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Advances in quantum teleportation

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Quantum teleportation is one of the most important protocols in quantum information. By exploiting the physical resource of entanglement, quantum teleportation serves as a key primitive across a variety of quantum information tasks and represents an important building block for quantum technologies, with a pivotal role in the continuing progress of quantum communication, quantum computing and quantum networks. Here we summarize the basic theoretical ideas behind quantum teleportation and its variant protocols. We focus on the main experiments, together with the technical advantages and disadvantages associated with the use of the various technologies, from photonic qubits and optical modes to atomic ensembles, trapped atoms and solid-state systems. After analysing the current state-of-the-art, we finish by discussing open issues, challenges and potential future implementations.

It has been over two decades since the discovery of quantum teleportation, in what is arguably one of the most interesting and exciting implications of the 'weirdness' of quantum mechanics. Prior to this landmark discovery, the fascinating idea of teleportation belonged in the realm of science fiction. First coined in 1931 by Charles H. Fort[1], the term 'teleportation' has since been used to refer to the process by which bodies and objects are transferred from one location to another, without actually making the journey along the way. Since then it has become a fixture of pop culture, perhaps best exemplified by Star Trek's celebrated catchphrase "Beam me up, Scotty."

In 1993, a seminal paper[2] described a quantum information protocol, dubbed quantum teleportation, that shares several of the above features. In this protocol, an unknown quantum state of a physical system is measured and subsequently reconstructed or 'reassembled' at a remote location (the physical constituents of the original system remain at the sending location). This process requires classical communication and excludes superluminal communication. Most importantly, it requires the resource of quantum entanglement[3,4]. Indeed, quantum teleportation can be seen as the protocol in quantum information that most clearly demonstrates the character of quantum entanglement as a resource: without its presence, such a quantum state transfer would not be possible within the laws of quantum mechanics.

Quantum teleportation plays an active role in the progress of quantum information science[5–8]. On the one hand, it is a conceptual protocol that is crucial in the development of formal quantum information theory; on the other, it represents a fundamental ingredient to the development of many quantum technologies. Quantum repeaters[9], quantum gate teleportation[10], measurement-based quantum computing[11] and port-based teleportation[12] all derive from the basic scheme of quantum teleportation. The vision of a quantum network[13] draws inspiration from this scheme. Teleportation has also been used as a simple tool for exploring 'extreme' physics, such as closed time-like curves[14].

Today, quantum teleportation has been achieved in laboratories around the world using a variety of different substrates and technologies, including photonic qubits (light polarization[15–21], single rail[22,23], dual rails[24,25], time-bin[26–28] and spin-orbital qubits[29]), nuclear magnetic resonance (NMR)[30], optical modes[31–39], atomic ensembles[40–43], trapped atoms[44–48] and solid-state systems[49–52]. Outstanding achievements have been made in terms of teleportation distance[20,21], with satellite-based implementations forthcoming. Attempts at scaling to more complex quantum systems have also begun[29].

Basics of quantum teleportation

We start by reviewing the basic quantum teleportation protocol in both finite- and infinite-dimensional settings.

Quantum teleportation of qubits and discrete variables. Quantum teleportation was originally described for two-level quantum systems, which are referred to as qubits[2]. The protocol considers two remote parties — Alice and Bob — who share two qubits, A and B, prepared in a pure entangled state. In the ideal case, this is taken to be maximally entangled, such as $|\Phi\rangle = (|0,0\rangle + |1,1\rangle)/\sqrt{2}$ (known as a Bell pair[5]). At the input, Alice is given another qubit a whose state ρ is unknown. She then performs a joint quantum measurement, called Bell detection[53–55], which projects her qubits a and A into one of the four Bell states $(\mathcal{P}_k \otimes I)|\Phi\rangle$ with $k = 0, 1, 2, 3$, where $\mathcal{P}_k \in \{I,X,Z,ZX\}$ is a Pauli operator[5,6] (X is the bit-flip operator and Z is the phase-flip operator). As a result, the state of Alice's input qubit has been collapsed by measurement while Bob's qubit B is simultaneously projected onto $\mathcal{P}_k^{\dagger}\rho\mathcal{P}_k$. In the last (feed-forward) step of the protocol, Alice communicates the classical outcome k of her measurement to Bob, who then applies $\mathcal{P}_k$ to recover the original input state ρ.

Note that Alice's input state is assumed to be unknown, otherwise the protocol reduces to remote state preparation[56]. Furthermore, this state may itself be part of a larger composite quantum system that is shared with a third party (in which case, successful teleportation requires reproducing all correlations with that third party). In typical experiments, the input state is taken to be pure and belonging to a limited alphabet, for example, the six poles of the Bloch sphere[5] or another unbiased sample of states. In the presence of decoherence, the quality of the reconstructed state may be quantified by its teleportation fidelity $F \in [0, 1]$. This is the fidelity[5] between Alice's input state and Bob's output state, averaged over all the outcomes of the Bell detection and input state alphabet. For small values of the fidelity, strategies exist that allow for an imperfect teleportation while making no use of any entangled resource. For example, Alice

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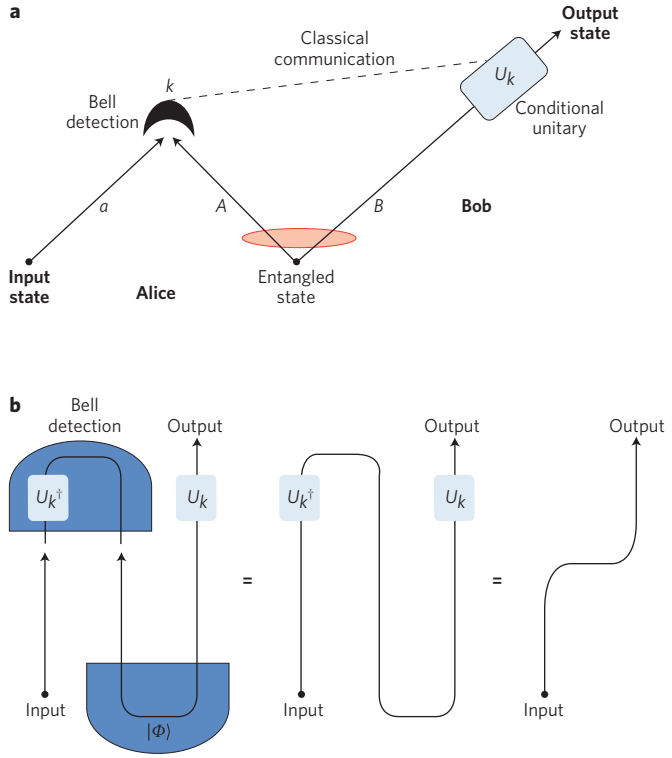

Figure 1 | Theory of quantum teleportation. a, Basic protocol. Alice's unknown input state is teleported to Bob using a shared entangled state and a classical communication channel. Alice performs a Bell state measurement on her systems, *a* and *A*, and classically communicates the outcome *k* to Bob. Using the measurement result, Bob applies the conditional unitary U_k to his system *B*, thus retrieving an output state that is an exact replica of Alice's input state in the ideal case ($F = 1$). The outcomes of the Bell detection are $k = 0, \ldots, d^2 - 1$ for DV systems, and *k* is a complex number for CV systems. In qubit-teleportation ($d = 2$), the input state is typically pure, the entangled state is a Bell pair, and U_k is a qubit Pauli operator $\mathcal{P}_k$. In CV teleportation ($d = \infty$), the systems are bosonic modes (for example, optical), the input is typically a coherent state, the entangled state is an EPR state, and U_k is a phase-space displacement. Variations on this basic protocol may occur depending on the actual technologies adopted. **b**, Ideal teleportation process in terms of Penrose-inspired space-time diagrams[134]. Let us consider a maximally entangled state $|\Phi\rangle$ as a shared quantum resource (that is, a Bell pair for qubits, or an ideal EPR state for CVs). The Bell detection then corresponds to applying $\langle\Phi|(U_k^\dagger \otimes I)$, where the outcome *k* is randomly selected by the measurement. As a result, an arbitrary input state ρ is transformed into $U_k^\dagger \rho U_k$ where the unitary $U_k^\dagger$ is correspondingly 'undone' by Bob.

may directly measure her input state, thereby sending the results to Bob for him to prepare an output state[57]. Such a measure–prepare strategy is known as 'classical teleportation' and has the maximum fidelity[58] $F_{\text{class}} = 2/3$ for an arbitrary input qubit state or, equivalently, an alphabet of mutually unbiased states, such as the six poles of the Bloch sphere. Thus, the requirement $F > F_{\text{class}}$ is a clear benchmark for ensuring that quantum resources are utilized.

