NEWS & VIEWS

QUANTUM PHYSICS

Entanglement on demand

Two experiments show that non-classical correlations can be distributed between distant nodes of a quantum network in a deterministic way. The work smooths the path for extended quantum networks. SEE LETTERS P.264 & P.268

JULIEN LAURAT

The phenomenon of entanglement, by which two physical systems can be more strongly correlated than is possible in classical physics, is at the heart of quantum mechanics. The efficient distribution of entanglement between distant nodes of a quantum network has become a cornerstone of future quantum technologies — from secure long-distance communication to powerful quantum computing. However, the simultaneous entanglement of more than a few nodes remains a tremendous challenge. On pages 264 and 268, respectively, Kurpiers *et al.*[1] and Humphreys *et al.*[2] demonstrate two methods for delivering entanglement in a deterministic way that could greatly facilitate the construction of large-scale quantum networks[3].

Quantum nodes take a variety of forms. They c an comprise an ensemble of optical emitters, including laser-cooled atoms or ions that are embedded in a crystal. Alternatively, they can rely on a single emitter such as an atom, a defect in diamond or a superconducting quantum bit (qubit). Regardless of the physical platform, the generation of entanglement between two nodes needs to be done in a way that can be extended to many nodes. Probabilistic methods are unsuitable for such a task because simultaneously establishing a large number of entangled nodes leads to an exponential decrease in the overall chance of success.

The challenge of scalability is highlighted, for example, by the prospect of long-distance quantum communication. Unlike the signals in conventional telecommunications, quantum information cannot be amplified or regenerated. As a result, long-distance communication requires a quantum-repeater architecture, in which the distance between the two communicating parties is divided into shorter segments, and entanglement is generated in each segment. The segments can then be connected, enabling long-distance entanglement to be established for use in applications such as quantum teleportation and quantum cryptography. However, if the distribution of entanglement in each segment is probabilistic, the chance of success falls exponentially as the distance increases. This scaling issue is also present in local networks in which many modules need to be combined and entangled.

