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Universal tradeoff relations between resource cost and irreversibility of channels: General-resource Wigner-Araki-Yanase theorems and beyond

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Quantum technologies offer exceptional – sometimes almost magical – speed and performance, yet every quantum process costs physical resources. Designing next-generation quantum devices, therefore, depends on solving the following question: which resources, and in what amount, are required to implement a desired quantum process? Casting the problem in the language of quantum resource theories, we prove a universal cost-irreversibility tradeoff: the lower the irreversibility of a quantum process, the greater the required resource cost for its realization [1]. The trade-off law holds for a broad range of resources – energy, magic, asymmetry, coherence, athermality, and others – yielding lower bounds on resource cost of any quantum channel. Its broad scope positions this result as a foundation for deriving the following key results: (1) we show a universal relation between the energetic cost and the irreversibility for arbitrary channels, encompassing the energy-error tradeoff for any measurement or unitary gate; (2) we extend the energy-error tradeoff to free energy and work costs; (3) we extend the Wigner-Araki-Yanase theorem [2], which is the universal limitation on measurements under conservation laws, to a wide class of resource theories: the probability of failure in distinguishing resourceful states via a measurement is inversely proportional to its resource cost; (4) we prove that infinitely many resource-non-increasing operations in fact require an infinite implementation cost as a generalization of the results on the cost-diverging Gibbs-preserving operations [3]. These results can be regarded as a generalization of the earlier work on asymmetry [4,5], and we also discuss their relation to those studies.

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[3]H. Tajima, R. Takagi, Phys. Rev. Lett. 134, 170201, 2025 (QIP2025)
[4]H. Tajima, N. Shiraishi, K. Saito Phys. Rev. Lett. 121, 110403 (2018) (QIP2020)
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