Quantum teleportation is not restricted only to qubits, and may involve higher-dimensional quantum systems. One can formulate ideal teleportation schemes for every finite dimension *d*: this exploits a basis of maximally entangled states and a basis $\{U_k\}$ of unitary operators satisfying[59] $\text{tr}(U_j^\dagger U_k) = d\delta_{j,k}$. The scheme then follows the above lines, with the Pauli operators $\mathcal{P}_k$ replaced by U_k and the classical channel involves distinguishing d^2 signals. Such a protocol can be constructed for any finite-dimensional Hilbert space, for so-called discrete-variable (DV) systems (Fig. 1).

Quantum teleportation of continuous variables. Quantum teleportation can also be extended to quantum systems that have an infinite-dimensional Hilbert space, known as continuous-variable (CV) systems. These are typically realized by optical bosonic modes, whose electric field can be described by position- and momentum-like quadrature operators[7,8]. Following the first theoretical proposals[60,61], CV teleportation was demonstrated with optical modes[31]. Other CV systems can be considered, including optomechanical systems[62] and collective spins of atomic ensembles[40,41].

In the standard CV protocol with optical modes, the entangled resource corresponds to a two-mode squeezed vacuum state[8], also known as an Einstein–Podolsky–Rosen (EPR) state. This is a zero-mean Gaussian state[7] whose entanglement can be quantified in terms of the logarithmic negativity[63–65] as $\max\{0, -\log_2 \varepsilon\}$, where $\varepsilon \geq 0$ can be computed from the covariance matrix[7]. Suppose Alice is given an input mode *a* in an unknown state; typically, a coherent state $|\alpha\rangle$ with unknown amplitude α. She then applies a CV Bell measurement on her modes, *a* and *A*, which consists of mixing them on a balanced beamsplitter and measuring the output ports with two homodyne detectors[66]. This realizes the projection onto the quadratures $\hat{q}_- = (\hat{q}_a - \hat{q}_A)/\sqrt{2}$ and $\hat{p}_+ = (\hat{p}_a + \hat{p}_A)/\sqrt{2}$. In the last step, Alice communicates the classical outcome $k = q_- + ip_+$ to Bob, who performs a conditional displacement on his mode *B* (Fig. 1).

The teleportation fidelity for the alphabet of coherent states is given by $F = (1 + \varepsilon)^{-1}$. Perfect teleportation occurs only for unbounded entanglement $\varepsilon \to 0$, where the entangled state approximates the ideal EPR state, thus giving the perfect correlations $\hat{q}_A = \hat{q}_B$ and $\hat{p}_A = -\hat{p}_B$. Without entanglement ($\varepsilon = 1$) we have $F = F_{\text{class}} = 1/2$; that is, the classical threshold for teleporting coherent states[67,68]. A more stringent threshold asks that the teleported state is the best copy of the input allowed by the no-cloning bound[69], requiring $F > 2/3$. Note that this basic CV protocol can be extended to more general Gaussian state settings[70], for which suitable fidelity benchmarks can be derived[71–74]. Finally, CV teleportation can also go broadband[75].

Variants of teleportation

Teleportation is an important primitive that has been extended in a number of ways. Some of these extensions are actual protocols of quantum technology, whereas others are of conceptual value in theoretical models. In this section, we mention some of these variants and outline some of the most recent developments.

Entanglement swapping and quantum repeaters. As previously mentioned, the input to be teleported can itself be part of an entangled state; teleportation would then also transfer the entanglement. When the Bell detection is performed by a third party, say Charlie acting as a middle relay, this variant is called entanglement swapping. Suppose that Alice and Bob do not share entanglement, but instead locally prepare two entangled states; ρ_{aA} at Alice's station and ρ_{bB} at Bob's. They retain systems *a* and *b*, while sending systems *A* and *B* to Charlie for Bell detection. After the measurement outcome *k* has been classically broadcast, Alice and Bob share the conditional output state $\rho_{ab|k}$, which is entangled. This can be implemented with DV systems[76] (for example, polarization qubits[77]), CV systems[78–81] (for example, optical modes[34,82]) or adopting a hybrid approach that involves both DVs and CVs[83].

This protocol forms the basis of a quantum repeater[9], in which the combination of entanglement swapping and distillation[84,85] allows for the distribution of entanglement over large distances. Once that maximal entanglement has been distilled along a long chain of repeaters, teleportation between the end-users provides the perfect transfer of quantum information. The remote correlations created by swapping can also be exploited in quantum cryptography: even when Charlie is present in the role of an eavesdropper (untrusted relay), Alice and Bob can transform their resulting correlations into a secret key[86,87].

Quantum teleportation networks. Another important extension is to a quantum teleportation network, where $n > 2$ parties share a multipartite entangled state to allow teleportation between any two parties. For simplicity, we describe the simplest case of a three-party network, where, for example, Alice can teleport to either Bob or Charlie. One simple strategy is known as assisted teleportation, whereby Charlie performs a local measurement on his system and broadcasts the result with the aim of improving the fidelity of quantum teleportation from Alice to Bob. This requires Charlie's operation to be tailored so as to increase the bipartite entanglement of the remaining parties.

With qubits, three-party assisted networks can be constructed using the Greenberger–Horne–Zeilinger state[88]. In particular, this state makes teleportation equivalent to quantum secret sharing[89], whereby Alice's quantum information can be recovered by Bob if and only if Charlie assists. With CV systems, three-party assisted networks can be constructed with Gaussian states[70] generated, for example, using squeezed vacua at the input of two beamsplitters[90], as used in the first experimental demonstrations[91,92]. In general, by using one or more squeezed vacua in an interferometer, one can create multiparty assisted networks that involve an arbitrary number of bosonic modes[8,90].

A second strategy is unassisted teleportation, whereby Charlie, rather than helping Alice, also receives a copy of the input. In this case, the protocol corresponds to quantum telecloning, with Alice teleporting to Bob and Charlie simultaneously, though with a teleportation fidelity limited by the no-cloning bound (5/6 for qubits[93,94] and 2/3 for coherent states of CV systems[95]). Quantum telecloning, from one sender to two recipients, has been experimentally implemented with polarized photonic qubits[96] and coherent states of optical modes[97]. Theoretically, the protocol can be formulated for an arbitrary number of recipients, both in the case of qubits[98] and CV systems[99].

Quantum gate teleportation and quantum computing. Quantum teleportation can be expressed in terms of primitive quantum computational operations[100], and its protocol can be extended to quantum gate teleportation[10,101]. This idea is rooted in the observation that unitary state manipulation can be achieved by preparing auxiliary entangled states, performing local measurements and applying single-qubit operations. This approach is at the heart of linear-optical quantum computing[102] and plays an important role in fault-tolerant quantum computation. Essentially, certain gates are prepared offline as the entanglement resource for a teleportation protocol[5]. This resource is then also easier to implement in a fault-tolerant manner. Experimentally, two-qubit gates have been teleported[103].

