Quantum equivalent of thermodynamics' second law discovered for entanglement manipulation

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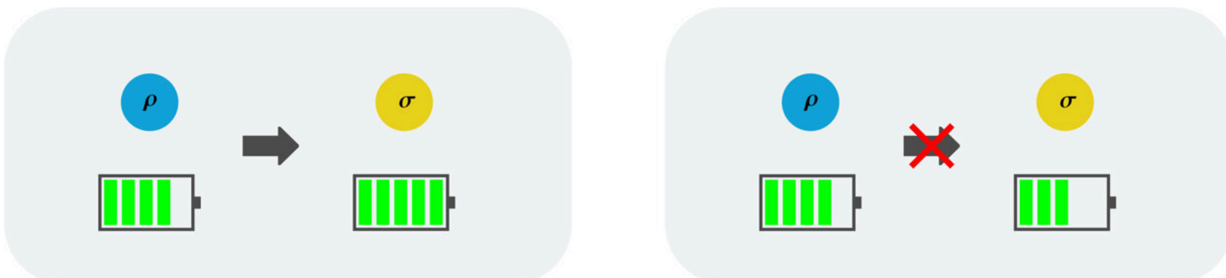

Illustration of an entanglement battery. The battery allows reversible interconversion between any two entangled states. Credit: American Physical Society

Just over 200 years after French engineer and physicist Sadi Carnot formulated the second law of thermodynamics, an international team of researchers has unveiled an analogous law for the quantum world. This second law of entanglement manipulation proves that, just like heat or energy in an idealized thermodynamics regime, entanglement can be reversibly manipulated, a statement which until now had been heavily contested.

The new research—released on July 2, 2025 in *Physical Review Letters*—deepens understanding of entanglement's basic properties and provides critical fundamental insight into how to efficiently manipulate entanglement and other quantum phenomena in practice.

Entanglement is arguably the central feature of quantum mechanics. If two microscopic particles are said to be entangled, then if someone measures a quantum property of one of the particles and then repeats the measurement on its entangled partner, they will always find that the pair is correlated, even when the two particles are separated by vast distances. Therefore, knowing the state of one particle automatically provides information about the other.

Entanglement was introduced about 90 years ago as proof of the absurdity of quantum theory if treated as a complete description of nature. Yet it is not regarded as absurd today.

After exhaustive proofs of entanglement's authenticity in the real world, it is now the key resource in quantum information theory, allowing quantum teleportation and quantum cryptography, and offering significant advantages in quantum computing, communication and precision measurements.

Though entanglement still appears counterintuitive to our lived experience of the world, researchers have discovered striking parallels with something much more familiar: thermodynamics. In fact, many similarities have emerged between the theories of quantum entanglement and thermodynamics. For example, "entanglement entropy" is a characteristic of idealized, noiseless quantum systems that mimics the role of thermodynamical entropy.

However, an equivalent to the second law of thermodynamics—which dictates that processes tend towards increasing disorder (the aforementioned entropy) and that perfect reversibility is an attainable though rare and highly efficient ideal—has remained stubbornly out of reach. Here, reversibility does not refer to time symmetry but the ability of an external agent to manipulate the system into a different state and then manipulate it back to its initial state without any loss.

"Finding a second law analogous to the second law of thermodynamics has been an open problem in quantum information science," says study co-author Tulja Varun Kondra. "Solving this has been our primary motivation."

Much work towards addressing this problem has focused on a scenario in which two distant parties (often called Alice and Bob) want to exchange quantum information, but are restricted to acting locally on their quantum systems and communicating classically, by say, phone or the internet. This limitation to local operations and classical communication (LOCC) simplifies the situation, meaning whatever Alice and Bob do, they cannot affect the intrinsically nonlocal properties of entanglement between their quantum systems.

"It is known that under LOCC operations in this scenario, entanglement is irreversible," explains senior author of the study, Alexander Streltsov. "So the question is, can we somehow go beyond LOCC in a meaningful way, and recover reversibility?" The team's answer is 'yes,' as long as Alice and Bob share an additional entangled system: an entanglement battery.

Just as an ordinary battery stores energy which can be used to inject or store work in the context of thermodynamics, an entanglement battery injects and stores entanglement. The battery can be used in the state transformation process and the state of the battery itself can be changed to perform operations. There is only one rule: whatever Alice and Bob do, they must not decrease the level of entanglement within the battery.

And just as a regular battery allows tasks to be performed that would be impossible without one, so too does an entanglement battery. By assisting standard LOCC operations with their hypothetical entanglement battery, the team demonstrated that any mixed-state entanglement transformation can be made perfectly reversible.

This achievement is a significant contribution to the debate around whether entanglement manipulation is generally reversible. But a more important outcome of this work is that the researchers have shown that the methods they have developed are applicable beyond mixed-state entanglement transformation, allowing them to leverage the entanglement battery to verify reversibility in various scenarios. Proving that entanglement manipulations across all quantum states are reversible is expected to lead to a family of second laws for entanglement manipulation.

The entanglement battery may even find uses outside entanglement theory. For example, the same principles apply to systems involving more than two entangled particles, paving the way for understanding and manipulating complex quantum networks and perhaps developing future, highly efficient quantum technologies.

In addition, generalizing the concept of an entanglement battery to a resource battery—an additional quantum system that participates in the transformation process without reducing the resource in question—could allow the systematic demonstration of reversibility across quantum physics based on a minimal set of assumptions.

"We can have a battery that is supposed to preserve coherence or free energy, and then we can formulate a reversible framework in this setting where, instead of entanglement, we reversibly manipulate that particular resource of our system," says Streltsov. "Though many of these other principles of reversibility have already been confirmed via other approaches, our technique offers a unified proof framework based on well-established physical principles."

More information: Ray Ganardi et al, Second Law of Entanglement Manipulation with an Entanglement Battery, *Physical Review Letters* (2025). DOI: 10.1103/kl56-p2vb. On *arXiv*: DOI: 10.48550/arxiv.2405.10599

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