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The Rise of the Quantum Internet

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The Internet just turned 50: five decades that shaped the world we live in. But what comes next, the so-called Quantum Internet, will be even more revolutionary, likely in ways we can't imagine yet.

On 29 October 1969, the first successful message was exchanged over the Arpanet, the predecessor to what we now know as the Internet. In the five decades since, the Internet has revolutionized communications to the extent that its impact on our lives is not only technological but rather has affected almost every facet of business and lifestyle, throughout the structure of society.

The Internet itself evolved amazingly during these decades, from a network comprising a few static nodes in the early days to a leviathan interconnecting half of the world's population through billions of devices. Yet the fundamental underlying assumption—the Internet's primary purpose of transmitting messages that can be successfully encoded in a sequence of classical bits—has been unchanged since the beginning.

The advent of the engineering phase of quantum technologies is challenging the Internet's fundamental assumption because quantum devices require—as communication primitives—the ability to transmit quantum information. Hence, research groups throughout the world, and ours as well, are investing their efforts to design and engineer the Quantum Internet.[1–6] But there's still a long way to go and no guarantee of getting there very soon.

THE QUANTUM REVOLUTION

Quantum technology advances have successfully enticed tech giants, such as IBM, Google, and Intel, to participate in the so-called quantum race. Several start-up companies also have been founded to join in this monumental endeavor. A very significant milestone was achieved at the end of 2019 by a group of researchers at Google, which announced quantum supremacy by solving a classically intractable problem with its quantum processor[7,8] (see "The Quantum Supremacy").

Immense interest in the future of quantum technologies is not only displayed by industry but also by governments around the world. To mention some initiatives, in April 2017, the European Commission launched a 10-year, €1 billion flagship project to accelerate European

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quantum technologies research.[9] Meanwhile, across the Atlantic, in September 2018, the U.S. House of Representatives unanimously approved the establishment of a National Quantum Initiative funded with US$1.25 billion over 10 years.[10]

Within this context of a real quantum revolution, the ultimate vision is to build a quantum network infrastructure—also known as the *Quantum Internet*—to interconnect remote quantum devices so that quantum communications among them are enabled.[2,3] The reason behind this vision is that the Quantum Internet is capable of supporting functionalities with no direct counterpart in the classical Internet—ranging from secure communication[5] to blind computing[11] through distributed quantum computing[1,2]—as recently overviewed by the Internet Engineering Task Force.[12]

Although it is too early to tell when and how this quantum network will be deployed, our goal here is to describe how the Quantum Internet differs from the current Internet. For this, we introduce the very basic idea of the Quantum Internet and its underlying foundation, and we highlight the necessary steps as well as the novel challenges we will face on our journey toward the Quantum Internet design and deployment.

THE QUANTUM INTERNET

The Quantum Internet is a network enabling quantum communications among remote quantum devices. What sets it apart from the classical Internet is the ability to transmit quantum bits (qubits), which differ fundamentally from classical bits, and create distributed, entangled quantum states with no classical equivalent.[3]

> The direct transmission of qubits so far appears limited to relatively short distances in the context of specific applications that can tolerate low-transmission success rates.

Specifically, the Quantum Internet is governed by the laws of quantum mechanics. Hence, phenomena with no counterpart in classical networks, such as entanglement, the impossibility to safely read and copy the quantum information impose terrific constraints for the network design. That means most techniques adopted within the classical Internet cannot be reused here.[2]

Just consider how important storing information for long periods at network nodes is to classical Internet functionalities. This cannot be taken for granted in the Quantum Internet because the phenomenon known as *decoherence* rapidly corrupts quantum information, making it challenging to rely on quantum memories.

Another constraint that makes things harder is the no-cloning theorem. Indeed, the classical Internet operates by extensively duplicating information among the different components of a network node and among different nodes. In the Quantum Internet, the no-cloning theorem forbids copying an unknown qubit. Hence, the commonly used methods for keeping the integrity of information, for example, retransmission of the same information, are now forbidden. Finally, quantum states cannot be read without affecting their states. Any attempt to measure a qubit makes its state collapse into a classical bit value—0 or 1. For this particular reason, and for the no-cloning theorem as well, the direct transmission of qubits so far appears limited to relatively short distances in the context of specific applications that can tolerate low-transmission success rates.

