mechanics in membrane-bound receptor and protein assays. ❒

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QUANTUM COMPUTING

Three of diamonds

Quantum computers require error correction protocols to repair the state of the quantum bits. This has now been demonstrated using a 'majority voting' protocol among a cluster of three defect spins in diamond.

John J. L. Morton and Jeroen Elzerman

From DNA replication to satellite communication, identifying and fixing errors is an essential part of building robust large-scale systems. Common approaches to error correction make use of redundancy (encoding copies of information across more than one entity) and rely on the fact that multiple errors are less likely to occur than a single error. For error correction in quantum information processors, such redundancy requires control over at least three coupled quantum bits (qubits), which is challenging in many systems. Now Gerald Waldherr and co-workers writing in *Nature* and Ronald Hanson and co-workers writing in *Nature Nanotechnology*, report the use of the spins of defects in diamond along with trace nuclear spins in the host lattice to demonstrate the control required to implement a quantum error correction protocol[1,2].

Qubits are extremely sensitive to disturbances from their environment, often leading to quantum information lifetimes in the millisecond range, or less. To make matters worse, performing a measurement on a qubit destroys the information it represents, ruling out error-handling approaches such as continuously measuring and re-setting the qubit (as happens when dynamic random access memory is refreshed). Practical quantum computing therefore only became a real prospect with the advent of quantum error correction protocols[3,4], which map the quantum state of a 'data' qubit across two further qubits, known as ancillae. Using a procedure analogous to majority voting among the three qubits (Fig. 1), it is possible to correct errors in the data qubit without ever measuring its state, thus leaving the quantum information intact. The errors are effectively filtered off into the ancilla qubits, which are periodically reset.

Nitrogen–vacancy (NV) defect centres in diamond (Fig. 2) are among the most promising systems being investigated as potential qubits. They possess an electronic spin whose state can be initialized and read out optically, even at room temperature[5]. This electron spin interacts strongly with the nuclear spin of the defect's nitrogen atom (^{14}N); however, to find the three or more spin qubits requisite for quantum error correction, one has to look to the

