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Practical limits on entanglement manipulation

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Entanglement is a powerful resource for quantum technologies but real-world computation limits can drastically change what is achievable. Now research reveals that computational constraints reshape our understanding of entanglement manipulation.

The remarkable speedup achieved in quantum computing, the enhanced security provided by quantum cryptography, and the improved precision of quantum metrology all fundamentally depend on harnessing suitable forms of quantum entanglement[1]. Traditionally, the quantification and manipulation of entanglement have been studied within an information-theoretic framework that assumes access to unlimited copies of entangled states, and unbounded computational power to process them. Now, writing in *Nature Physics*, Lorenzo Leone and colleagues[2] establish an alternative view on the power of entanglement processing: when computational constraints are taken into account, the capabilities of entanglement manipulation are much more limited.

To enable practical quantum applications, readily available forms of entanglement must be transformed into those required for downstream tasks. Of particular importance is the conversion of partially entangled states to and from the fully entangled bit (ebit), which serves as a universal unit of entanglement. High-quality ebits can be extracted from imperfect entangled sources using a process known as entanglement distillation. Then, the entangled states necessary for a particular application can be constructed from ebits by so-called entanglement dilution. An illustrative figure is given in Fig. 1.

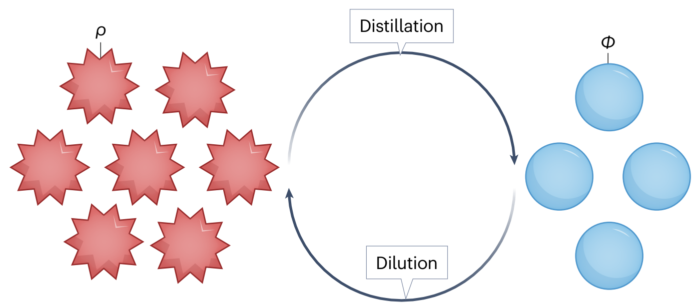

Fig. 1 | Entanglement distillation and dilution. Entanglement distillation transforms many copies of partially entangled states ρ (red) to fewer copies of fully entangled bits Φ (blue), while entanglement dilution constructs entangled states ρ from entangled bits Φ.

Entanglement represents inherent correlations between spatially separated subsystems. If distant parties have access to shared entanglement, they can coordinate using only local operations and classical communication to control their own systems and exchange messages. The manipulation of entanglement is usually studied in an information-theoretic framework, which assumes access to an infinite number of independent and identically distributed entangled states, and unlimited computational resources for processing. In this idealized setting, it has long been established[3] that the number of ebits that can be extracted during distillation or is required for dilution is determined by a single quantity – the von Neumann entropy, which sets the theoretical limit for transforming one form of entanglement into another.

Although this framework is mathematically elegant, it does not reflect real-world constraints, where resources such as space and time are always limited. In line with computational complexity theory, Leone and colleagues reframed entanglement manipulation within the context of computational efficiency. They considered protocols that have access to a limited number of entangled states – which only grows as a polynomial function of the number of qubits within each shared entangled state – and require all local operations and classical communication to be completed within a time that also scales polynomially.

Leone and colleagues studied how this more realistic, computationally efficient framework affects the ultimate performance of entanglement manipulation. They explored the case of manipulating many copies of a pure entangled state shared between two parties, Alice and Bob. Their results show that, when only computationally efficient protocols are allowed, the operationally relevant measures for entanglement distillation and dilution are very different from the information-theoretic ideals.

Allowing unlimited computation permits entangled state transformations at rates set by the von Neumann entropy. However, Leone and colleagues proved that including computational efficiency constraints reduces the attainable distillable entanglement to a much lower value governed by the so-called min-entropy. This discovery highlights a significant difference between theoretical possibilities and practical limitations.

The team constructed explicit protocols and families of quantum states that highlight a surprisingly large gap between entanglement manipulation with and without computational constraints. For the constructed families of states, the amount of ebits that can be distilled using efficient computation can be vanishingly small, even when the information-theoretic framework would predict a maximal rate of distillation.

Their protocol is state-agnostic, meaning it does not require knowledge of the specific state being manipulated. Even if Alice and Bob indeed have an efficient classical description of the state, this still does not improve the conversion rates of entanglement manipulation in the worst case, as long as certain common quantum computational hardness assumptions (such as the 'learning with errors' conjecture[4]) hold.

Furthermore, in the conventional information-theoretic model, entanglement manipulation is reversible – meaning that, asymptotically, the ebits extracted from a quantum state can be used to perfectly reconstruct the original state. This reversibility breaks down entirely when computational limits are imposed. Leone and colleagues identified quantum states for which nearly all inherent entanglement becomes 'locked' away: efficiently distilling ebits from these states is nearly impossible, yet reconstructing them may still require the maximum possible consumption of ebits.

By exposing the gap between information-theoretic and computationally achievable rates, Leone and colleagues have profoundly shifted the discussion about entanglement as an operational resource. In realistic scenarios — be it quantum computing, communication, or metrology — what really matters is what computationally bounded agents can observe and manipulate. Therefore, for scalable quantum technologies, these results reshape expectations about what can be achieved in practice.

The ideas presented by Leone and colleagues prompt several important questions. They focused on pure, bipartite states, and so it would be valuable to establish similar results for more general mixed or multipartite states. More broadly, entanglement theory is only an example in a wider landscape of quantum resource theories[5] such as magic[6], non-Gaussianity[7], thermodynamics[8] and coherence[9]. An open question is how these other resource theories should be reformulated when computational limitations are taken into account. These considerations underscore the urgent need to develop computational quantum resource theories, ensuring that our models of quantum information are more closely aligned with practical realities.

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Competing interests

The author declares no competing interests.