It becomes evident that a paradigm shift is required. Indeed, the very concept of information transmission has to be rethought and reformulated for Quantum Internet design. Thankfully, quantum mechanics provides us an amazing tool for transmitting quantum information, the quantum teleportation process, astonishingly, without the physical transfer of the qubit.

BEYOND DIRECT QUBIT TRANSMISSION

By using a unique feature of quantum mechanics, known as *entanglement* (see "Introducing Entanglement"), in 1993 Bennett et al.[13] showed that it is possible to instantaneously transfer the quantum state encoded in a qubit at a certain sender to a qubit stored at a certain receiver without, surprisingly, the physical transfer of the qubit at the sender.[3] This quantum communication protocol, already experimentally verified, is known as *quantum teleportation*.

In a nutshell, the teleportation process, portrayed in Figure 1 for a

THE QUANTUM SUPREMACY

The term *quantum supremacy* was coined by J. Preskill in 2011[S1] to describe the moment when a programmable quantum device would solve a problem that cannot be solved by classical computers, regardless of the usefulness of the problem.

Reference

S1. J. Preskill, "Quantum computing and the entanglement frontier," in *Proc. 25th Solvay Conf. Physics*, Oct. 2011.

single qubit, requires 1) the generation and distribution of a maximally entangled pair of qubits (referred to as an EPR pair) between the source and destination, and 2) a classical transmission to send two classical bits. Consequently, a classical link for sending classical information and a quantum link for entanglement generation and distribution need to be established in advance.

Moreover, each teleportation process destroys the entanglement-pair member at the source. A successive teleporting requires the generation and distribution of a new entangled pair between source and destination. This, in turn, implies radically new challenges from a network design perspective, completely changing the classical concepts of network connectivity and throughput. Indeed, the connectivity between two quantum nodes is strictly determined by the availability of a shared entangled pair, and it inherently varies in time as a consequence of the depletion of the entanglement-pair member at the source.

The challenges are not limited to the above-mentioned ones. In fact, long-distance entanglement distribution still constitutes a key issue due to the decay of the entanglement distribution rate as a function of the distance.[1,3] And because qubits cannot be copied due to the no-cloning theorem, classical signal amplification techniques cannot be employed. In this context, quantum teleportation relies on intermediate nodes, known as *quantum repeaters*, that are capable of entangling distant nodes—without physically sending an entangled qubit through the entire distance—by swapping the entanglement generated through shorter links,[14] as illustrated in Figure 2.

It is evident that the design of the Quantum Internet constitutes a breakthrough from an engineering perspective. Each network functionality must be redesigned and reengineered with a solid integration of classical and quantum communications resources.[15] In this regard, the classical resources for transmitting classical bits will likely be provided by integrating such classical networks as the current Internet with the Quantum Internet.[2]

Paving a journey toward the Quantum Internet is indeed not a straightforward task. Historically, predictions about technological developments prove themselves true hardly or in ways the predictor didn't expect at all. Hence, there will definitely be twists and turns in the design of the Quantum Internet, with uncertainty on when and how this goal will be accomplished (see "Realizing the Qubit").

However, we may envision roughly three subsequent necessary steps, whose complexity scales as a function of the time and the level of platform

INTRODUCING ENTANGLEMENT

Entanglement is one of the most distinguishing quantum phenomena with no counterpart in the classical world, in which the quantum states of two or more particles become inextricably linked even if they are separated by a great distance. The entanglement of quantum particles demonstrates a relationship between their fundamental properties that cannot happen arbitrarily. When a measurement is performed on one of the particles, the other particle will be instantly influenced.

