Quantum information transfer using photons

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Optical communication channels have redefined the scope and applications of classical computing; similarly, photonic transfer of quantum information promises to open new horizons for quantum computing. The implementation of light–matter interfaces that preserve quantum information is technologically challenging, but key building blocks for such devices have recently been demonstrated by several research groups. Here, we outline the theoretical framework for information transfer between the nodes of a quantum network, review the current experimental state of the art and discuss the prospects for hybrid systems currently in development.

Quantum physics is one of the most important intellectual achievements of the twentieth century. It has profoundly changed our view of the world and spawned revolutionary technologies such as the laser and NMR imaging. During the past two decades, quantum physics has entered the fields of information processing and communication. New quantum concepts for computational purposes have stimulated enormous efforts to develop platforms and protocols that enhance classical computation and communication devices. While quantum information processors rely on the manipulation of quantum bits (qubits), quantum communication naturally seeks to operate with photons. Thus, the transfer of quantum information between two stationary nodes by photons — often dubbed flying qubits — has become a focal point for new quantum information technology.

Stationary qubits (such as atoms, quantum dots and superconducting circuits) are able to store quantum information for certain intervals, known as coherence times, which are limited by the coupling of the qubits to the surrounding environment. Photons, on the other hand, interact very little with each other or the environment, and hence they are ideally suited to transport information over large distances. Quantum information transfer with photons is thus understood as the remote distribution of information that preserves the underlying quantum states. Quantum communication has already matured to encompass practical applications such as quantum key distribution and cryptography, and visionary concepts such as the ‘quantum internet’ have been conceived and are currently being pursued in the laboratory.

Such technology has made new areas of physics accessible; for example, quantum information transfer permits issues at the foundations of quantum physics, such as non-locality, to be studied (that is, non-classical states spanning classical distance scales and the quantum correlations of such extended systems). With the development of quantum processors and interfaces between stationary and flying qubits, even distributed quantum computation appears possible, promising scalable quantum information processing at multiple sites on the same device or across longer distances within a network. Quantum information transfer with photons hence bridges the microscopic and macroscopic worlds and may pave the way towards new applications of quantum physics in everyday life.

Requirements for quantum information transfer

Quantum information is typically stored in superpositions $|\Psi\rangle = c_0|0\rangle + c_1|1\rangle$ of two-level systems $|0\rangle$, $|1\rangle$, which can be realized as long-lived electronic states in atomic and solid-state quantum bits. The first requirement for quantum information transfer is thus a quantum node, at which quantum information is not only stored but also generated and processed. This Review discusses both quantum nodes and quantum memories. In contrast to quantum nodes, quantum memories are intended solely for information storage; for example, quantum information generated at one or several remote nodes may be cached in a memory before it is processed.

Next, a quantum channel is required to transmit quantum information. Long-distance quantum communication, either earth-bound or involving satellites, can be realized by free-space optical channels, but it is often convenient to take advantage of optical fibres for photon transport. Finally, the linking of quantum nodes and quantum channels requires implementing a light–matter quantum interface. The technical implementation of qubits dictates the design and construction of the interfacing element, whereas the optical quantum channel should be compatible with fibre-based or free-space optical technology used for classical communication. High-fidelity qubits have already been realized in diverse experimental settings, and the use of photons for quantum communication and quantum key distribution is well established. The crucial element required for quantum information transfer using photons is hence a light–matter interface that allows one to map (stationary) atomic or solid-state qubits to (flying) photonic qubits.

This Review therefore focuses on the realization of such quantum interfaces, and, in particular, emphasizes recent experimental progress in this field since the review by Kimble (published in 2008). In the first section, we describe the general function of a light–matter interface, distinguish between deterministic and heralded protocols, and highlight the role of optical cavities. The next section gives a more detailed description of several key experiments for remote atom–atom entanglement mediated by light. We then outline how quantum repeaters enable long-distance quantum communication. The final section highlights upcoming techniques, possible improvements and perspectives for future developments.