More generally, such gate teleportation strategies lie at the heart of cluster-state quantum computing[11] and other schemes for measurement-based quantum computing[104]. In these schemes, a number of nodes (qubits or qumodes[7]) are prepared in a multipartite entangled state (for example, a cluster state) or other suitable tensor network state. Then, a suitable measurement on one node teleports its state onto another node with the concurrent application of a desired quantum gate[11,105]. Large cluster states can be generated with CV systems[106,107], with one experiment employing more than 10^4 optical modes[108].

Port-based teleportation. In port-based teleportation[12,109], Alice and Bob share n Bell pairs, which are referred to as ports. Alice then performs a suitable joint measurement on her n qubits and the system to be teleported, then communicates the outcome $k = 1, ..., n$ to Bob. Finally, Bob discards all his systems except qubit k, which will be in the unknown state of Alice's input. Compared with conventional teleportation, port-based teleportation has the advantage that Bob does not need to apply a correction at the end of the protocol. The disadvantage, however, is that the teleportation fidelity approaches unity only in the limit of large n.

This scheme has limited practical applications owing to the large entanglement resources needed (although this can be improved by entanglement recycling[110]), but has significant importance for conceptual studies in quantum information theory. This approach is an important primitive for devising programmable quantum processors[12] that can store a unitary transformation and then apply it to an arbitrary state. It has also been used in ideas of instantaneous non-local quantum computation[111], in attacking schemes of position-based cryptography[111], and in assessments of communication complexity tasks. In fact, advantages in quantum communication complexity have generally been linked to violations of Bell inequalities, with port-based teleportation being the main proof tool[112].

Experimental status and challenges

We now discuss the main experimental achievements and challenges of quantum teleportation. Ideally, an experiment of quantum teleportation is successful when the following basic requirements are met:

(1) The input state is arbitrary (within a suitable alphabet).
(2) A third party, say Victor, supplies the input state to Alice and independently verifies Bob's output state (for example, through quantum state tomography or fidelity estimation).
(3) Alice performs a complete Bell detection, which allows her to distinguish an entire basis of entangled states.
(4) Bob applies conditional unitaries in real-time before Victor's verification (active feed-forward).
(5) Teleportation fidelity exceeds the appropriate threshold, which is achievable by classical measure–prepare strategies.

In the laboratory, some of these conditions may not be met. In particular, the failure of condition (3) has led to probabilistic teleportation, wherein only a subset of the Bell states are accessible. In this case, the protocol has an associated Bell-efficiency that provides an upper bound to its overall success probability. For contrast, if condition (3) can be met, one can in principle perform deterministic teleportation.

Another critical condition is the realization of active (or real-time) feed-forward, whereby the outcomes of the Bell measurement are communicated in real-time to Bob and the conditional unitaries are actively performed on the output state, before being verified by Victor. This qualifies a teleportation experiment as 'active'. In 'passive' experiments, the feed-forward is either not implemented (for example, in those with 25% Bell-efficiency) or simulated in post-processing (that is, the unitaries are numerically applied during the tomographic reconstruction of the output). It is clear that the most complete teleportation experiments are those that are both deterministic and active.

Photonic qubits. The practical realization of a complete Bell detection is still a major issue for photonic qubits, as the simplest use of linear optics and photodetection allows at most two of the four Bell states to be distinguished[53–55] — a Bell-efficiency limit of 50%. In principle, using linear optics and n ancillary qubits allows a single qubit to be teleported with better Bell-efficiencies[102], approaching 100% for infinite n. This theoretical possibility clearly implies an overhead of quantum resources that is a non-trivial experimental challenge. Solving this problem is an active area of research[113–115].

The Innsbruck experiment[15] probabilistically teleported a polarization qubit at a Bell-efficiency of 25%, with a later demonstration achieving 50% in a 600 m fibre-optic implementation across the river Danube[16]. One point[116] about the Innsbruck experiment is that, because its implementation required Bob's teleported qubit to be detected, condition (2) above was rendered problematic. One might argue that this experiment achieved teleportation as a postdiction, which might earn it the term[116,117] '*a posteriori* teleportation'.