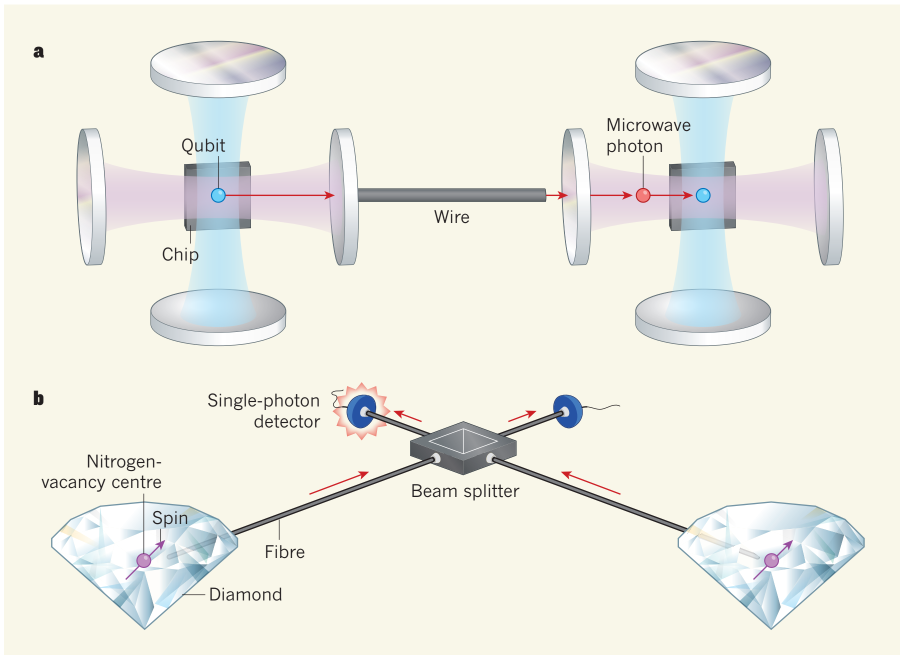

Figure 1 | Entanglement delivered on time. Kurpiers *et al.*[1] and Humphreys *et al.*[2] report two methods for distributing entanglement — or non-classical correlations — between distant nodes of a quantum network in a deterministic fashion. **a**, In Kurpiers and colleagues' experiment, the two nodes consisted of superconducting quantum bits (qubits) that were fabricated on separate chips. Entanglement was generated by a highly efficient process comprising the emission of a microwave photon from one qubit and its capture by the other, through a wire. The authors used devices known as microwave cavities (shown as pairs of disks) to prepare and read out the qubit, and to transfer the photon. **b**, In Humphreys and colleagues' experiment, the two nodes were defects known as nitrogen-vacancy centres in diamond. For each node, the spin (magnetic moment) of the nitrogen-vacancy centre was entangled with the presence or absence of an optical photon emitted into a fibre. The two fibres were connected by a device called a beam splitter, and the detection of a single photon (indicated by the flash) projected the two spins into an entangled state. By producing entanglement more quickly than it was lost, the authors turned a probabilistic protocol into a deterministic one.

One way to overcome this limitation is to generate entanglement in a deterministic manner: press a button to get entanglement. This is the landmark advance that Kurpiers and colleagues demonstrate. In their experiment, the quantum nodes consisted of two superconducting qubits that were fabricated on separate chips and then connected by a 90-centimetre-long wire (Fig. 1a). Each qubit was strongly coupled to two devices known as microwave cavities. One cavity enabled the preparation and read-out of the qubit, whereas the other facilitated the transfer of microwave photons through the wire.

Kurpiers and colleagues' demonstration relied on a 20-year-old seminal proposal for directly transferring a quantum state from a sender to a receiver[4]. The authors began by preparing one qubit in a specific state. They then applied microwave pulses to the qubit, which caused it to release a photon that was captured by the other qubit. Because the processes of photon emission and capture can be extremely efficient in superconducting chips, this set-up leads to the distribution of entanglement every 0.02 milliseconds, with an overall fidelity (a parameter that measures how close the entanglement is to the ideal state) of close to 80%. Improvements to the experiment could push this to more than 90%, and error-correction procedures might improve this number even further. Such on-demand generation of entanglement was also reported recently[5] using a different chip implementation from that of Kurpiers and colleagues.

The direct-transfer strategy has also been carried out using optical photons between distant atoms or ions[6]. In that case, reaching high efficiencies of photon emission and capture remained a challenge. But another way to overcome the prohibitive scaling of quantum networks is to turn a probabilistic method into a deterministic one.

Under a probabilistic protocol, each attempt to produce entanglement has a low chance of success. However, if enough attempts are realized in a given length of time, the generation of entanglement can be ensured in this time frame. Such an approach can therefore provide deterministic entanglement at a predetermined time. But there is a crucial requirement for achieving this goal: entanglement must be produced more quickly than it is lost, or else the generated entanglement could be gone before it has been delivered.

In 2015, a trapped-ion experiment succeeded in breaking this threshold[7]. Humphreys and colleagues have now achieved the same feat using a solid-state system. In their work, the two quantum nodes were single defects, known as nitrogen-vacancy centres, in diamond (Fig. 1b). The authors placed diamonds in cooling devices that were separated by a distance of 2 metres. They then generated entanglement between the spins (magnetic moments) of the nitrogen-vacancy centres by adopting a 'heralded' technique that has been used for other platforms and has enabled rudimentary versions of quantum-repeater segments[8,9].

