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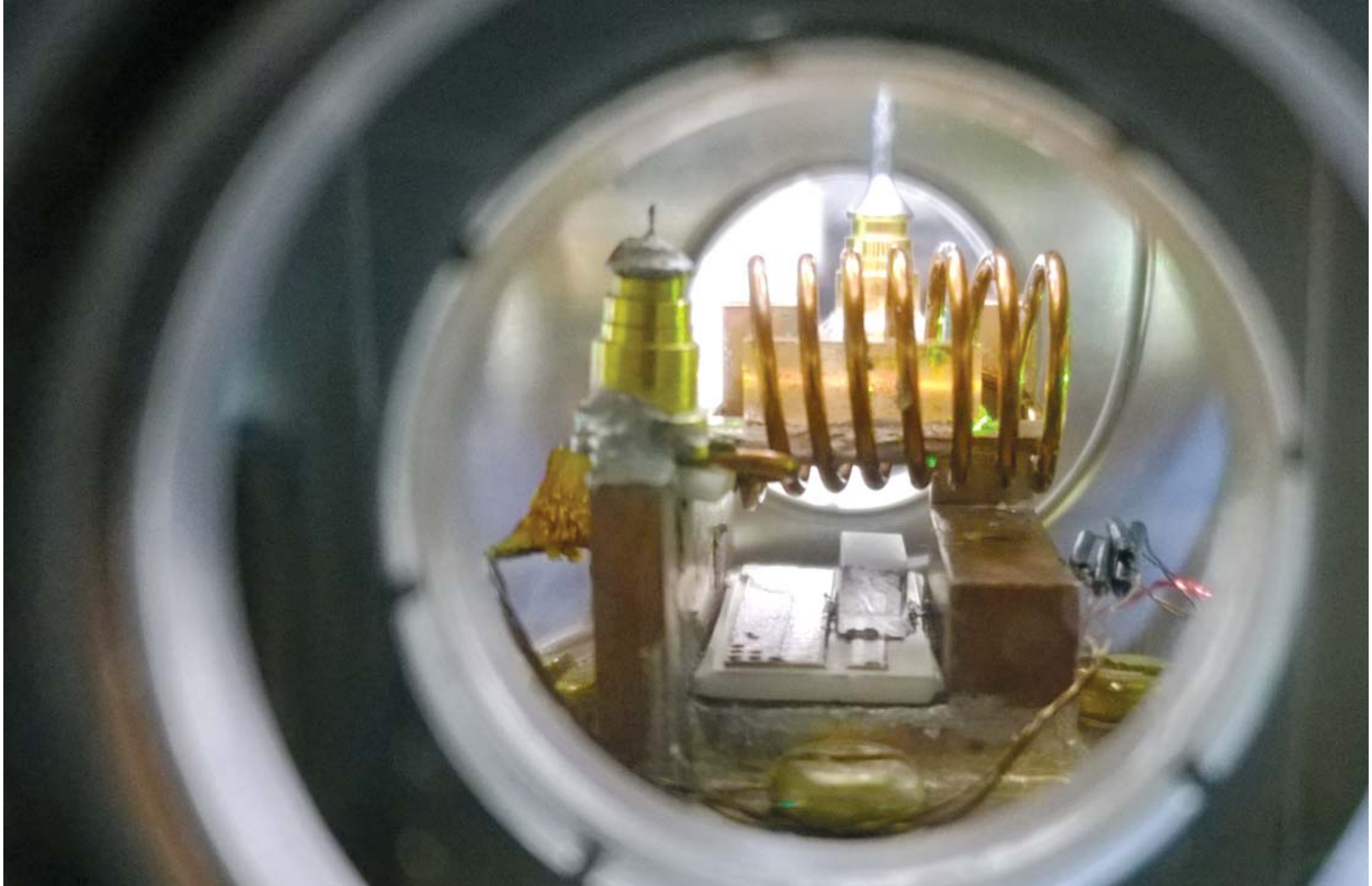

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The quantum state of a photon can be transferred to a single trapped atom or to a bunch of atoms in a gas or solid and be stored for later release on demand.

