REVIEW SUMMARY

QUANTUM INFORMATION

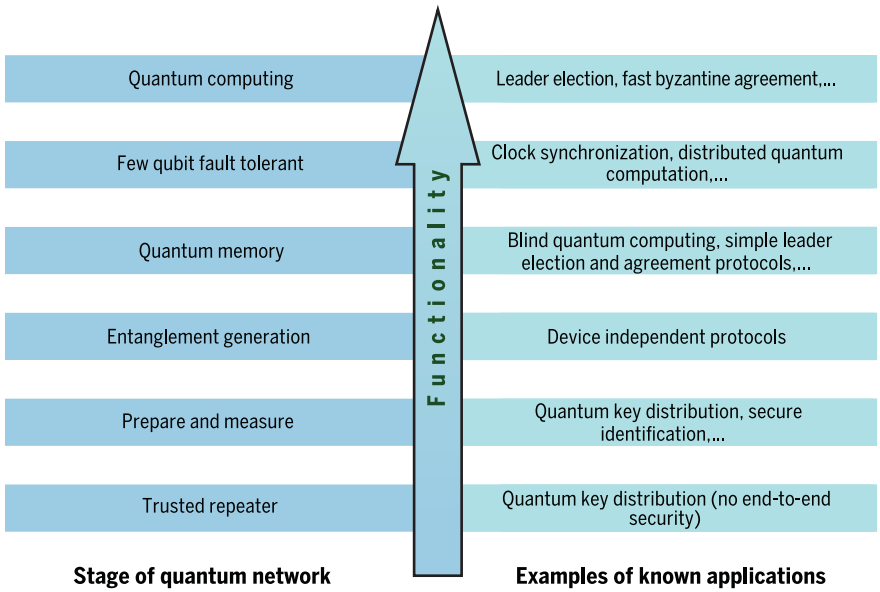
# Quantum internet: A vision for the road ahead

**Stephanie Wehner*, David Elkouss, Ronald Hanson**

**BACKGROUND:** The internet has had a revolutionary impact on our world. The vision of a quantum internet is to provide fundamentally new internet technology by enabling quantum communication between any two points on Earth. Such a quantum internet will—in synergy with the "classical" internet that we have today—connect quantum information processors in order to achieve unparalleled capabilities that are provably impossible by using only classical information.

As with any radically new technology, it is hard to predict all uses of the future quantum internet. However, several major applications have already been identified, including secure communication, clock synchronization, extending the baseline of telescopes, secure identification, achieving efficient agreement on distributed data, exponential savings in communication, quantum sensor networks, as well as secure access to remote quantum computers in the cloud.

Central to all these applications is the ability of a quantum internet to transmit quantum bits (qubits) that are fundamentally different than classical bits. Whereas classical bits can take only two values, 0 or 1, qubits can be in a superposition of being 0 and 1 at the same time. Moreover, qubits can be entangled with each other, leading to correlations over large distances that are much stronger than is possible with classical information. Qubits also cannot be copied, and any attempt to do so can be detected. This feature makes qubits well suited for security applications but at the same time makes the transmission of qubits require radically new concepts and technology. Rapid experimental progress in recent years has brought first rudimentary quantum networks within reach, highlighting the timeliness and need for a unified framework for quantum internet researchers.




**Stages in the development of a quantum internet.** Each stage is characterized by an increase in functionality at the expense of greater technological difficulty. This Review provides a clear definition of each stage, including benchmarks and examples of known applications, and provides an overview of the technological progress required to attain these stages.

**ADVANCES:** We define different stages of development toward a full-blown quantum internet. We expect that this classification will be instrumental in guiding and assessing experimental progress as well as stimulating the development of new applications by providing a common language and reference frame for the different scientific and engineering disciplines involved.

More advanced stages are distinguished by a larger amount of functionality, thus supporting ever more sophisticated application protocols. For each stage, we describe some of the application protocols that are already known and that can be realized with the functionality provided in that stage. It is conceivable that a simpler protocol, or better theoretical analysis, may be found in the future that solves the same task but is less demanding in terms of functionality. In parallel to the daunting experimental challenges in making quantum internet a reality, there is thus an opportunity for quantum software developers to design protocols that can realize a task in a stage that can be implemented more easily. We identify relevant parameters for each stage to establish a common language between hardware and software developers. Last, we review technological progress in experimental physics, engineering, and computer science that is required to attain such stages.

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**OUTLOOK:** Building and scaling quantum networks is a formidable endeavor, requiring sustained and concerted efforts in physics, computer science, and engineering to succeed. The proposed stages of development will facilitate interdisciplinary communication by summarizing what we may actually want to achieve and providing guidelines both to protocol design and software development as well as hardware implementations through experimental physics and engineering. Although it is hard to predict what the exact components of a future quantum internet will be, it is likely that we will see the birth of the first multinode quantum networks in the next few years. This development brings the exciting opportunity to test all the ideas and functionalities that so far only exist on paper and may indeed be the dawn of a future large-scale quantum internet. ■

The list of author affiliations is available in the full article online.
*Corresponding author. Email: s.d.c.wehner@tudelft.nl
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