Beyond the first law: Peculiarly quantum conservation laws in thermodynamics

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Starting in undergraduate statistical physics, we study small systems that thermalize by exchanging quantities with large environments. Such thermalization helps define time's arrow, and the exchanged quantities–heat, particles, electric charge, etc.–are conserved globally. If quantum, the quantities are represented by Hermitian operators. We often assume implicitly that the operators commute with each other–for instance, in derivations of the thermal state's form. Yet operators' ability to not commute underlies quantum phenomena such as uncertainty principles. What happens if thermodynamic conserved quantities fail to commute with each other? This question, mostly overlooked for decades, came to light recently at the intersection of quantum thermodynamics and information theory [1]. Noncommutation of conserved thermodynamic quantities has been found to enhance entanglement [2], decrease entropy-production rates, alter the eigenstate thermalization hypothesis [3], and more. This growing subfield illustrates how 21st-century quantum information science is extending 19th-century thermodynamics.

[1] Majidy, Braasch, Lasek, Upadhyaya, Kalev, and NYH, Nat. Rev. Phys. (2023). https://www.nature.com/articles/s42254-023-00641-9

[2] Majidy, Lasek, Huse, and NYH, Phys. Rev. B 107 045102 (2023). https://journals.aps.org/prb/abstract/10.1103/PhysRevB.107.045102

[3] Murthy, Babakhani, Iniguez, Srednicki, and NYH, Phys. Rev. Lett. 130, 140402 (2023). https://doi.org/10.1103/PhysRevLett.130.140402