R. J. Schoelkopf, Cavity state manipulation using photon-number selective phase gates, Phys. Rev. Lett. **115**, 137002 (2015).