Blueprints for a light–matter interface

The first blueprint for a light–matter interface was conceived just a few years after Shor’s factoring algorithm sparked widespread interest in quantum computing and strings of trapped ions were shown to offer a promising architecture. Cirac and colleagues suggested that such atom-based computers could be linked together by transferring information to and from photons via an optical resonator. Tuning the resonator’s

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frequency near an atomic transition permits one to take advantage of the dipole coupling between the atoms and the cavity field, that is, the fundamental interaction of cavity quantum electrodynamics. This interaction allows a single quantum of information stored in the electronic states of an atom to be reversibly exchanged with a single photon in the field. A schematic representation of such an interface is shown in Fig. 1, with details presented in Box 1. Note that whereas the original proposal encoded quantum states in the photon number basis $|0\rangle$, we here use a basis of linearly polarized photons $|H\rangle$, $|V\rangle$, which has the advantage of being more robust to losses in the transmission channel. A third option would be to use a time-bin qubit, in which the photon exits the cavity in a superposition of two possible time windows.

This scheme enables the deterministic transfer of a quantum state between remote quantum nodes. An experimental implementation presents several challenges: neutral atoms or ions must be stably trapped and positioned within an optical cavity, which should have low scattering and absorption losses and a high atom–cavity coupling rate with respect to the decoherence rates of the system. Even when a state-of-the-art cavity that satisfies the strong-coupling criterion is used, the transfer process will nevertheless accumulate errors, and hence quantum error correction will be necessary.

More recently, a second framework for a quantum interface has emerged that promises a reduced technical overhead. This implementation is heralded rather than deterministic; that is, not every attempt to transfer quantum information is successful, but the successful cases are flagged. The user thus executes the transfer protocol repeatedly until the heralding signal is received. At first glance, it may seem that heralded transfer must be less efficient than deterministic transfer, but in fact, it depends on the physical parameters of the implementation. Furthermore, the heralding process is robust to certain errors, so that the quantum state is transferred faithfully.

Heralded transfer can be viewed as a three-step process, consisting of photon generation, measurement and teleportation (Fig. 2). The first step is either to excite weakly each of two spatially separated atoms so that at most one of them generates a photon or to entangle each atom with a photon. Next, the photon paths from the two atoms coalesce at a beam splitter, which erases ‘which-way’ information. If a certain detection outcome is recorded on photon counters at the beam-splitter outputs, the measurement event will project the remote atoms into an entangled state. Finally, this atom–atom entanglement is used as a resource to teleport quantum information between the two sites. For example, assume that the quantum information is encoded in a third atom, a neighbour of the second. A joint measurement on the second and third atoms extends those results across a range of experimental settings. In the deterministic case, a necessary precursor has been the development of sophisticated techniques for trapping and manipulating atoms and ions within low-loss resonators. Neutral atoms can now be confined to the cavity region by an off-resonant standing-wave field or by a transverse field for intervals on the order of a minute. Furthermore, the transverse field can be used as a conveyor belt to position the atoms precisely with respect to the cavity mode. In experiments in the strong-coupling regime, the coherent interaction between a single atom and a photon dominates the system dynamics.