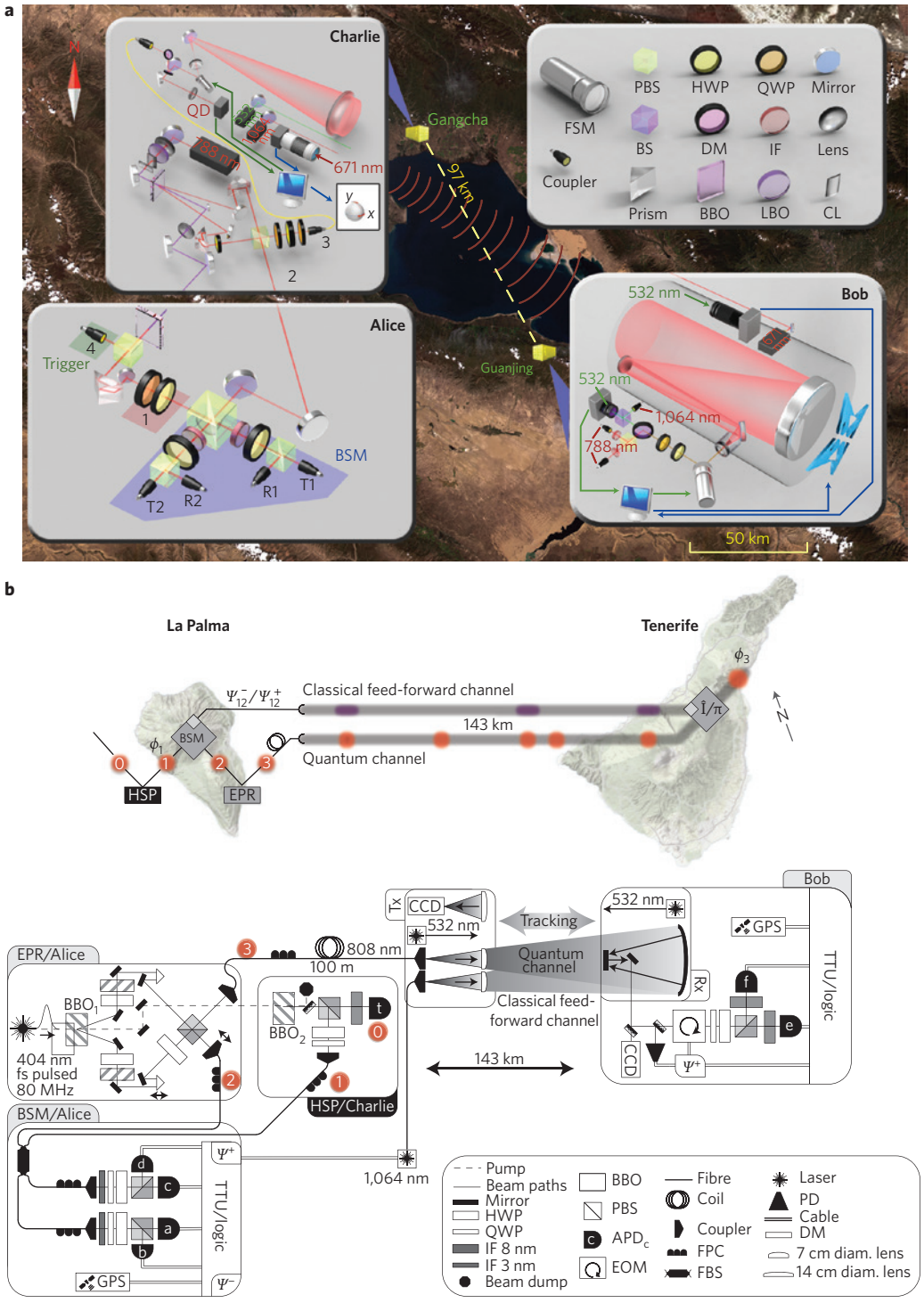

Figure 2 | Long-distance quantum teleportation with polarization qubits. a, A free-space, ground-level link measuring ~100 km across the Qinghai lake in China[20]. Passive teleportation was implemented with 50% Bell-efficiency and 80% fidelity. The channel attenuation between Alice and Bob varied in the range of 35–53 dB. Besides atmospheric loss, major attenuation came from the beam spreading wider than the 40 cm aperture of the receiver telescope. The experiment relied on a point-and-track control system for the telescopes to compensate for atmospheric turbulence and ground settlement. Entanglement distribution over two ~50 km links (total loss of ~80 dB) was also implemented. T1, T2, R1 and R2 are detectors. BSM, Bell-state measurement; FSM, fast steering mirror; PBS, polarizing beamsplitter; BS, beamsplitter; HWP, half-waveplate; QWP, quarter-waveplate; DM, dichroic mirror; IF, interference filter; BBO, beta-barium borate; LBO, lithium triborate; CL, cylindrical lenses. **b**, A free-space link measuring 143 km at an altitude of 2,400 m between the Canary islands of La Palma and Tenerife[21]. Teleportation was implemented with 50% Bell-efficiency and a fidelity of 86% (for passive teleportation) and 83% (for active teleportation). A telescope with 1 m aperture was used at Bob's site, and the total channel attenuation varied in the range of 28–39 dB. The experiment involved a suitable tracking system and techniques to enhance the signal-to-noise ratio, including low-noise single-photon detectors with large active areas and entanglement-assisted clock synchronization. HSP, heralded single photon; Tx, transmitter; Rx, receiver; TTU, transistor–transistor unit; APD, avalanche photodiode; FPC, fibre polarization controller; FBS, fibre beamsplitter; PD, photodiode. All other acronyms as defined in **a**. Figures adapted with permission from: **a**, ref. 20, NPG; **b**, ref. 21, NPG.

To achieve complete Bell detection, the Rome experiment[17] entangled photons in both spatial and polarization degrees of freedom. The input state was prepared within the set-up over one of the entangled photons, thus losing the ability to teleport entangled or mixed states. This implies that the input state cannot be independently supplied from outside, which violates condition (2) above. The scheme was later extended to free-space teleportation over 16 km at a fidelity of 89%[18]. Complete Bell detection has also been attempted using nonlinear interactions, although this leads to a very inefficient protocol. Using optical upconversion[19], only one out of ~10^{10} polarization qubits takes part in the nonlinear process.

Photonic qubits have also been physically realized in other ways. One is the single-rail qubit, or vacuum-one photon qubit[118], which corresponds to the two-dimensional subspace spanned by the vacuum and the one-photon state of an optical mode. Such a qubit was teleported[22] with 50% Bell efficiency and 95% fidelity. This implementation was later extended to real-time feed-forward with slightly reduced fidelity (~90%) in the first active experiment with photonic qubits[23]. A direct generalization is the dual-rail qubit, which is a single photon encoded in one of two spatially separated modes[102]. This was teleported with 25% Bell efficiency and 80% fidelity by exploiting single photons generated by a quantum dot[24].

A photonic qubit has also been realized as a time-bin qubit[119], which is a single photon populating one of two temporal modes. Time-bin qubits have been teleported along a 2 km spool of telecommunications fibre with 25% Bell-efficiency and 81% fidelity[26]. The qubit was teleported between photons of different wavelengths (1.3–1.55 μm). This experiment was then extended to a relay configuration[27], where the Bell detection was performed by a third party, connected with Alice's input state and the entangled source by means of 2 km of coiled fibres. In this set-up, the challenge was to preserve the indistinguishability of the photons involved in the Bell detection. See ref. 28 for an implementation in a commercial telecommunications network.

Photonic qubits are excellent carriers for long-distance quantum communication. This is particularly true in free space, where birefringence is weak and photon absorption is small at optical frequencies (for example, compared with fibres). Two experiments with polarization qubits in free space[20,21] achieved very long distance quantum teleportation. This suggests that the atmosphere can be traversed, placing satellite-to-ground implementations within reach of current technology (Fig. 2).

A complementary challenge is the photonic miniaturization of teleportation for applications in quantum processors based on linear optics and probabilistic gates[102]. Dual-rail qubits have been teleported within a photonic chip[25]. Bell detection was performed with an efficiency of 1/27, and a fidelity of 89% was extrapolated by simulating the feed-forward operations in the post-processing. Active feed-forward remains a major challenge in photonic chips owing to the need for ultrafast photon detection and integrated electronics with terahertz bandwidths.

Finally, we have witnessed the (probabilistic and passive) teleportation of multiple degrees of freedom of a composite quantum system. The spin (polarization) and orbital angular momentum of a single photon have been teleported simultaneously[29], with a fidelity in the range of 57–68%. This is above the classical threshold of 40% given by the optimal state estimation for a single copy of a two-qubit system. The experiment exploited a hyper-entangled Bell detection with an efficiency of 1/32. The Bell detection was designed to be a quantum non-demolition measurement involving an additional teleportation set-up.

Nuclear magnetic resonance. Complete Bell detection is achievable in NMR teleportation[30], where the qubits are nuclear spins. The spins of two carbon nuclei (C_1 and C_2) and a hydrogen nucleus (H) were considered in a molecule of labelled trichloroethylene (more precisely, an ensemble of such molecules, so that the results are averaged). After creating entanglement between C_1 and H through spin–spin interactions, teleportation was realized from C_2 to H by making a complete Bell detection on the two Carbon nuclei[30]. This detection was performed in two steps[100]: the Bell basis was first rotated to the computational basis using radiofrequency pulses and a spin–spin coupling; then, a projection on this basis was performed by exploiting the natural phase decoherence of the carbon nuclei (the fastest in the molecule, with times <0.4 s). Real-time feed-forward was easily implemented using radiofrequency pulses. Because NMR teleportation is limited to inter-atomic distances, it is not suitable for quantum communication, but could still be used as a subroutine for NMR quantum computing.

Optical modes. The first and simplest resolution of the Bell detection problem came from the use of CV systems — in particular, optical modes[31]. As mentioned previously, the CV version of this measurement can easily be implemented with linear optics, using a balanced beamsplitter followed by two conjugate homodyne detections at the output ports. Both the beamsplitter visibility and the homodyne quantum efficiency can be extremely high, so that the overall detection can approach 100% efficiency. CV teleportation satisfies all conditions (1)–(5), the only restriction being that the input states must belong to a specific alphabet, as a consequence of the infinite-dimensionality of the Hilbert space. Real-time feed-forward can easily be implemented using electro-optical modulators (EOMs). The first experiment with optical modes[31] was indeed deterministic and active, and successfully teleported an alphabet of fixed-energy phase-modulated coherent states with 58% fidelity — above the relevant classical threshold.

This experiment was later improved to beat the no-cloning bound, reaching fidelities of 70%[34] and 76%[35]. These high-fidelity CV teleporters are able to transfer non-classical features such as non-positive Wigner functions. Other experiments with coherent states involved phase scanning at different amplitudes (61% fidelity[33]) and simultaneous amplitude and phase modulation (64% fidelity[32]). Other types of states have been teleported, including squeezed states[35,36], Schrödinger cat states[37] and entangled states (see entanglement swapping[34,82,83]). Figure 3 shows typical experimental set-ups.

Unfortunately, CV teleportation fidelities cannot reach 100% because CV systems do not allow a maximally entangled state to be prepared with finite resources. Realistic EPR states, with good but finite two-mode squeezing, can be realized using a single, non-degenerate optical parametric oscillator[120,121]. Alternatively, one can first produce two single-mode squeezed states, for example via parametric downconversion in two degenerate optical parametric oscillators, and then combine them in a balanced beamsplitter. Even with the high levels of squeezing currently feasible (~10 dB) this resource also requires good phase-locking in a teleportation experiment. The current fidelity record[38] for CVs is 83%.