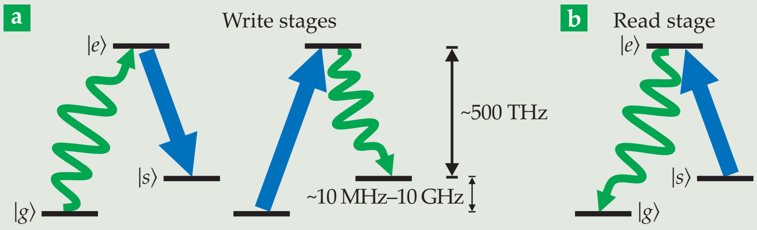
Communication through optical fibers has revolutionized the way people access information and has given rise to the network of connected computer nodes known as the internet. The photons that traverse the fibers are also nearly ideal carriers of quantum information: They are easy to entangle in polarization, amplitude and phase, or other degrees of freedom; they are easy to detect; and they can propagate quickly over large distances with little attenuation. Today physicists are developing the technologies needed for a quantum version of the information network, which might be used for, among other applications, long-distance cryptography, distributed quantum computing, and remote sensing.

Still in their infancy, the building blocks for those ambitions include compact sources of entangled pairs of single photons, efficient single-photon detectors, and devices that are able to manipulate the frequency and shape, both spatial and temporal, of the coherent wavepackets carried by single photons from node to node (see the article by Michael Raymer and Kartik Srinivasan, PHYSICS TODAY, November 2012, page 32). Quantum memories, another key building block, would act as the nodes where the photons—or rather, their quantum states—are temporarily stored while the system completes some other processing in the network.

One can define a quantum memory as a stationary device that can take a fragile quantum state—in our case, a quantum state encoded onto a single photon—and preserve it in time. Because photons can be lost en route through optical fibers, several trials may be needed to successfully establish a link between two nodes. And once established, the quantum processes that may take place—a computation using a qubit logic gate, say—often do so

Mikael Afzelius and **Nicolas Gisin** lead the applied physics group at the University of Geneva; **Hugues de Riedmatten** is an ICREA Professor in quantum optics at the Institute of Photonic Sciences in Barcelona, Spain.

Box 1. Storing a single photon in an atom



In its simplest form, a quantum memory can be represented as an atom with three internal states $|g\rangle$, $|s\rangle$, and $|e\rangle$ whose energy-level structure resembles the letter Λ and that interact with two optical fields—a weak signal that carries the quantum information and a strong control field that determines which energy state stores it. The atomic states $|g\rangle$ and $|s\rangle$ are often electron spin states closely spaced in energy, on the frequency scale of microwaves, whereas $|e\rangle$ is a highly excited state whose energy corresponds to a photon in the optical (terahertz) spectrum.

Panel a shows two writing processes for an atom initially in its ground state $|g\rangle$. An incoming photon (green) can be stored via absorption in the atom while a strong control pulse (blue) is applied at the same time. As its name implies, the control field steers, or writes, the single photon into the atom's state $|s\rangle$, where it is stored. Alternatively, the control pulse can excite the atom from $|g\rangle$ to $|e\rangle$, which triggers the spontaneous emission of a photon along with the storing of an excitation into state $|s\rangle$. In that second type of write stage, no input photon is required (see figure 1).

In both cases, the stored excitation can later be read out using another control pulse, which converts the excitation into an optical photon emitted by the atom, as illustrated in panel b. The basic scheme represented in these write and read stages can be extended to provide more functionality. For instance, two spin states with different spin quantum numbers can be used as qubits to store photons in superpositions of different polarizations.

probabilistically. Accordingly, a network without memories would quickly become inefficient as it grows in size. One can therefore think of a quantum memory as akin to cache memory in a classical computer's central processing unit—that is, as the short-term memory used to increase the speed of the CPU—as opposed to the permanent memory of a hard drive. But a quantum memory should be able to store fragile superposition states and entanglement, whereas a normal cache memory only stores classical bit values.