Humphreys *et al.* prepared the two nodes so that they had an identical spin state. For each system, the authors used laser pulses to generate entanglement between the spin of the nitrogen-vacancy centre and the presence or absence of an optical photon emitted into a fibre. The fibres from both systems were connected, and the detection of a single photon midway between the nodes projected the two spins into an entangled state. This is because there was no way of knowing, even in principle, from which node the photon was emitted. This single-photon scheme was one of two key ingredients of the authors' work: it enabled a much higher rate of entanglement production than could be achieved in a previous study[10] using nitrogen-vacancy centres that relied on a two-photon process.

The second key ingredient was a dramatic extension in the lifetime of the stored entanglement to a period of hundreds of milliseconds. The authors achieved this by protecting the stored state after it was produced. Overall, the combination of the two ingredients enabled entanglement to be generated almost ten times faster than it was lost. Thanks to this achievement, Humphreys and colleagues demonstrated a deterministic delivery of entanglement roughly every 100 milliseconds.

The long-awaited advances of these two research groups demonstrate that the prospect of realizing functional quantum networks — either on the local scale between superconducting modules or on a larger scale between communication nodes that are connected by optical fibres — is getting closer to reality (see *Nature* **554**, 289–292; 2018). The numbers still need to be improved; in particular, the rate at which long-distance entanglement can be delivered remains too low for practical applications. However, an increase by a factor of about 100 should be achievable in the near future.

To demonstrate large-scale and long-haul quantum networks, a combination of techniques and tools will be necessary. Among other methods, complementary approaches that rely on ensemble-based quantum memories are being developed at a fast pace[11]. When combined with massive multiplexing in time, frequency or space — a process that has been necessary for the development of the Internet — these methods should be able to provide entanglement at a high rate.

Another important goal will be the realization of an efficient quantum converter that links microwave photons to optical photons[12]. Such a device should enable the platforms used in these two studies, which have different capabilities, to be connected. Putting these blocks together will be a tremendous challenge for science and engineering, but it promises to lead to versatile networks in which quantum processors are interconnected through a quantum-communication web. ■

Julien Laurat *is at the Laboratoire Kastler Brossel (Sorbonne Université, CNRS, ENS, Collège de France), Sorbonne Université, Campus Pierre et Marie Curie, 75005 Paris, France.*
e-mail: julien.laurat@sorbonne-universite.fr

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IMMUNOLOGY

Tumour tamed by transfer of one T cell

The T cells of the immune system can be engineered to target a tumour, but why some people respond better than others to such therapy is unclear. One patient's striking response to treatment now offers some clues. See Letter p.307

MARCELA V. MAUS

The use of genetically engineered immune cells to target tumours is one of the most exciting current developments in cancer treatment. In this approach, T cells are taken from a patient and modified *in vitro* by inserting an engineered version of a gene that encodes a receptor protein. The receptor, known as a chimaeric antigen receptors (CAR), directs the engineered cell, called a CAR T cell, to the patient's tumour when the cell is transferred back into the body. This therapy can be highly effective for tumours that express the protein CD19, such as B-cell acute leukaemias[1,2] and large-cell lymphomas[3,4]. However, some people do not respond to CAR T cells, and efforts to optimize this therapy are ongoing. On page 307, Fraietta *et al.*[5] report the fortuitous identification of a gene that positively affected one person's response to treatment with CAR T cells.

Therapies involving engineered immune cells use viral vectors based on retroviruses or lentiviruses to insert a DNA sequence, such as one encoding a CAR, into a person's T cells. However, given that there is no control over where the sequence inserts into the genome, it is possible that the engineered gene could insert at a location that disrupts another, important gene. In the early 2000s, a clinical trial[6] enrolled people with immunodeficiencies arising from the lack of a functional copy of a particular immune gene. The trial used viral vectors to insert a wild-type copy of this gene into their stem cells. Unfortunately, however, several people developed uncontrolled T-cell proliferation that evolved into T-cell leukaemia. This event was linked[7] to the gene inserting within the sequence of the *LMO2* gene, disrupting the normal regulation of *LMO2*.

The pattern of genomic integration sites for various viral vectors has been found to be specific for a given combination of vector