To overcome the limitations due to finite squeezing, CV teleportation has been 'integrated' with DVs into a hybrid formulation[122,123]. Deterministic and active CV teleportation of a photonic qubit has been realized[39] by applying a broadband CV teleporter to the temporal modes of a time-bin qubit. Such an approach aims to solve the problem of a complete Bell detection (thanks to CVs) while achieving a high teleportation fidelity thanks to DVs. Using only moderate levels of squeezing, one can achieve fidelities beyond 80% (Fig. 3b).

Optical modes are well-suited for integration into communication technologies, thanks to the use of high-performance homodyne detectors and off-the-shelf parts, like the EOMs used for the state input preparation and output displacements. Although it is unclear whether the CV teleportation distance is limited only to middle-range distances due to increased fragility with respect to loss (all previous experiments have been table-top), the possibility to go broadband and achieve high-rates is clearly appealing.

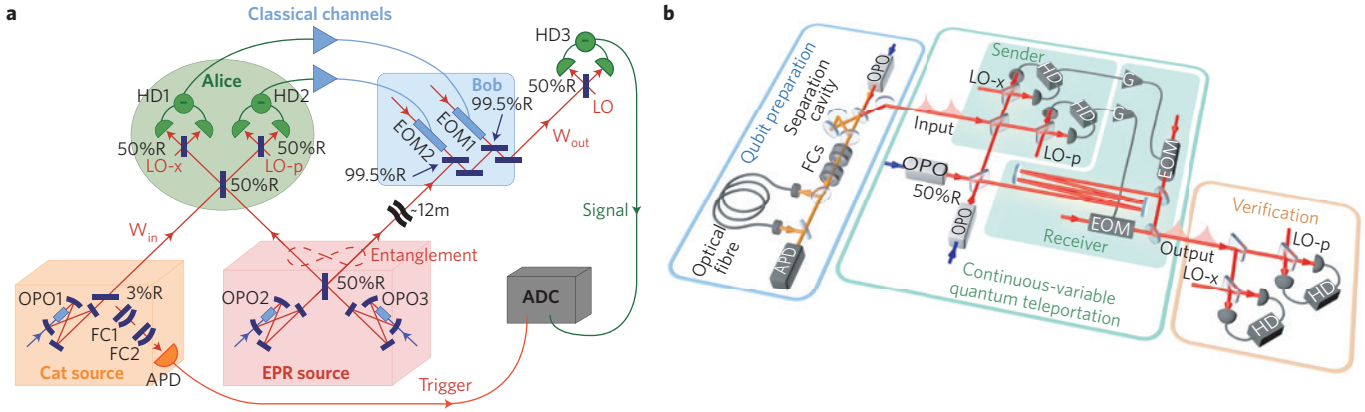

Figure 3 | Quantum teleportation with optical modes. a, Set-up of a full CV teleportation experiment with optical modes[37]. An EPR state is generated by using two degenerate optical parametric oscillators (OPOs) and a balanced beamsplitter. At Alice's station, part of the EPR state is combined with the input state (here a cat state) in a CV Bell detection; that is, another balanced beamsplitter with two homodyne detectors at the output ports. The classical outcomes are transmitted to Bob who displaces his part of the EPR state by using two EOMs. Note that both the preparation of the input state and the verification of the output state are independently done by Victor. ADC, analog-to-digital converter; R, reflectivity; FC, filter cavity; HD, homodyne detector; LO, local oscillator; LO-x, local oscillator locked at x-quadrature; LO-p, local oscillator locked at p-quadrature. **b**, Hybrid experiment where a time-bin qubit (prepared on the left) is teleported via CV teleportation (green middle section), involving an EPR state, complete CV Bell detection and EOMs[39]. G, gain. All other acronyms as defined in **a**. Figures adapted with permission from: **a**, ref. 37, AAAS; **b**, ref. 39, NPG.

Atomic ensembles. Quantum teleportation may be performed between quantum systems of a different nature, for example, between light and matter. The first experiment to show this feature[40] involved teleporting coherent states of an optical mode onto the collective spin of an atomic ensemble comprising ~10^{12} room-temperature caesium atoms. Because the collective transverse atomic spin components can be described by quadrature operators, this scheme implements a CV teleportation scheme.

Light–matter entanglement was generated by sending a strong light pulse through Bob's atomic sample[40], thus yielding coherent scattering, with the light being subject to the Faraday effect and the atoms evolving by the dynamic Stark effect. The optical output was combined with another optical pulse (modulated by an EOM) at Alice's station, where a complete Bell measurement was performed using a balanced beamsplitter followed by two sets of polarization homodyne detectors. Conditioned on the outcome, Bob performed spin rotations on the atoms by applying radiofrequency magnetic field pulses (Fig. 4a).

In this way, deterministic and active light-to-matter teleportation was realized[40] with a fidelity of 58%. All conditions (1)–(5) were achieved, for an input alphabet of coherent states. We note that atomic ensembles have the potential for good quantum memories[124] with subsecond coherence times and millisecond storage times[125]. This is an important feature for the construction of a scalable quantum network, where teleportation is used to store flying data (optical modes) into stationary media (atomic ensembles).

This experiment was extended to deterministic and active matter-to-matter CV teleportation[41], between two ensembles of ~10^{12} room-temperature caesium atoms, by using a four-wave mixing interaction. As before, Bob's ensemble (B) was subject to a strong driving pulse whose scattering created a co-propagating sideband field (C) entangled with its collective spin. This field reached Alice's ensemble (A), which was prepared in a coherent state by application of radiofrequency magnetic field pulses. The interaction with A led to a partial mapping of its state onto C, which was then subject to polarization homodyning. Conditioned on the outcome, Bob rotated the spin of B through radiofrequency magnetic field pulses, thus completing the teleportation from A to B with a fidelity of 55%–70%, depending on the size of the input alphabet. This protocol was also used to teleport time-evolving spin states, which makes it the first example of stroboscopic teleportation (Fig. 4b).

Light-to-matter teleportation has also been achieved with DVs by using cold atomic ensembles[42]. This increased the distance and fidelity but made the protocol probabilistic (50% Bell-efficiency) and passive. A polarization qubit has been transported[42] over a 7 m fibre onto a collective atomic qubit made from two cold ensembles of ~10^6 rubidium atoms. Teleportation was performed with 78% fidelity, and the output state was stored for 8 μs. This protocol was extended to matter-to-matter teleportation between two cold ensembles of ~10^8 rubidium atoms (at 100 μK) connected by a 150 m spool of optical fibre[43]. A single collective atomic excitation (spin wave) was teleported between the ensembles with the aid of polarization qubits. Through Raman scattering, Bob's spin wave qubit (B) was entangled with a photonic qubit (B′) travelling to Alice. Here, Alice's spin wave qubit (A) was converted into another photonic qubit (A′). Bell detection of A′ and B′ teleported the state of A onto B with 88% fidelity and a storage time of 129 μs. Note that subsecond storage times are possible with cold atomic ensembles[126].

Trapped atomic qubits. Deterministic and active qubit teleportation has been realized with trapped ions[44–46], with all conditions (1)–(5) being satisfied. Even if distances are very limited owing to the short-range Coulomb interactions, the storage times in these systems are very long. This makes them good quantum memories for using teleportation as a subroutine in quantum computing.

One study[44] considered three beryllium ions ($^9Be^+$) confined in a segmented linear Paul trap, with an inter-ion spacing of 3 μm. The qubits were provided by ground-state hyperfine levels, coupled via stimulated Raman transitions. Resonance fluorescence was used for complete Bell detection and, exploiting spin-echo pulses, a fidelity of 78% was achieved. Another study[45] considered three calcium ions ($^{40}Ca^+$) in a linear Paul trap, with an inter-ion distance of 5 μm. An ion qubit was encoded in a superposition of the $S_{1/2}$ ground state and the metastable $D_{5/2}$ state (lifetime ~1.16 s) and manipulated by laser pulses tuned to the 729 nm quadrupole transition. Complete Bell detection was performed by observing resonance fluorescence on photomultiplier tubes. Using rephasing spin-echo pulses, this study achieved a fidelity of 75% with storage lifetimes of 10 ms, with later results[46] achieving a fidelity of 83%.