Optical quantum memories can synchronize the various parts of the network. But to do so, they must fulfill certain requirements. The transfer of information between nodes introduces delays due to the finite speed of light. The storage time must be commensurate with those delays. Internode distances could range from hundreds of meters inside a building to thousands of kilometers across a continent; the storage times would therefore range from less than a microsecond to more than 10 milliseconds. Longer storage times, on the scale of a few seconds, will certainly be required to build complex, large-scale quantum networks.

Other requirements are independent of network size. The memory should fail as little as possible (high efficiency), and the read-out state should be as similar as possible to the stored state (high fidelity). It has turned out to be very challenging to achieve all the requirements in one device.

Storing light

How does one stop a photon to encode or access its quantum state? As already mentioned, light is a great information carrier because it can travel far and fast. In the best telecommunications fibers, as much as 30% of the photons remain in the fiber after 30 km of propagation; that's a loss of just 0.16 dB/km. One approach for a quantum memory is to send the photon into a stationary fiber loop using an optical switch that can contain the photon and release it on demand. Unfortunately, close to 50% of the photons in the fiber can be lost each time a light pulse passes the switch, irrespective of whether the switch is open or closed. Those losses prevent the formation of an efficient memory for more than a few tens of microseconds.

The techniques being investigated today are mostly based on transferring the quantum state carried by the photon into an excitation created in some kind of matter system, as outlined for a generic system in figure 1 and for an atom in box 1.[1] The goal is to make the excitation as controlled and coherent an interaction as possible in a system where the stored quantum state can be sufficiently protected from a noisy environment. To achieve that goal, physicists are exploring a wide range of materials, including laser-cooled gases and trapped atoms, impurity-doped crystals, semiconductor materials, and optomechanical systems (see the article by Markus Aspelmeyer, Pierre Meystre, and Keith Schwab, PHYSICS TODAY, July 2012, page 29).

As figure 1 illustrates, a quantum memory can interact with light in different ways. Some quantum memories absorb a single photon, which often is entangled with another one. In most cases the photon is later retrieved at some chosen time, which makes the system a reversible, read–write memory. But in some cases the photon is left in the memory, possibly for later processing there, making the system a write-only memory. Still other memories spontaneously emit a single photon that is entangled with