Experimental building blocks
In the past decade, a handful of research groups have implemented both deterministic and heralded schemes and are working to extend those results across a range of experimental settings. In the deterministic case, a necessary precursor has been the development of sophisticated techniques for trapping and manipulating atoms and ions within low-loss resonators. Neutral atoms can now be confined to the cavity region by an off-resonant standing-wave field or by a transverse field for intervals on the order of a minute. Furthermore, the transverse field can be used as a conveyor belt to position the atoms precisely with respect to the cavity mode. In experiments in the strong-coupling regime, the coherent interaction between a single atom and a photon dominates the system dynamics.
In a scheme based on ref. 8 and illustrated in Fig. 1, at any given time, a single trapped atom interacts with the cavity field. That atom may be part of a larger ensemble, that is, a small-scale quantum computer. (The interaction of the other atoms with the cavity may be turned off via electronic shelving to an uncoupled state, or by positioning the atoms so that they do not couple to the spatial mode of the field.) An atom is prepared in one of two long-lived states, \( |\psi\rangle \) and \( |e\rangle \), or in a superposition of both. The cavity is nearly resonant with the transitions between a third ground state, \( |s\rangle \), and the excited states \( |r\rangle \) and \( |r'\rangle \). If a classical field \( \Omega(t) \) coupling \( |s\rangle \) to \( |r\rangle \) is applied to the atom, and if the frequency difference between \( \Omega_1(t) \) and the cavity matches the energy gap between \( |g\rangle \) and \( |s\rangle \), then a Raman process will transfer an atom in \( |g\rangle \) to \( |s\rangle \), coherently generating a single photon in the cavity. Similarly, a field \( \Omega_2(t) \) generates a single photon if the atom starts in \( |e\rangle \), again mapping the atom to \( |s\rangle \). For the appropriate choice of electronic states, the photons generated by \( \Omega_1(t) \) and \( \Omega_2(t) \) are orthogonally polarized; let us assume that their polarization is either horizontal \( (|H\rangle) \) or vertical \( (|V\rangle) \).

The simultaneous application of \( \Omega_1(t) \) and \( \Omega_2(t) \) then implements the transfer of a quantum state from an atom to a photon: \( \sin \theta |g\rangle + e^{i\phi} \cos \theta |e\rangle \rightarrow \sin \theta |H\rangle + e^{i\phi} \cos \theta |V\rangle \), where \( \theta \) and \( \phi \) parameterize the quantum state on the Bloch sphere, or in the case of the photon, the Poincaré sphere. The photon exits the cavity in a well-defined spatial mode, and its temporal shape can be symmetrized by tailoring the pulse shapes of \( \Omega_1(t) \) and \( \Omega_2(t) \) so that their polarization is either horizontal \( (|H\rangle) \) or vertical \( (|V\rangle) \).

The ion–cavity system can also be used as one node of a heralded interface. The ion is prepared in one ground state, and ion–photon entanglement results from coherently coupling the ion to two states in the \( 3^2D_{5/2} \) manifold. The photon is then sent over an optical fibre link to a second cavity, where the process is time-reversed: a second atom is initialized in \( |s\rangle \), and as the photon enters the cavity, the mirror-image waveforms \( \Omega_1'(t) \) and \( \Omega_2'(t) \) map the atom to \( |g\rangle \) and \( |e\rangle \), respectively.

Using trapped ions, it is comparatively easier to obtain long storage times, because a Paul trap for charged particles is typically several orders of magnitude deeper than an optical-dipole trap. However, a small cavity mode volume is necessary to obtain a high atom–cavity coupling rate. It is difficult to achieve such a small mode volume in an ion-trap setting while maintaining optical access for lasers and avoiding perturbations of the trapping potential due to the dielectric cavity mirrors. Thus, experiments have not yet reached the single-ion strong-coupling regime, although fibre-based cavities offer a promising route.

Both neutral atoms and ions can be localized to length scales much shorter than the cavity standing wave by cooling to the vibrational ground state — a technique first implemented in ion traps. Cooling has also been demonstrated using the cavity to extract blue-detuned photons from the system and by feedback to the dipole field seen by intracavity atoms.