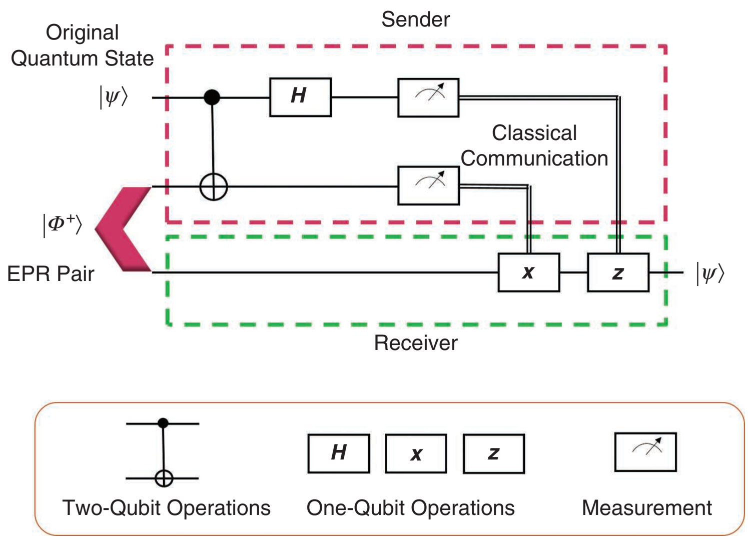

FIGURE 1. A general schematic of quantum teleportation protocol, where the standard bra-ket notation $|\cdot\rangle$ is adopted for describing quantum states. Notice in the figure that after quantum teleportation, the original qubit and the entanglement are destroyed. As weird as it seems, quantum teleportation fully obeys the fundamental principles of quantum mechanics. Therefore, the cost of transmitting quantum information can be exchanged with entanglement and classical communications. Because the entanglement is always destroyed after every single teleportation, it constitutes the primary consumable resource in the Quantum Internet, which means it needs to be generated continuously.

REALIZING THE QUBIT

Currently, there exist multiple technologies for realizing a qubit (quantum dots, transmons, ion traps, photons, and so forth), with each technology characterized by different pros and cons. This hardware heterogeneity will impose its own additional challenges to create an integrated Quantum Internet ecosystem.

heterogeneity, as portrayed in Figure 3. The very first step involves interconnecting multiple quantum processors within a single quantum computer. The qubits are likely to be homogeneous among the different processors, although heterogeneity may arise within due to different hardware technologies underlying memory and computational units. The link for connecting the qubits is very short, and the network topology is fixed so that only a simple addressing and routing protocol is required. Timing and synchronization need to be carefully designed. Network functionalities that are unavailable in classical networks must be designed and implemented. For instance, quantum decoherence must be carefully accounted for within the network design so that it can be used to represent a key metric for the network functionalities. Local operations among qubits within a single processor must be complemented by remote operations—operations among qubits placed at different processors. The tradeoff between qubits devoted to computation and entangled qubits devoted to communication represents a key issue with no counterpart in the classical network design. The very concept of distributed quantum algorithm design must explicitly take such a tradeoff and the delay induced by remote operations into consideration.

The second step involves interconnecting multiple quantum computers within the same farm. At this stage, the hardware heterogeneity among the different quantum computers may arise. Such heterogeneity must be considered in network functionalities. The entanglement distribution benefits from the controlled farm environment and relatively short distances. Delay imposed by classical communication times is slightly longer compared to interprocessor wiring. Hence, this requires more sophisticated timing and synchronization. The network topology is more complex, and it may vary in time as the number of nodes in the network changes. This, in turn, induces dynamics at the network bootstrap/functioning, which