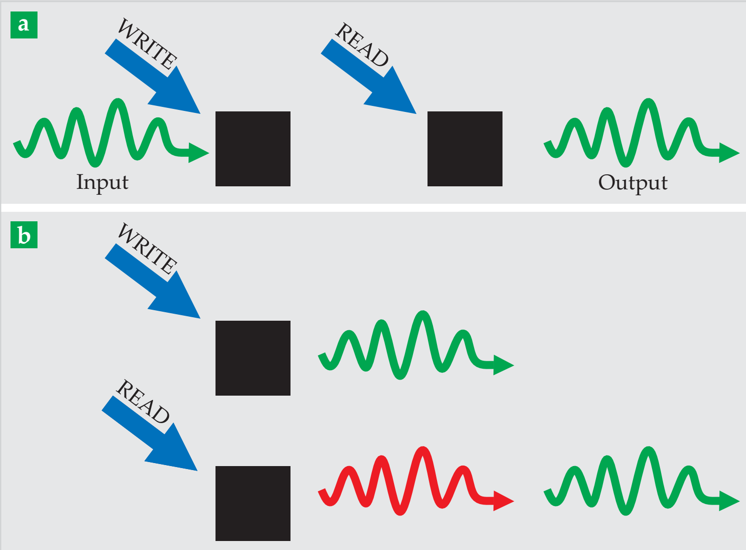


Figure 1. Optical quantum memories in a nutshell. (a) In most quantum memory schemes, an incoming photon (green) is written into some matter system (the black box) using a strong laser pulse (blue). The laser pulse maps the photon's state onto some internal degree of freedom, such as spin, of the system. (To see how that mapping works on the atomic level, see box 1.) The memory can then be read out using another laser pulse. The reversibility of the process—write and read pulses can be the same kind of laser field—makes the memory a so-called read–write memory. **(b)** Another common type of quantum memory uses a strong laser pulse (blue) to excite the matter system—no separate input photon is required. A single photon (green) that is entangled with the stored excitation is then emitted. With a second laser pulse, the stored excitation can be read out, after some delay, as another single photon (red). The scheme, which produces a pair of entangled photons separated in time, is called a read-only memory.

the quantum state left behind in the memory. The stored excitation can later be converted into another single photon, such that the two emitted photons form an entangled pair. What makes that approach, known as a read-only memory, attractive for the practical implementation of a quantum network is that it combines an entanglement source with a memory function in a single device.

Enhancing the light–matter interaction

The probability of successfully writing and reading a quantum state into and out of memory depends on the strength of the light–matter interaction. Although a single atom has natural appeal and conceptual simplicity as a quantum memory for a single photon, the interaction between the two is usually extremely weak. One way to improve it is to place the atom in an optical cavity, as shown in figure 2a. Light shining into the cavity repeatedly reflects from its mirrors, and the potentially thousands of round-trips made by even a single photon can dramatically increase the absorption cross section to essentially unity. Since the first demonstration of strong coupling in the optical regime by Jeff Kimble's group at Caltech a quarter century ago, the approach, known as cavity quantum electrodynamics, has enabled impressive progress. And recently Gerhard Rempe and his group at the Max Planck Institute of Quantum Optics in Garching, Germany, created an efficient read–write quantum memory using a single rubidium atom trapped inside an optical cavity.[2]

Another, opposite approach is to use a large collection of atoms to absorb the single photon, as illustrated in figure 2b. Think of the atoms, all initially prepared in their ground state, as in a large superposition, in which each atom has a small probability amplitude of having absorbed the photon. The state of the photon is thus delocalized, shared by all the atoms in the ensemble. That collective state is not only fascinating but also useful because it can be converted efficiently back into a single photon with a well-defined direction, provided one can reverse the absorption process and eliminate potential dissipation and dephasing of the collective state. Box 2 describes two popular methods for achieving that reversal process in practice. The high read-out efficiency—defined as the intensity ratio of the retrieved signal to the input signal—scales with the number of atoms in the ensemble and arises from their constructive interference.

In 2003 Kimble's group first demonstrated the effect, known as collective enhancement, in a read-only memory.[3] Eugene Polzik (Niels Bohr Institute) and colleagues followed with a write-only memory the next year using a weak laser pulse consisting of few photons.[4] And shortly afterwards, the groups of Alex Kuzmich (then at the Georgia Institute of Technology) and Mikhail Lukin (Harvard University) produced read–write quantum memories for single-photon states.[5] Since then, several groups have worked toward increasing the efficiency of ensemble-based memories, for both read–write and read-only types. The current efficiency records for each type are around 80%, obtained by the groups of Benjamin Buchler (Australian National University), Ite Yu (National Tsing Hua University), Philippe Grangier (CNRS), and Jian-Wei Pan (Hefei National Laboratory). All those experiments were based on cesium and rubidium vapor.

In 2008 our group in Geneva demonstrated that solid crystals doped with rare-earth ions present an interesting and promising alternative kind of memory.[6] (The photograph on page 42 shows an example: europium-doped yttrium silicon oxide, sitting inside an RF coil and fluorescing in response to a yellow laser beam incident along the long axis.) As a frozen ensemble of ions trapped in the crystal lattice, the rare-earth ions are photon absorbers with great coherence properties at low temperature because the ions couple so weakly to the crystal lattice, a feature that Matthew Sellars and colleagues from the Australian National University exploited five years ago[7] to realize 69% efficiency in a read–write memory (see PHYSICS TODAY, August 2010, page 13). At the time, that was a four-fold efficiency increase over any previous read–write memory based on atomic vapors.