With these techniques in hand, deterministic transfer has been demonstrated in both directions: from light to matter and from matter to light. Using a weak coherent state (that is, a laser pulse with a mean photon number of about one), it was shown that this state could be reversibly transferred to and from the hyperfine levels of a trapped caesium atom in a cavity. In this case, information was encoded in the number basis \( \{|0\}, |1\rangle \) representing the absence or presence of a photon. Given a lossy transmission channel, however, information encoded in \( |1\rangle \) at the input may be identified as \( |0\rangle \) at the output, hence reducing the fidelity of the transfer process. An important step was thus the realization of a polarization-based interface, linking two atomic hyperfine states with orthogonal cavity photons. Assuming both polarizations experience equal losses in the optical channel, the encoding is robust in the sense that losses do not affect the process fidelity (although they do reduce its efficiency). Polarization states of light can be mapped into and out of an atom–cavity system with coherence times exceeding 100 μs.

This light–matter interface has now been extended to spatially separated systems linked by optical fibre. A single trapped rubidium atom was entangled with a cavity photon, which was sent over optical fibre to a second laboratory and stored in a Bose–Einstein condensate, thus generating remote entanglement. More recently, quantum information was transferred from one atom to a cavity photon and then mapped to a second atom in a distant cavity. These results not only synthesize key techniques for a quantum network, but also highlight the contrast between quantum nodes (as exemplified by atoms in cavities) and quantum memories, where quantum degenerate gases offer long storage times. State transfer from an atom to a photon has also been demonstrated in an
interface based on a trapped calcium ion 47 (Fig. 3). The initial quantum states of ions can be prepared deterministically, and because techniques for coherent manipulation and detection of ions are well established, the final states can be read out from the ions in an arbitrary basis 35, 47.

What does it mean to say that the transfer process in these experiments is deterministic? The key concept is that the state of an atom is mapped onto a cavity photon, and vice versa, with a probability approaching one. This deterministic character originates from the coherence (and hence the reversibility) of the dipole interaction between an atom and a cavity. The probability is not exactly one, as there is a small chance for the atom to emit a photon spontaneously into free space during this process, which erases information from the system. One should also note that even if a cavity photon is created deterministically, it can be scattered or absorbed in the cavity mirrors or, after exiting the cavity, in an optical channel. For example, state transfer has been demonstrated from atoms to photons with a probability of 16% (ref. 47) and from photons to atoms with a probability of 20% (ref. 25); these probabilities are limited by mirror losses and the cavity coupling strength.

Heralded schemes, in contrast, do not need to work every time and are thus suited to a wider range of experimental systems. In fact, light–matter entanglement — a key building block — has been realized in a diverse range of systems, including ions 49, 50, single atoms 51, atomic ensembles 52, 53, nitrogen–vacancy centres in diamond 54, diamond crystals 55 and quantum dots 56– 58. In these schemes, optical cavities are no longer an essential ingredient, but they greatly enhance the photon collection rate and also provide the ability to tune the entangled state parameters 25, 44, 59.

Light–matter entanglement is not in itself sufficient to achieve heralded entanglement between remote quantum nodes. In addition, the photons sent from both nodes to a common location must be indistinguishable, so that each photon carries no information that could reveal its origin. Such indistinguishability is typically verified by the observation of Hong–Ou–Mandel interference, in which two identical photons impinge on a beam splitter always exit as a pair at one output 41. Weakly exciting two quantum memories in order to entangle remote nodes 19 is equivalent to entangling the electronic state of each memory with the photon number state. In this case, not only photon indistinguishability but also interferometric path stability between the nodes is required. Heralded remote entanglement has been demonstrated between atomic ensembles 51, single ions 41, neutral atoms 53, crystals doped with rare-earth ions 41 and nitrogen–vacancy centres 58.