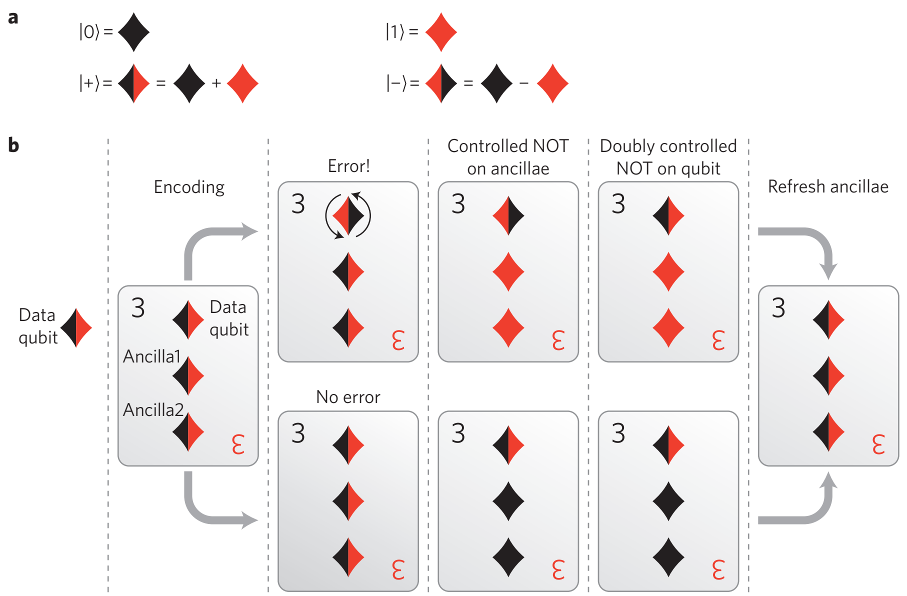

Figure 1 | Schematic representation of a simple three-qubit quantum error correction protocol. **a**, The two qubit basis states |0⟩ and |1⟩ are denoted as a black and red diamond, respectively. The two qubit superposition states denoted |+⟩ and |−⟩ differ only in the phase between the two parts of the superposition. **b**, The error correction protocol is started by encoding the state of a single data qubit onto two additional 'ancilla' qubits. A single phase-flip error can occur on any of the three qubits, changing its state from |+⟩ to |−⟩, but it will most likely leave the other two unaffected (provided errors are uncorrelated and rare). To correct an error on the data qubit, a controlled-NOT operation is performed on the two ancillae, which changes their state from |0⟩ to |1⟩ or vice versa if the data qubit is in state |1⟩. Then a doubly controlled NOT operation is carried out on the data qubit, which changes its state from |0⟩ to |1⟩ if both ancillae are in state |1⟩. This procedure automatically corrects the phase error in the data qubit without performing any error detection measurement. After the ancillae are refreshed to their initial states, the protocol can be repeated.

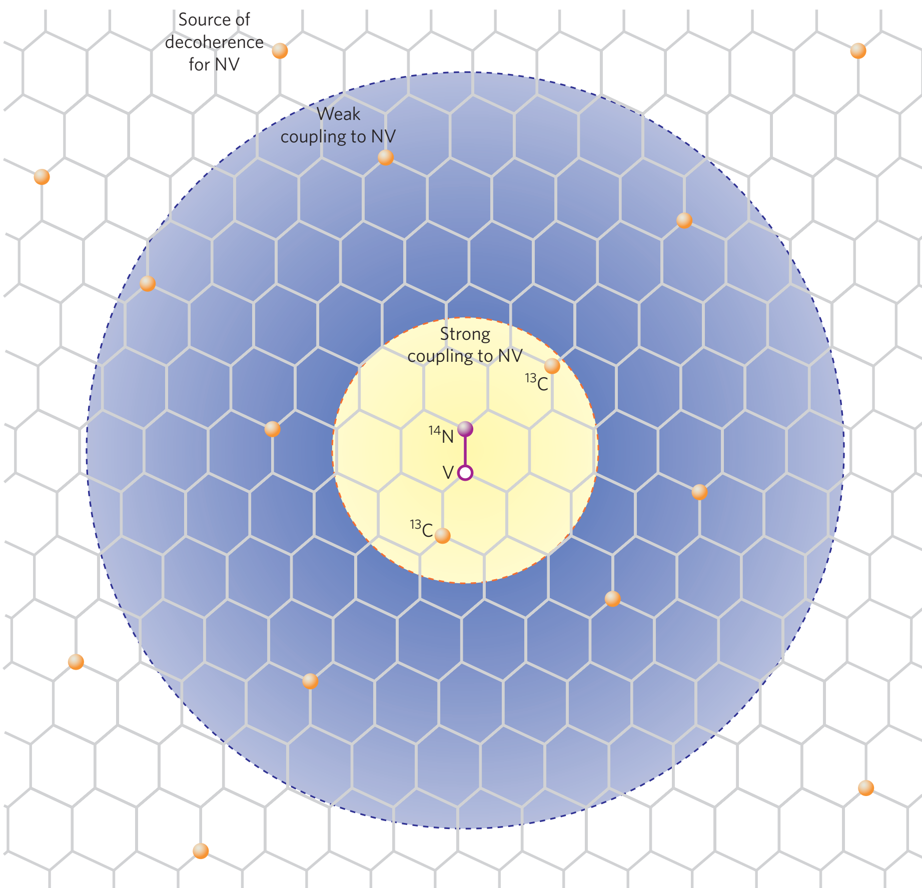

Figure 2 | The NV centre in diamond consists of a substitutional nitrogen atom (N) next to a vacant lattice site (V). Directly associated with the defect are an electronic spin and the spin of the nitrogen nucleus (^{14}N). Additional nuclear spins from the ^{13}C isotope are randomly distributed throughout the host lattice. Nearby ^{13}C spins (within the yellow circle) are relatively strongly coupled to the NV electron spin allowing them to be directly addressed by externally applied excitations, however they are found less frequently. Conversely, distant ^{13}C spins (within the blue circle) are always present around NV centres, but their weak coupling to the electron spin means more elaborate methods are needed to separately control them. In either case, the spins within and around the NV centre have now been shown to form a hybrid quantum register. (The diameter of the blue sphere has been reduced and the natural abundance of ^{13}C in the lattice has been exaggerated for illustrative purposes.)

diamond lattice and use the nuclear spin of randomly distributed ^{13}C isotopes occurring naturally with ~1% abundance.