Both cavity and ensemble approaches have advantages and drawbacks. A single atom can be made to interact with other atoms in a controllable way, such that one can envision making quantum gates and other joint operations with neighboring nodes. Researchers have also shown that single-atom memories can achieve what's known as heralded

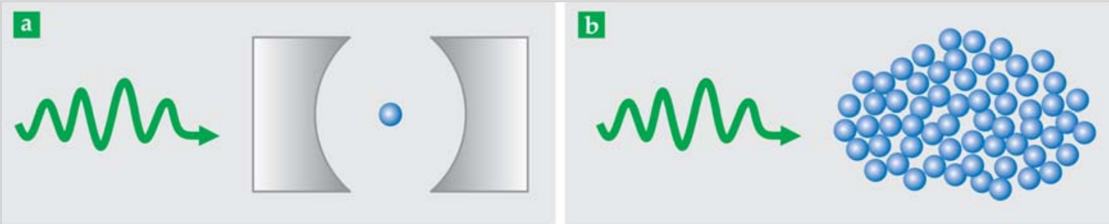


Figure 2. Enhancing the light–matter interaction. Two different approaches ensure that a single photon strongly couples to an atom (or atoms), which is essential to form an efficient memory. **(a)** One approach is to place a single atom in a highly reflective optical cavity. The thousands of round-trips experienced by an entering photon can increase its absorption probability to near unity. **(b)** In the other approach, called collective coupling, the photon makes a single pass through an ensemble of atoms. The light–matter coupling increases with $\sqrt{N}$, where N is the number of atoms.

storage, a situation in which the detection of one photon reveals, or heralds, that a memory has been successfully charged with a stored excitation. Both features lend new powerful network functionalities. On the downside is the technical difficulty of trapping a single atom and making the high-quality mirrors required for optical cavities. Moreover, the quantum state encoded into a single atom is sensitive to dephasing by the ambient environment.

The collective state in an ensemble of atoms, on the other hand, is more robust to environmental dephasing. Another advantage is the opportunity that a large ensemble provides for storing multiple photons in a single memory. On the downside, it is difficult (though not impossible) to make controlled interactions between ensemble-based quantum memories.

Lifetime

A quantum state is stored in memory as a superposition between matter states—typically two spin states of an atom, as described in box 1. The time scale on which the superposition state is preserved is called the coherence time. If the spin states are sensitive to magnetic fields—through a Zeeman interaction, for instance—then a fluctuating magnetic field within the sample or in the environment will dephase the superposition, rendering the state incoherent and useless. Scientists encountered the problem decades ago when they were developing accurate atomic clocks with cesium atoms and resorted to magnetic-insensitive spin transitions, now called clock transitions, to avoid the dephasing. Similar techniques are today applied to quantum memories to make the relevant storage transitions between atomic states insensitive, at least to first order, to fluctuating electric and magnetic fields.

Another way to beat fluctuating fields is to isolate the system from its environment using a technique, known as dynamical decoupling, borrowed from nuclear magnetic resonance. Two years ago Thomas Halfmann and colleagues at the Technical University of Darmstadt adopted the approach, in which the nuclear spins of a system are repeatedly flipped to cancel out noise, to store classical laser pulses for up to one minute in a rare-earth-doped crystal.[8] And earlier this year, Sellars and his coworkers achieved an astonishing six-hour coherence time by combining a clock transition and dynamical decoupling in a similar rare-earth-doped crystal.[9] Because neither experiment was performed at the single-excitation level, though, the schemes cannot yet be called quantum memories.