The final step in heralded information transfer — teleportation — requires a local measurement, the result of which is transmitted over a classical channel. For example, in ref. 50, an initial state \( |0 \rangle_\alpha + |1 \rangle_\beta \) was stored in the hyperfine states \( |0 \rangle \) and \( |1 \rangle \) of a trapped Yb+ ion at site A. Given a second ion at site B, located 1 m from site A, the ion–photon entangled states \( \Psi_A = |0 \rangle_\alpha |\varphi_{\text{vac}} \rangle + |1 \rangle_\beta |\psi_{\text{vac}} \rangle \) and \( \Psi_B = |0 \rangle_\alpha |\varphi_{\text{vac}} \rangle + |1 \rangle_\beta |\psi_{\text{vac}} \rangle \) were created and then projected by photon detection into the ion–ion entangled state \( |0 \rangle_\alpha |1 \rangle_{\lambda_0} - |1 \rangle_\beta |0 \rangle_{\lambda_0} \) where \( \varphi_{\text{vac}} \) and \( \psi_{\text{vac}} \) are photon frequencies. The final step was a local rotation of the ion at A, followed by a fluorescence measurement projecting it into either \( |0 \rangle \) or \( |1 \rangle \). This classical result was sent to B and used to determine the appropriate rotation to prepare \( a|0 \rangle_\alpha + b|1 \rangle_\beta \). This demonstration of teleportation between remote ions followed earlier results using ions stored in the same trap 66, 67; a heralded quantum gate was also implemented using the same system of remote Yb+ ions 64. Recently, teleportation has been achieved with both neutral atoms 69 and atomic ensembles 70, 71.

To classify either a deterministic or a heralded implementation as ‘quantum’, one must demonstrate that the result surpasses the best possible classical outcome. Moreover, even if a process satisfies this criterion, it is interesting to quantify the fidelity of the process.

Figure 4 | A quantum process described by the matrix \( \chi \) maps an arbitrary input density matrix \( \rho_i \) to the output matrix \( \rho_o \). As the transfer process should leave \( \rho_i \) unchanged, in the ideal case all entries of \( \chi \) will be zero except the identity term \( F = 1 \). a, Process tomography is used to characterize teleportation of quantum information between two Yb+ ions separated by 1 m (ref. 50). Each ion is entangled with the frequency of a single photon, and the two photons then interfere on a beam splitter (BS). Simultaneous detection of photons at photomultiplier tubes (PMTs) after polarization filtering by a polarizing beam splitter (PBS) heralds ion–ion entanglement, a resource for teleportation. The \( \chi \)-matrix is determined from measurements of six teleported states in three orthogonal photon bases. Absolute values of the matrix entries are plotted, with rows and columns labelled by the Pauli operators \( X, Y, Z \). The \( (X_0, Y_0) \) entry corresponds to a process fidelity \( F = 82(2)\% \). b, The relationship between \( \chi \) and the Bloch/Poincaré sphere picture is shown for the transfer of a quantum state from an ion to a cavity photon 47. The process maps the pure states on the surface of the sphere to a set of states that are slightly deformed (specifically, reduced in amplitude and rotated), corresponding to a process fidelity \( F = 92(2)\% \). c, Another method for evaluating a quantum process is to measure correlations that provide information about coherence. In ref. 63, simultaneous detection of two photons projects atoms in two separate traps into a maximally entangled Bell state. This Bell-state measurement (BSM) combines the photons on a fibre beam splitter (BS), after which they are rotated by half- and quarter-wave plates (\( \lambda/2, \lambda/4 \)) and detected on avalanche photodiodes (APDs) at the horizontal (H) and vertical (V) ports of a polarization beam splitter. Entanglement is verified by reading out the atoms’ internal spin states and determining the probability that the spins are correlated or anticorrelated. Oscillations in the correlation probability as the spin basis for one atom is varied (parameterized by angle \( \beta \)) are shown here for the Bell state \( |\Psi^- \rangle \), and together with further measurements can be used to estimate a state fidelity \( F = 81(3)\% \) with respect to \( |\Psi^- \rangle \). Figure reproduced with permission from a, ref. 50, © 2009 AAAS and c, ref. 63, © 2012 AAAS. Figure b adapted with permission from ref. 47, © 2013 NPG.
Mathematically, a quantum process is fully described by the process matrix $\chi$, which represents the mapping between the input and output density matrices, $\rho_{\text{in}} \rightarrow \rho_{\text{out}}$.