Increasing the transmission distance beyond micrometres could be achieved using a photonic-matter interface, whereby photonic

qubits are employed as quantum carriers for state mapping and entanglement distribution, although a practical linear-optics implementation would provide incomplete Bell detection. One study[47] reported the probabilistic teleportation between two ytterbium ions ($^{171}Yb^{+}$) with 90% fidelity (Fig. 4c). This method could be used to build a modular quantum network of trapped ions in which long-distance entanglement between atomic qubits is generated at a rate faster than the decoherence rate[127].

Trapped ions provide long coherence times but their free-space interface may suffer from inefficient photon collection. An alternative solution may come from cavity quantum electrodynamics, where collection efficiencies are enhanced by the strong atom–cavity coupling, albeit at the expense of shorter coherence times. Following this idea, researchers investigated[48] probabilistic teleportation between two neutral rubidium atoms (^{87}Rb) trapped in two distant optical cavities, with a fidelity of 88% (Fig. 4d).

Solid-state systems. Probabilistic light-to-matter teleportation can be performed between photonic qubits and solid-state quantum memories composed of semiconductor quantum dots (QDs)[49] or rare-earth-doped crystals[50]. The first experiment[49] probabilistically teleported a photonic-frequency qubit generated by a neutral QD (that is, a single-photon pulse in a superposition of two frequencies) onto the electron spin of a charged QD separated by 5 m in a different cryostat. A fidelity of 78% was reported for the four equatorial poles of the Bloch sphere (for which $F_{class} = 3/4$), with the spin coherence time extending to 13 ns using spin-echo pulses (Fig. 5a).

In the second experiment[50], telecommunications-wavelength polarization qubits were probabilistically teleported onto a single collective excitation of a rare-earth-doped crystal (a neodymium-based quantum memory that stored photons for 50 ns), achieving a fidelity of 89%. One state was teleported over long distance with slightly reduced fidelity, in a relay configuration where the Bell detection was performed at the output of two 12.4-km-long fibre spools (Fig. 5b). This approach is promising for the availability of quantum memories with very long coherence times[128].

Deterministic and active matter-to-matter teleportation has also been achieved in solid-state devices. In one study[51], researchers considered superconducting transmon qubits separated by 6 mm

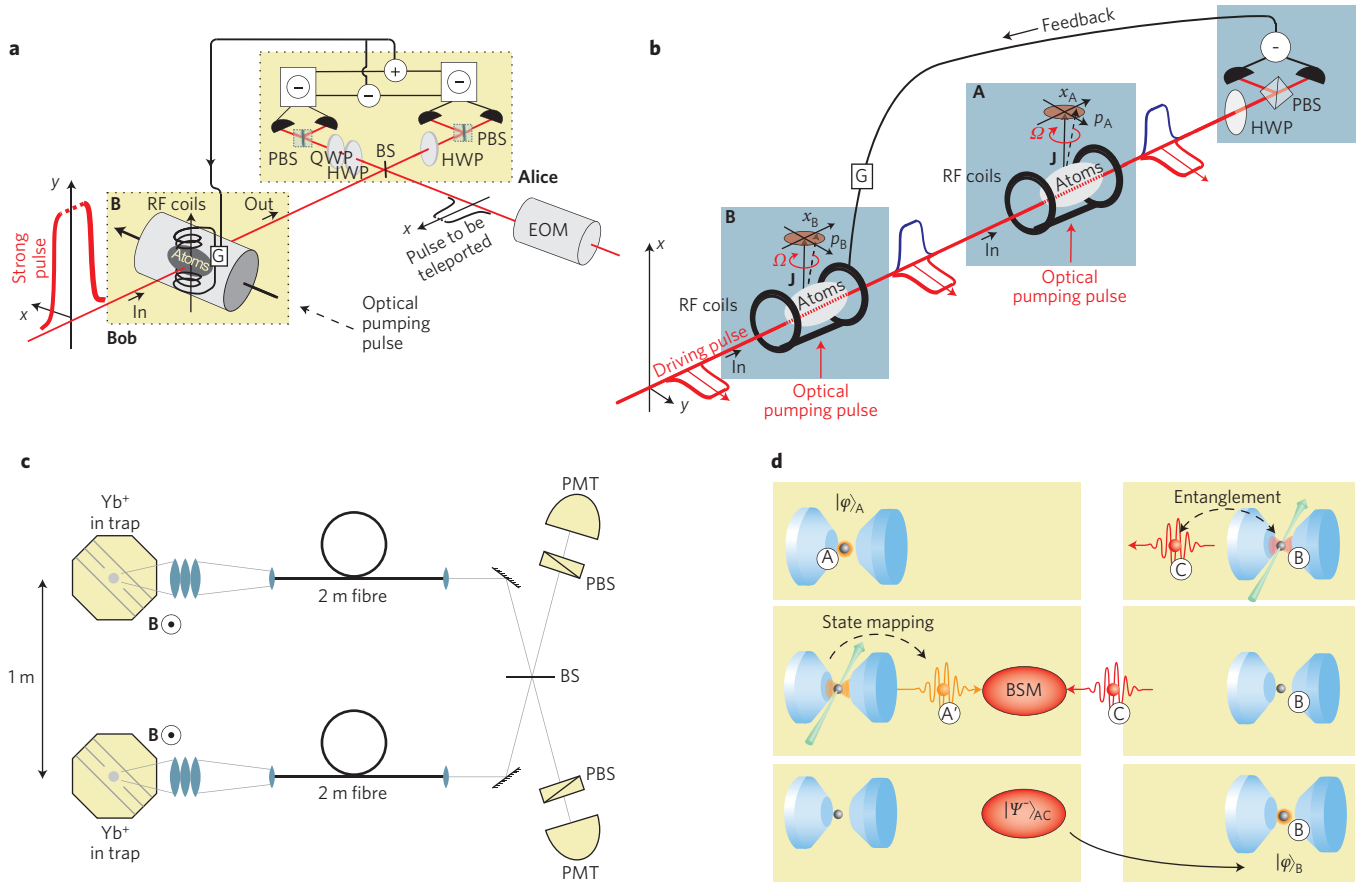

Figure 4 | Quantum teleportation with matter. a,**b**, Teleportation experiments with atomic ensembles of caesium atoms at room temperature, showing light-to-matter teleportation of a coherent state of an optical mode into a collective atomic spin[40] (**a**) and matter-to-matter teleportation between the collective spins of two atomic ensembles[41] (**b**). RF, radiofrequency. **c**,**d**, Set-ups with single trapped atoms, where teleportation is achieved by an incomplete Bell detection on emitted photonic qubits. **c**, Teleportation between trapped ytterbium ions, confined in independent Paul traps[47], 1 m apart and optically connected by a 4 m fibre. Each atomic qubit was encoded in the hyperfine states of the $^2S_{1/2}$ level having coherence times of ~2.5 s, and were manipulated by resonant microwave pulses at 12.6 GHz. Spontaneously emitted photons were coupled into fibres and directed to a beamsplitter, where the output ports were filtered in polarization and detected by single-photon photomultiplier tubes (PMTs), implementing a Bell detection with 25% efficiency. **d**, Teleportation between two neutral rubidium atoms (A and B) trapped in optical cavities separated by a 21 m optical fibre[48]. Qubits were encoded in two Zeeman states of the atomic ground-state manifold. Atom–photon entanglement and state mapping were efficiently achieved by vacuum-stimulated Raman adiabatic passage. The generated photonic qubits (A′ and C) were then subject to an incomplete Bell detection (25% efficiency). Upon selecting one of the four Bell states $|\Psi^-\rangle$, the input state $|\varphi\rangle$ was teleported from atom A to atom B. Figures adapted with permission from: **a**, ref. 40, NPG; **b**, ref. 41, NPG; **c**, ref. 47, AAAS; **d**, ref. 48, APS.