Several obstacles must be overcome before the techniques can be applied to a quantum memory experiment. Noise produced by the dynamical decoupling technique itself becomes relevant when storing single photons but does not impact the conventional spin-coherence measurements used by Sellars and his team. Although we believe that hours-long quantum memory for photons is not an unrealistic goal,[10] quantum memory lifetimes achieved so far are on the order of a few milliseconds for write-only and read–write memories and up to 100 ms for a read-only memory,[11] albeit with an efficiency below 10%. Those lifetimes are close to the useful range even for long-distance quantum networks. A goal for current research is to achieve long memory lifetime and high efficiency in the same device; the rapid progress we have seen in recent years makes us confident it is a realistic goal.

Fidelity

Ideally, the quantum state ρ_{out} of the retrieved photon should be identical to the quantum state $|\Psi_{\text{in}}\rangle$ of the input photon before storage. The fidelity of the storage process is defined as the overlap between the input and output states or, more precisely, $\langle\Psi_{\text{in}}|\rho_{\text{out}}|\Psi_{\text{in}}\rangle$. To qualify as a quantum memory, that fidelity must be higher than the highest fidelity achievable with classical strategies, such as estimating the input state via measurement, writing down the classical result, and re-creating the estimated state when the memory is read. That measure-and-prepare strategy has a limited fidelity that depends on the type of quantum state that is stored. For qubits, such as spin-½ states, the threshold fidelity is ⅔, whereas for continuous variables, such as phase and amplitude, it is ½. Although both qubits and continuous variables can provide entangled states for quantum information, most quantum memory experiments to date have been based on qubit states, for which several groups have demonstrated fidelities around 90%. That's large enough to violate Bell inequalities, the quintessential test of quantum correlations between two spatially separated quantum systems (see the article by Reinhold Bertlmann, PHYSICS TODAY, July 2015, page 40).

The high fidelity attained is essentially because the detection scheme for qubits relies on single-photon counting, and a loss of a qubit-encoding photon from inefficiencies in the system has no impact on the fidelity. Somehow, nature does the error correction for you: Those photons that are not lost retain high fidelity. The detection scheme for continuous variables does not allow such "post-selection" counting of photons, and all losses, including memory inefficiency, reduce the fidelity. Nevertheless, the groups of Polzik, Alexander Lvovsky, Mikio Kozuma, and Buchler have demonstrated storage of light states in the continuous-variable regime and with fidelities higher than any possible classical memory strategy.

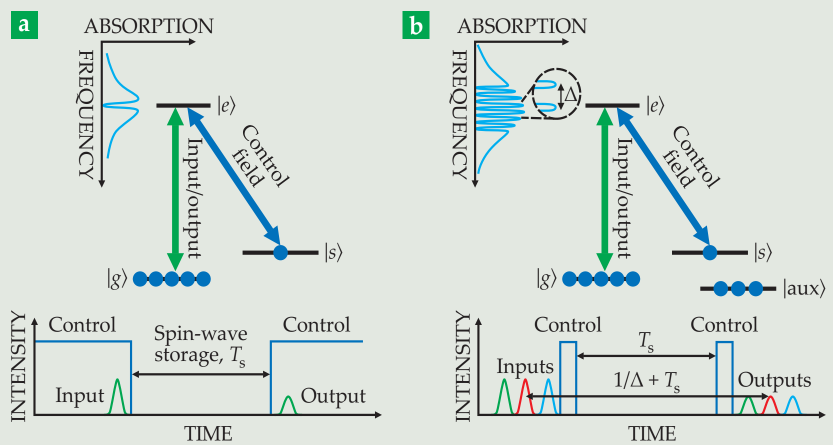
Toward functional quantum networks

To build an eventual quantum-information network, many distant memories must be entangled and exchange information. The basic resource for achieving that ambitious goal is the probabilistic entanglement between photons and quantum memories. The photons carry off their entangled cargo to far-flung parts of the network, forming an elementary link between remote nodes using processes described in figure 3.