$$\rho_{\text{out}} = \sum \chi_{ij} A_i \rho_{\text{in}} A_j^\dagger$$

Here, the operators $A_i$ comprise a basis for operators on the Hilbert space. (For systems comprised of qubits, it is convenient to define $A_i$ as tensor products of the Pauli operators.) As the ideal quantum-information transfer process leaves $\rho_{\text{in}}$ unchanged, the process fidelity is defined as $F = \text{tr}[(\rho_{\text{out}} - \rho_{\text{in}})\rho_{\text{in}}^{1/2}\rho_{\text{out}}^{1/2}] = \chi_{00}$. $F = 1$ corresponds to perfect transfer, whereas 50% represents the classical limit. For $N$ qubits, $\chi$ can be characterized by sampling the Hilbert space with $4^N$ inputs and measuring each output in $3^N$ bases,$^2$, as illustrated for a single qubit in Fig. 4.

Process tomography provides a complete picture, but it is not required for establishing that the fidelity is nonclassical; an appropriate set of correlation measurements is sufficient. In ref. 63, for example, the entanglement of two rubidium atoms over 20 m was analysed based on correlation measurements of fluorescence from the atoms (Fig. 4). The measurement basis of each atom was determined by the linear polarization of lasers that transferred population between Zeeman states. By rotating the basis of one atom with respect to the other, the researchers observed oscillations in the correlation probability sufficient to violate Bell’s inequality.

**Long-distance transfer**

Fidelity measures how faithfully a quantum state can be transported; another important question to ask is how far that state can be sent. We have seen that photons act as carriers of quantum information in both deterministic and heralded schemes. The deterministic case is straightforward: a photon physically transports information from one site to another. The heralded case is more abstract: teleportation is only possible because two photon paths from remote atoms converge at a common location. In either case, if we are interested in long-distance transfer, we must contend with the losses inherent in optical channels. The classical approach in a fibre-optic network is to intersperse the channel with repeater stations at which the signal is amplified, but in the quantum–mechanical world, this amplification is forbidden by the no-cloning theorem.$^7$

Instead, the solution is a quantum repeater, by means of which entanglement over relatively short distances is first purified and then extended to increasingly longer distances via entanglement swapping.$^4$ Quantum memories are essential for building up entanglement between successive repeater nodes; they allow quantum states to be stored at one node until an entangled pair is generated at the next node. A quantum repeater scheme based on atomic ensembles was first proposed in 2001,$^75$, and significant progress has subsequently been made towards its experimental realization,$^76$, including the demonstration of elementary repeater segments.$^77,78$. In fact, repeater architectures based on all of the quantum memories discussed above, including ions$^4$ and nitrogen–vacancy centres$^79$, are being pursued by several research groups around the world. It is an indication of the complexity of these architectures that entanglement swapping between quantum memories has not yet been achieved.

A central challenge faced in all of these experiments is that the rate of entanglement generation between repeater nodes must be faster than the rate at which entanglement decoheres. Otherwise, if entanglement is lost through interactions with the environment before it can be harnessed, it will not be possible to extend the range of quantum networks via entanglement swapping. This problem can be addressed in two ways: by speeding up the rate of entanglement generation and by increasing the storage times of quantum memories.
The particular approach for speeding up entanglement generation will be specific to each implementation, but the photon collection efficiency is typically the bottleneck in these schemes. Schemes based on spontaneous emission can be improved by integrating specialized objectives. For ions and neutral atoms, such optics may include in-vacuum lens systems with high numerical apertures, parabollic or spherical mirrors\textsuperscript{48,49}, or Fresnel optics\textsuperscript{50}. To scale up the number of atoms or ions at a given node, it will be important to integrate scalable collection optics, such as microfabricated lenses\textsuperscript{51,52} and optical fibres\textsuperscript{53}. For single-photon emission from nitrogen-vacancy centres, solid immersion lenses fabricated around the site have been shown to enhance the collection efficiency by an order of magnitude\textsuperscript{54,55}. Finally, enclosing the emitters in cavities enables efficient collection of photons into a well-defined optical mode\textsuperscript{56,57}.