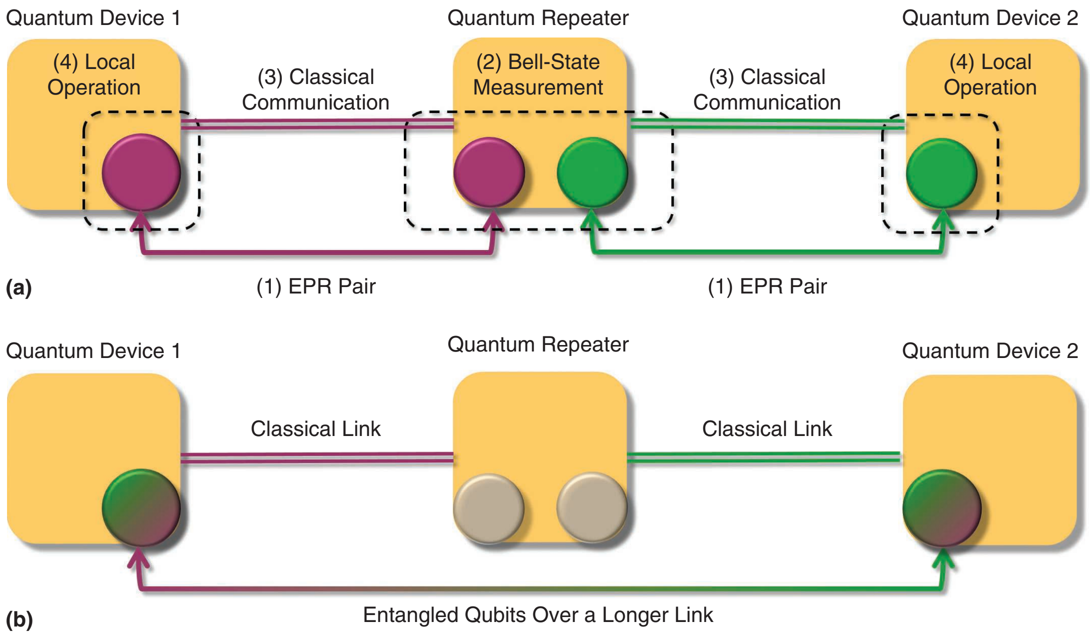

FIGURE 2. The entanglement swapping portrait. (a) Each quantum device shares an EPR pair with an intermediate node, the quantum repeater. The repeater performs Bell-state measurement on the two qubits in its possession, which results in the collapse of their quantum states into classical bits. The repeater sends the classical bits obtained from the measurement operation to the quantum devices. Finally, based on the received bits, the quantum devices perform local operations to complete the swapping process. (b) The result is that the entanglement between the quantum devices is created over a longer distance.

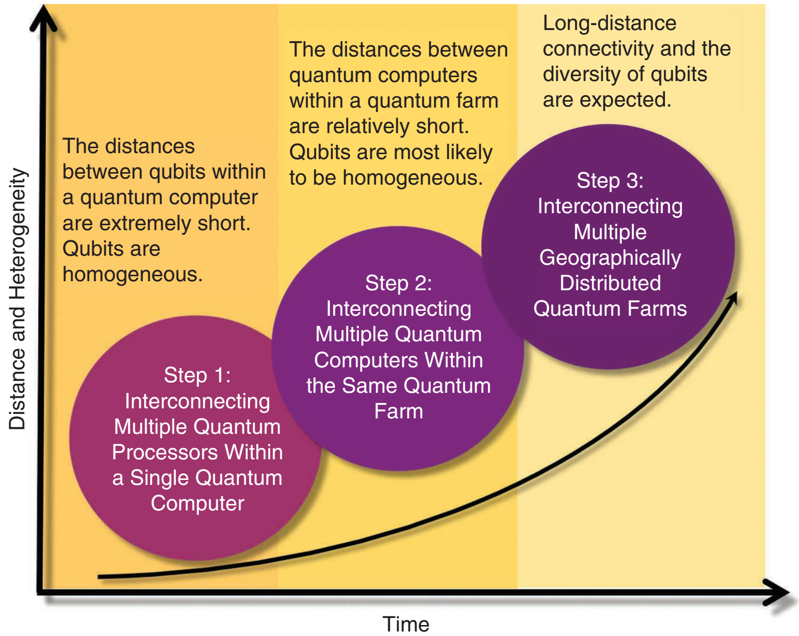

FIGURE 3. The necessary steps toward the envisioned Quantum Internet. We hypothesize that the complexity scales proportional to the distance of connectivity and level of platform heterogeneity among quantum farms.

requires more sophisticated strategies for routing and access as well as for mitigating quantum errors. Finally, the balance between local and remote operations—between computational and communication qubits—becomes even more intricate.

The final long-term step involves interconnecting multiple geographically distributed quantum farms. One of the key challenges is the heterogeneity among different quantum farms, which may be operated by different companies. This requires significant efforts in terms of network standardization. Furthermore, the heterogeneity among quantum links, for example, optical, free space, or satellite, will arise. The delays induced by the distances will introduce severe challenges on the entanglement generation and distribution. The increasing number of quantum devices to be wired and the heterogeneity of the environments hosting the quantum computers must be taken into account.

One of the judicious questions raised from this discussion is when will we see the Quantum Internet? There is no definite answer to this question. However, we firmly believe this is a goal that requires a collaborative effort and a multidisciplinary approach between academics and industry. The required competences and skills are many and diverse, and each is interconnected with and vital to the others. ■

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