The ability to scale small networks into large ones with many links depends on the ability to herald the success of having created the initial entanglement. The heralded detection implies there must be a delay between two successive entanglement trials. For memories separated by large distances, that delay, which corresponds to the travel time between the memories, represents a significant limitation that will lead to prohibitively low entanglement rates. Fortunately, the problem can be solved using memories capable of storing tens or hundreds of qubits in distinguishable modes.[12] Ensembles of atoms that store information using spatial, temporal, or frequency multiplexing can do just that (see box 2).

Several groups have now published schemes for heralded entanglement between distant quantum memories. The groups led by Kimble and Pan performed the first demonstrations of one-link quantum networks composed of cold-atom ensembles.[13,14] Our own group and that of Wolfgang Tittel at Calgary University demonstrated entanglement

Box 2. Slow light and memory



In panel a, when a strong laser beam (the control field, dark blue) shines on an ideally homogeneous ensemble—one in which all the atoms have identical absorption frequencies—it creates a narrow transmission window in the ensemble's absorption spectrum (light blue) at the frequency corresponding to the energy difference between states $|g\rangle$ and $|e\rangle$. The atoms (dots), whose energy levels are $|g\rangle$, $|s\rangle$, and $|e\rangle$, are initially in their ground state $|g\rangle$. Thanks to the laser beam's effect, known as electromagnetically induced transparency, an input photon with a frequency spectrum comparable to the transmission window is abruptly slowed and spatially compressed in the medium (see the article by Stephen Harris, PHYSICS TODAY, July 1997, page 36).

When the compressed signal is inside the ensemble, the control field can be turned off, which causes the window to collapse and converts the single photon into a coherent atomic spin excitation called a spin wave. To retrieve the signal as an output photon a time T_s later, one simply reverses the process and turns the control field back on.

Electromagnetically induced transparency of a homogeneous ensemble is an excellent method for storing a single pulse; for one thing, it eliminates the effect of dissipation in the excited state $|e\rangle$. However, because any photons must be compressed inside the memory before the control field is turned off, the method is inadequate for storing a train of single photons. As depicted in panel b, ensembles in which the resonant frequencies of the atoms differ are said to be inhomogeneous broadened and do a far better job storing trains of single photons. Using materials such as rare-earth ions doped into a crystal, one can store the Fourier spectrum of the input pulse sequence because the frequency information is stored by the atoms at different resonance frequencies, without the need for spatial compression.

The inhomogeneous spectrum also leads to fast dephasing. One way to compensate for that coherence loss is to shape the absorption spectrum into a periodic grating, or atomic frequency comb,[6] using optical-pumping techniques. The pumped-away ions are put into the auxiliary state $|\mathrm{aux}\rangle$. A single input photon with a spectrum broader than the frequency spacing Δ between the teeth of the comb can be entirely absorbed by the comb. And thanks to the grating, the ions are all back in phase after a time $1/\Delta$. One might think that the incoming photon is likely to pass between the teeth, but the absorption process is so fast that the photon has no time to "see" that fine structure, thanks to the energy–time uncertainty relation, which makes full absorption possible.

After the photon has been absorbed, but before the rephasing occurs, a strong control pulse transfers the coherence from the excited state to a long-lived spin state.[10] To read out the memory a time T_s later, a second control pulse transfers the coherence back to the excited state and the rephasing process continues and leads to an output. (The photon is thus stored for a time $1/\Delta$ in $|e\rangle$ and a time T_s in spin state $|s\rangle$.) If a train of input photons (green, red, and blue) has been stored, the output will consist of an identical train of pulses.