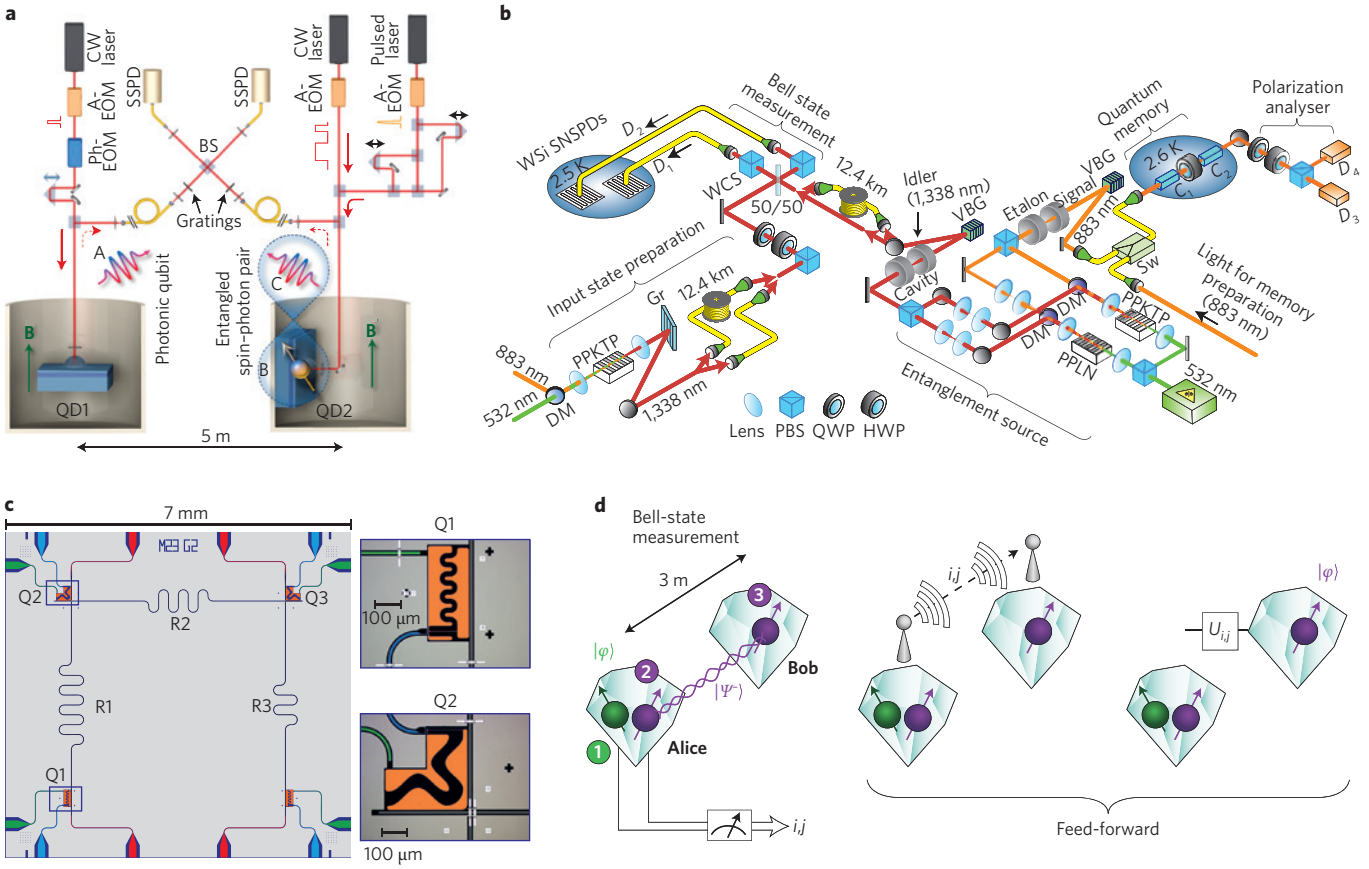

Figure 5 | Quantum teleportation with solid-state systems. a, Teleportation of a photonic frequency qubit *A*, generated by exciting a neutral QD (QD1), onto the electron spin *B* of a charged QD (QD2)[49]. By means of resonant optical excitation, the spin *B* was entangled with a second frequency qubit *C*, sent to interfere with *A* in a Hong–Ou–Mandel interferometer. A coincidence detection at the output of the interferometer heralded successful photonic-to-spin teleportation with 25% Bell efficiency. A-EOM, amplitude EOM; Ph-EOM, phase EOM; SSPD, superconducting single-photon detector. **b**, Set-up for teleporting a telecommunications polarization qubit onto a rare-earth-doped crystal quantum memory[50]. Two polarization-entangled photons were generated via spontaneous parametric downconversion in nonlinear waveguides, and one of the photons (883 nm) was stored in the quantum memory 10 m away. The other photon (1,338 nm) was sent to interfere with the input polarized photon at the Bell analyser (25% Bell efficiency), where they were measured by superconducting-nanowire single-photon detectors (SNSPD) operating at 2.5 K. Teleportation of the specific state $|+\rangle$ was extended to a total of 24.8 km in coiled fibre. PPKTP, periodically poled potassium titanyl phosphate; Gr, grating; VBG, volume Bragg gratings; Sw, switch; WCS, weak coherent state; PPLN, periodically poled lithium niobate. **c**, Chip design for teleportation between two superconducting transmon qubits, from Q1 to Q3, using the middle qubit Q2 and the two resonators, R1 and R2. The resonators act as quantum buses for entanglement generation and complete Bell detection[51]. The qubits were manipulated by applying microwave pulses through individual charge gate lines, and Bell state detection was performed using Josephson parametric amplifiers. **d**, Teleportation between two nitrogen-vacancy centres in diamonds[52]. Once the electronic spins (2 and 3) are entangled, the nitrogen nuclear spin (1) is Bell-detected together with the electronic spin (2) of the same centre. Finally, real-time feed-forward yields teleportation onto the other electron spin (3). Figures adapted with permission from: **a**, ref. 49, NPG; **b**, ref. 50, NPG; **c**, ref. 51, NPG; **d**, ref. 52, AAAS.

and coupled to waveguide resonators in a circuit quantum electrodynamics set-up[129] (Fig. 5c). The experiment[51] realized probabilistic teleportation (fidelity ~81%) and deterministic teleportation (fidelity ~77%) — also including real-time feed-forward (fidelity ~69%) — at a rate of 10^4 Hz with microsecond coherence times. The set-up employed a quantum bus technology capable of scaling to more complex planar architectures, with non-trivial implications for solid-state quantum computing.

Finally, researchers have also successfully teleported between two diamond nitrogen–vacancy centres separated by 3 m, with complete Bell detection and real-time feed-forward[52]. These centres were addressed by cryogenic confocal microscopes, and their spins were manipulated by spin-resolved optical excitations and microwave pulses. The electronic spins of the centres were entangled through entanglement swapping (coupling them with optical fields that were subsequently overlapped at a beamsplitter and detected). Conditioned upon success of this procedure, the nitrogen nuclear spin of the first centre was prepared and Bell-detected together with the electronic spin of the same centre. Teleportation onto the electronic spin of the second centre was achieved with an estimated fidelity of 86% (Fig. 5d). Nitrogen–vacancy centres are particularly attractive for combining an optical interface (via the electron spin) with a long-lived nuclear spin memory, having coherence times exceeding 1 s at room temperature[130].

