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The second law of quantum thermodynamics as an equality

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The traditional second law of thermodynamics says that the average amount of work required to change one state into another while in contact with a heat reservoir, must be at least as large as the change in free energy of the system. Here, we consider a fine-grained notion of the free energy, and show that in terms of it, the second law can be written as an equality. We also obtain a generalisation of the Jarzynski fluctuation theorem which holds for arbitrary initial states, not just the case of an initial thermal state. We derive a generalisation of Gibbs-stochasticity, a condition originally found in the approach to thermodynamics inspired by quantum information theory. This generalisation directly incorporates the case of fluctuating work and serves as a parent equation which can be used to derive the second law equality and the generalisation of the Jarzynski equation. We further show that each of these three generalisations can be seen as the quasi-classical limit of three fully quantum identities. This allows for more general and fully quantum fluctuation relations from the information theoretic approach to quantum thermodynamics.