Physics VIEWPOINT

Entanglement as the Currency of Quantum Measurement

A powerful framework allows scientists to understand and classify joint quantum measurements—procedures essential for many quantum technologies.

By **Emanuele Polino**

Two key, yet enigmatic, aspects of quantum physics are entanglement and the act of measuring a quantum system. These elements combine in unique ways in so-called joint measurements, where multiple systems are simultaneously measured in a way that accounts for their entanglement. Joint measurements are valuable because they can extract hidden information about the combined state of the systems. Remarkably, the outcome of a joint measurement can be replicated even if the systems are kept far apart, which has many practical benefits. Such “localization” procedures require local operations to be performed on each system and some extra entanglement to be shared beforehand. Now Jef Pauwels and colleagues at the University of Geneva have investigated how much of this shared entanglement is needed to localize a given joint measurement [**1**]. Their results deepen our theoretical grasp of quantum measurements and provide insights into the resources required to advance quantum technologies.

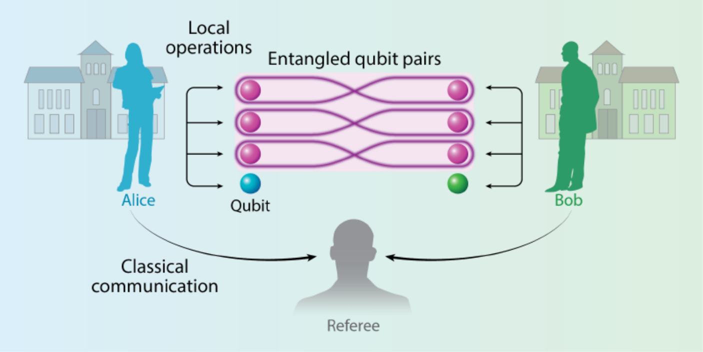

Figure 1: Pauwels and colleagues have studied scenarios in which two distant parties (Alice and Bob) each perform local quantum operations on their own qubit as well as on their share of one or more entangled qubit pairs [**1**]. Alice and Bob convey the results of these operations to a referee through classical communication. If there are sufficiently many entangled pairs, the referee can use the received data to reconstruct the outcome of a joint measurement of Alice and Bob’s two qubits without having to bring those qubits together.
Credit: APS/Carin Cain

Arguably, entanglement is the most striking departure of quantum mechanics from classical physics. Two entangled systems must be thought of as an indivisible whole, even if they are far apart from each other. And in many scenarios, what happens to one system is instantaneously and strongly correlated with what happens to the other, even across vast distances. This phenomenon, known as quantum nonlocality, gives rise to correlations that defy any classical explanation consistent with the cause-and-effect structure of experiments [**2**]. Nonlocality underlies key quantum applications such as secure communication and the generation of truly random numbers [**2**].

In experiments on quantum networks, entanglement has conventionally been used at the initial stage within devices that generate entangled states and distribute them across the network. However, the phenomenon holds untapped potential when applied in other parts of these networks. For instance, embedding entanglement in network channels can enable and enhance nonlocal correlations [**3**, **4**]. When entangled resources are used in the final act of the experiment—the measurement stage—and when this stage involves joint measurements, completely new prospects and challenges arise. Joint measurements are crucial in several quantum information protocols, enabling quantum teleportation and entanglement swapping—a way to entangle systems that do not directly interact [**5**]. Furthermore, novel forms of nonlocality can emerge in complex networks subjected to entanglement-based joint measurements [**6**, **7**].

Despite their importance, our understanding of joint measurements is still poor, and several challenges remain to be addressed. It has been known that additional shared entanglement can enable the localization of any joint measurement—that is, the measurement's statistics can be reproduced through local quantum operations and certain classical communications called broadcast communications [**8**]. However, existing localization protocols often require an infinite amount of entanglement, making them both conceptually difficult and practically infeasible. This limitation raises critical questions: Which joint measurements can be localized using a finite and, ideally, minimal amount of extra entanglement? And can this "entanglement cost" be used to classify joint measurements? Answering these questions would have profound implications for the development of practical quantum networks and for the foundations of quantum mechanics—such as the compatibility of quantum measurements with special relativity [**9**].

Pauwels and colleagues have tackled this challenge by devising localization protocols based on quantum teleportation that require only finite quantum resources. Inspired by schemes using infinite entanglement, the team's approach explores what can be achieved with a specific, finite number of shared entangled qubit pairs (ebits), whose amount defines a hierarchy of joint measurements. By focusing on joint measurements of two individual qubits, the researchers analytically classify the measurements that can be localized within the first few levels of their proposed hierarchy. Their method determines the conditions under which a joint measurement's statistics can be reconstructed by two parties performing local operations (Fig. **1**). The main insight lies in relating the ability to localize a joint measurement using a certain number of ebits to specific mathematical conditions that the measurement must satisfy.

The researchers establish a significant link between their entanglement-based classification of joint measurements and the Clifford hierarchy—a well-established concept from quantum computing that characterizes the complexity of quantum operations. The team shows that joint measurements belonging to the lowest levels of their localization hierarchy often correspond to simpler operations in the context of quantum circuits. This connection offers a deeper understanding of the entanglement cost associated with localizing a joint measurement and of its relationship to the complexity of quantum information processing.

At the first level of the researchers' localization hierarchy, requiring just one ebit, experiments can realize two types of joint measurements, including so-called Bell-state measurements—crucial for quantum teleportation and entanglement swapping [**5**]. At the next level, requiring three ebits, the classification extends to include other notable measurements, such as the so-called elegant joint measurements, known for their symmetric properties and role in network nonlocality [**6**]. Interestingly, many of these measurements exhibit special symmetries, suggesting a deep connection between symmetry and the fundamental limits of quantum information processing.

By providing a framework for understanding joint measurements, Pauwels and colleagues have made a key step toward harnessing such measurements. This step could drive discoveries, deepen our understanding of quantum mechanics, and open avenues for realizing quantum technologies in resource-limited scenarios. Entanglement-based measurements hold the potential to reveal new forms of nonlocality emerging in complex networks where multiple parties are interconnected through entanglement sources [**7**]. Investigating the relationship between network nonlocality and the localizability of joint measurements could lead to novel ways of classifying quantum correlations in networks.

With the future advent of the quantum internet, an exciting and crucial research direction is to extend protocols that certify the randomness of measurement outcomes in multiparty quantum networks [**4**, **10**]. The approach developed by Pauwels and colleagues could play a major role here: Using joint measurements of varying complexity might enable the certification of different amounts of randomness. Additionally, localization protocols for joint measurements have direct applications in quantum cryptography [**1**].

As the researchers suggest and partially explore in their study, an important next step is to extend their framework to higher-dimensional quantum systems called qudits and to scenarios involving more than two parties. Such an extension could pave the way for future research into the largely uncharted domain of complex joint measurements. Achieving that goal will likely require innovative computational and analytical methods. Finally, experimental implementations of these protocols—perhaps adapted to nonideal conditions to facilitate practical realizations—seem to be on the horizon. Such realizations could enable new forms of quantum information processing for communication and computation.

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