Discussion and outlook

Table 1 summarizes the optimal experimental performances that are currently achievable using various substrates and techniques. It is clear that there is no single quantum system or technology that excels in all parameters. Still, we may try to identify preferred candidates in relation to specific applications of quantum teleportation. Suitable hybridization of these candidates with compatible substrates and techniques may provide the most promising future developments for quantum teleportation and its applications.

Short-distance teleportation (below 1 m) as a quantum computing subroutine is promising on solid-state devices, with the best

Table 1 | Comparing quantum teleportation technologies.

Quantum technology		Bell efficiency	Fidelity		Maximum distance	Quantum memory
			Passive	Active		
Photonic qubits	Polarization[15,16,20,21]	≤50%*	86%[21]	83%[21]	143 km[21]	N/A†
	Single-rail qubits[22,23]	50%	95%[22]	90%[23]	Table-top	N/A†
	Dual-rails in free-space[24]	25%	80%	—	Table-top	N/A†
	Dual-rails on chip[25]	1/27	89%	—	On-chip	N/A†
	Time-bins[26–28]	25%	81%[26]‡	—	6 km fibre[27]§	N/A†
	Spin-orbital qubits[29]	1/32	57–68%‖	—	Table-top	N/A†
NMR[30]		100%	—	~90%¶	~1 Å	~1 s
Optical modes	CVs[31–38]	100%	—	83%[38]	12 m[37]	N/A†
	Hybrid[39]	100%	—	79–82%	Table-top	N/A†
Atomic ensembles	(Hot) CV light-to-matter[40]	100%	—	58%	Table-top	4 ms[125]
	(Hot) CV matter-to-matter[41]	100%	—	55–70%	Table-top (0.5 m)	4 ms[125]
	(Cold) DV light-to-matter[42]	50%	78%	—	7 m fibre	100 ms[126]
	(Cold) DV matter-to-matter[43]	50%	88%	—	150 m fibre#	100 ms[126]
Trapped atoms	Trapped ions[44–46]	100%	—	83%[46]	5 μm[45]	50 s[135]**
	Trapped ions and photonic carriers[47]	25%	90%	—	4 m fibre††	50 s[135]**
	Neutral atoms in an optical cavity[48]	25%	88%	—	21 m fibre	184 μs[136]
Solid state	Frequency qubit to quantum dot[49]	25%	78%‡‡	—	5 m	≥1 μs[137]**
	Polarization qubit to rare-earth crystal[50]	25%	89%	—	24.8 km fibre§§	1 ms[138] ~6 h[128]**
	Superconducting qubits on chip[51]	100%	77%	69%	On-chip (6 mm)	<1 ms[139]**
	Nitrogen–vacancy centres in diamonds[52]	100%	—	86%	3 m	~0.6 s[140]‖‖ ≥1 s[130]¶¶

Comparison made in terms of various quality factors, including the practical efficiency of the Bell state analyser, the maximum teleportation fidelity (in active or passive set-ups), the maximum distance of teleportation in free-space (or fibre, where indicated), and the storage time of associated quantum memories. The storage time can be either the typical decay time of the stored qubit (estimated from the retrieval efficiency of the memory) or the time needed for the write–read fidelity to drop below the classical threshold value (for example, this is the definition used for CVs). In some cases, we show the maximum coherence time, which typically involves the use of dynamical decoupling techniques. Symbols: *Excluding set-ups with internal qubit preparation[17,18]; †Optical delays based on fibres or cavities that have very short storage times; ‡Fidelity of 93% was achieved for the four equatorial states[28]; §Coiled fibre, Alice–Bob flight distance ~55 m (extended to 550 m in ref. 28); ‖Two-qubit teleportation with classical fidelity of 40%; ¶Entanglement fidelity[30]; #Coiled fibre, Alice–Bob flight distance ~0.6 m; **Maximum coherence time; ††Alice–Bob flight distance ~1 m; ‡‡Equatorial states teleported; §§One state teleported over 24.8 km of coiled fibre with 81% fidelity (Alice–Bob flight distance ~10 m); ‖‖Coherence time for electronic spins at low temperatures (~77 K); ¶¶Coherence time for nuclear spins at room temperature.

approach being circuit quantum electrodynamics[129]. In particular, superconducting transmon qubits may guarantee both deterministic and high-fidelity teleportation on chip[51]. They also allow the implementation of real-time feed-forward, which seems to be more challenging with photonic chips[25]. Moreover, compared with earlier approaches such as trapped ions, they provide a more scalable architecture and better integration with existing technology. The current downside of these systems seems to be their limited coherence time (below 1 ms). This problem can be overcome by integrating circuit quantum electrodynamics with solid-state spin-ensemble quantum memories (nitrogen–vacancy centres or rare-earth-doped crystals), which can provide very long coherence times for quantum data storage. This is currently one of the biggest efforts across the community[131,132].

Teleportation-empowered quantum communication at the metropolitan scale (a few kilometres) could be developed using optical modes[31,38]. For sufficiently low loss, these systems provide high rates and bandwidths (for instance, see the high-rate performances achievable in CV quantum key distribution[87]). Experiments may be extended from table-top to medium-range implementations, in fibre or free-space, and to consider potential integration with ensemble-based quantum memories. Longer distances at lower rates may be achieved via a hybrid approach[39] or by developing good quantum repeaters based on non-Gaussian operations[85].

Research into long-distance quantum teleportation (beyond 100 km) is active but still affected by an unsolved problem. Although polarization qubits are the best carriers for (low-rate) teleportation over long fibres and free-space links, they currently make the protocol probabilistic owing to the incomplete Bell detection. Although probabilistic teleportation and entanglement swapping are acceptable for tasks such as entanglement distillation and quantum cryptography[86], the situation is clearly different for quantum communication, where the input quantum information must be fully preserved.

Thus, provided one is willing to work within the limitations imposed by probabilistic protocols, then satellite-based implementations are within the reach of current technology. Besides the integration of tracking techniques, the main challenge is to overcome the high losses associated with beam spreading. This could be achieved in a configuration where entanglement is distributed from a satellite to large-aperture ground-station telescopes. Assuming 1 m aperture telescopes and a 20 cm aperture satellite at an altitude of ~600 km, one can estimate a loss of ~75 dB for a two-downlink channel, which is less than the ~80 dB loss achieved at ground level for entanglement distribution[20]. Ground-to-satellite or inter-satellite implementations are more challenging.

The future use of quantum teleportation as a building block in scalable quantum networks depends on its integration with quantum memories. Such memories must come with excellent radiation–matter interfaces, in terms of conversion efficiency, write–read fidelity, storage time and bandwidth (high rate and storage capacity)[124]. The development of good quantum memories would enable not only the distribution of entanglement across a network (via quantum repeaters) and quantum communication via teleportation, but also the ability to store and process the transmitted quantum information. This could ultimately transform the network into a world-wide distributed quantum computer or backbone for a future quantum internet[13].

From this point of view, atomic ensembles are traditionally considered appealing for their efficient light-to-matter conversion[124] and their millisecond storage times, which can approach the ~100 ms required by light for transmission on a global scale. However, very promising developments are also coming from solid-state systems, where excellent spin-ensemble quantum memories offer direct integration with the scalable architecture of circuit quantum electrodynamics. These memories may not only extend the coherence time of circuit quantum electrodynamics, but also provide an optical–microwave interface for inter-converting propagating optical/telecommunications photons with on-chip microwave photons[132,133]. Thus, a revised hybrid architecture for the future quantum internet could be based on solid-state nodes (for local quantum information processing) suitably connected by long-distance quantum optical communication, which may be exploited for inter-node quantum teleportation.

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Author contributions

All authors contributed to selecting the literature, critical discussions and checking the manuscript for accuracy. S.P. reviewed the selected literature, and wrote the majority of the manuscript. J.E. and S.L.B. contributed to the writing/editing of the theory sections.

Additional information

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Competing financial interests

The authors declare no competing financial interests.