The second route towards realizing scalable quantum repeaters is to enhance the storage times of quantum memories, which are often limited by environmental fluctuations, such as drifting magnetic fields. These parameters can be actively stabilized, but a more robust solution is to use memories that are well isolated from the environment. For experiments using atomic ensembles as a storage medium, thermal diffusion and collisions are key decoherence channels, and thus one solution would be to shift to quantum degenerate gases, in which both mechanisms are suppressed\textsuperscript{58,59,60}. In ion traps, it is possible to confine multiple atomic species simultaneously, and there are advantages to distributing tasks between two species, which are coupled by shared motional modes\textsuperscript{61}. For example, by using one species as a memory and a second species for a quantum interface, the memory will then be shielded from laser interactions\textsuperscript{62}. This same separation between memory and communication tasks is promising for nitrogen–vacancy centres, where information can be transferred from the electronic spin state to and from a well-isolated nuclear spin nearby\textsuperscript{63}. Quite generally, in identifying the particular states of a quantum system in which information is stored, it may be useful to work in decoherence-free subspaces — special states that are decoupled from noise channels\textsuperscript{64}.

On the horizon Quantum network experiments are still in the proof-of-principle stage. Further development of existing interfaces based on atoms, ions and solid-state devices will result in substantial gains in both speed and fidelity. In addition, new hybrid systems are emerging that may allow us to combine the advantages of different platforms (Fig. 5). For example, quantum interfaces typically interact with photons in the visible or even ultraviolet region, but telecom frequencies in the infrared are better suited to long-distance communication because optical-fibre losses are minimized in these bands. An important line of research is thus the efficient conversion of photons to and from telecom frequencies in order to extend the range of quantum network channels\textsuperscript{65,66}.

Another hybrid system comes from the field of circuit quantum electrodynamics, which is based on Josephson-junction atomic atoms coupled to superconducting microwave resonators. In the past decade, circuit-quantum-electrodynamics devices have proved to be highly promising systems for quantum computing\textsuperscript{67,68}. Recent Hong–Ou–Mandel experiments have shown that these devices can produce indistinguishable photons, as required for remote entanglement\textsuperscript{69}; however, as microwave photons are not well suited for long-distance communication, an optical-to-microwave interface is needed. Potential routes towards such an interface can be found in recent work that couples a superconducting qubit to optical spin ensembles, such as nitrogen–vacancy centres\textsuperscript{70–79} or crystals doped with rare-earth ions\textsuperscript{80}.

We have already outlined the contrast between quantum nodes, which are essentially local quantum computers, and quantum memories, which focus on information storage and play an essential role in quantum networks. Rare-earth ions show particular promise as quantum memories, as they offer long coherence times\textsuperscript{81,82} and efficient storage\textsuperscript{83} within a solid-state platform, interactions at telecom wavelengths and multiplexed storage protocols that could significantly speed up long-distance entanglement rates\textsuperscript{84}. Storage of photonic polarization quantum bits has recently been demonstrated with both high efficiency and fidelity, paving the way for interactions with polarization-based quantum-information processors\textsuperscript{85–89}.

This Review has highlighted how optical cavities enable light–matter information transfer. Another role for optical quantum memories in cavities has recently emerged: such systems can act as transistors, that is, as single-photon gates for light fields\textsuperscript{90} that may be integrated in future quantum networks.

Quantum information science is still a young field — as we have seen, it is just within the past decade that the first realizations of photon-based transfer have been achieved. As progress continues, the crucial challenge will be to find systems where the efficiency and fidelity of information transfer are sufficiently high to implement error correction — the basis for a robust and scalable network.

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**Competing financial interests**

The authors declare no competing financial interests.