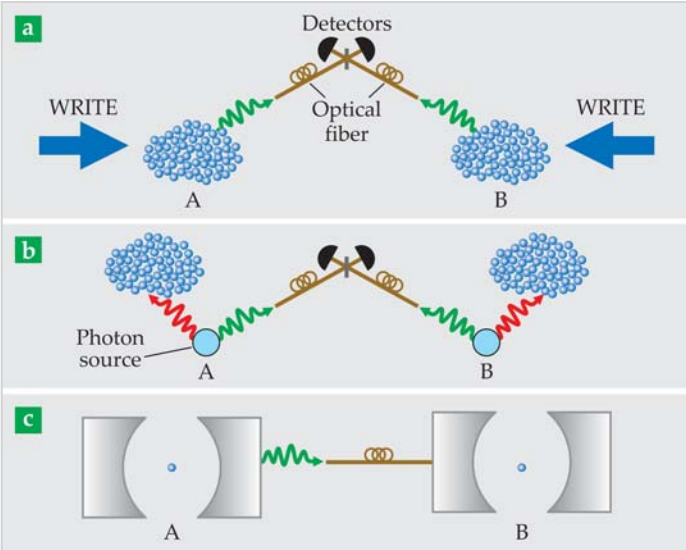


Figure 3. Linking distant quantum memories. Remote memories can be entangled by the quantum interference of photons that propagate from them. **(a)** At each site A and B, the read memory emits a photon entangled with the ensemble's collective spin excitation. The remote photons travel via optical fiber (brown) and arrive together at a beamsplitter (silver), which erases the information about their separate origins. The photons' detection after the beamsplitter heralds the entanglement of the remote memories.[13,14] **(b)** Sources A and B emit a photon pair: one (red) absorbed by the nearby read–write memory, the other (green) a photon sent to a beam splitter. As in panel a, the mixing of photons through the beam splitter and their subsequent detection project the two memories into an entangled state. **(c)** An atom in an optical cavity emits a photon entangled with the atom's quantum state. The photon is then transmitted to a second, distant atom, which absorbs it and stores its quantum state. The transmission transfers the light–atom entanglement into an entanglement between distant atoms.

between a telecommunications-wavelength photon and a rare-earth-doped crystal[15] as well as the teleportation of a qubit into a quantum memory over 25 km of optical fiber.[16] And still other groups have created quantum-network links between single atoms or ions.[17]

As mentioned in the introduction, researchers are exploring alternative materials in which to store photon states. So-called nitrogen-vacancy centers in diamond behave like artificial atoms, making them a prime candidate for implementation as a quantum memory in a solid-state environment (see reference 18 and the article by Lilian Childress, Ronald Walsworth, and Mikhail Lukin, PHYSICS TODAY, October 2014, page 38). Semiconductor quantum dots are another candidate and have already been demonstrated as a viable light–matter interface. But although the dots exhibit very strong optical transitions, which allow stored qubits to be quickly manipulated, they unfortunately suffer from short coherence times. Optomechanical resonators also seem promising: As they do not rely on sharp atomic transitions, the resonators could lead to quantum memories with tunable operation wavelengths.

Outlook

Researchers have made spectacular progress this past decade in the realization of quantum memories and have learned a lot about the physics of light–matter interactions at the single-photon level. Although essentially every optical-quantum-memory parameter, including efficiency, lifetime, and fidelity, has been demonstrated with values close to those required for real-life applications, we have a long way to go to build a single practical device that achieves every one. Moreover, it would be fascinating to store an entangled photon on the minute-to-hour time scale perceptible by human beings. That achievement would challenge our notion of entanglement as a state quickly destroyed by environmental interactions.

For the eventual entanglement of many quantum memories required for large-scale networks, researchers will have to develop reliable systems that are easily duplicated and connected to compact light sources. Solids may be more easily incorporated into devices than gases, and one tantalizing approach for local networks could be to integrate them onto the same chip, each connected by a waveguide. Alternatively, one might implement a hybrid system that connects different quantum memories—for example, ensemble based and single-atom based—with different capabilities.

Another emerging field of research is the development of quantum memories capable of storing such exotic states as optical Schrödinger cat states, the coherent superpositions of two states that could even be macroscopic (see the article by Serge Haroche, PHYSICS TODAY, July 1998, page 36). After all, researchers are striving not just for practical devices but to better understand the mysterious boundary between quantum and classical mechanics.

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