Waldherr and co-workers — who are based at the University of Stuttgart and other institutes in Germany, China and Japan — found a single NV centre in close proximity to two ^{13}C spins[1]. Together, these form a hybrid quantum register with the three nuclear spins (one ^{14}N plus two ^{13}C) acting as data and ancilla qubits, each individually addressable thanks to their strong hyperfine interaction with the NV centre electron spin. The electron spin was used only to initialize and read the state of the nuclear spins, and to provide fast entangling gates between them[6] (necessary because of their weak direct interaction). These entangling gates were used to demonstrate a simple error correction protocol, designed to correct for single-bit phase flips. As the method relies on finding two ^{13}C nuclear spins within about two unit cells from the NV centre (<0.6 nm) it took some luck and patience to find a suitable register (Waldherr and colleagues characterized a total of almost 3,300 different NV centres). Hanson and co-workers — who are based at Delft University of Technology and Iowa State University — provide a way to bypasss this issue: by not requiring strongly coupled ^{13}C nuclei close by, they were able to work with the first NV centre they found[2].

Distant and weakly coupled ^{13}C nuclear spins cannot be selectively addressed by externally applied radiofrequency excitation, but Hanson and colleagues employed a clever trick: by repeatedly flipping the NV electron spin at a particular frequency, they were able to create an effective oscillating magnetic field in the local vicinity of the defect, capable of picking out a handful of distant ^{13}C spins. Each of these could be subjected to both unconditional gates, as well as gates conditional on the electronic spin state, by judicious choice of the number and frequency of NV flips. As an added bonus, this regular flipping of the electron spin served to further protect it from slowly fluctuating noise sources, by following a technique known as dynamical decoupling[7]. In this way, every NV centre becomes suitable for use in a hybrid register, irrespective of the detailed configuration of nuclear spins in its environment.

Both reported experiments show that a simple quantum error correction protocol can be implemented in diamond. The protocol's effectiveness was tested by letting it correct uncorrelated errors introduced on purpose and with a known probability. Owing to the finite fidelity of all operations, the protocol did not result in a net improvement of the quantum state, except when the introduced error probability was high. Addressing this will require improving the accuracy of the operations, and protecting the nuclear spins from unwanted ionization of the NV centre during optical read out. Perhaps most critically, this error correction protocol works on the assumption that the errors on the different qubits are uncorrelated, yet naturally occurring errors will inevitably display some correlation (for example, a random flip of the electron spin could produce errors on all surrounding nuclear spins). Many of these issues can be addressed by using cryogenic temperatures, where random electron spin flips are less likely, and where resonant optical excitation can be used to avoid accidental ionization.

The error correction protocol demonstrated experimentally by the two research groups was among the first to be proposed for quantum information[3]. Newer models for protecting qubits based on topologically protected surface codes[8,9] possess very high error thresholds, although these come at the expense of increased qubit overheads (for example, a hundred physical qubits representing one logical qubit). Extending the demonstrations shown here to such scales is likely to be infeasible. However, remote NV centres can be entangled through interference of their emitted photons[10], such that each one could be a 'node' in a networked implementation of a surface code[11]. Notably, this model can benefit hugely if the nodes consist of small clusters of coupled qubits, such as those now demonstrated. ❐

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QUANTUM DOTS

Electrifying cavities

A design that allows electrical contacts to be created on semiconductor microphotonic structures brings quantum networks based on semiconductor single photon sources one step closer.

Ruth Oulton

The ideal photonic quantum network would have access to a large supply of single photons. We could imagine a chip that contains a large array of devices, with each of them producing exactly one photon when triggered electrically or optically. Single photons from each source must be indistinguishable in wavelength, polarization and bandwidth[1].

Reporting in *Nature Communications*, Pascale Senellart and co-workers from the Laboratoire de Photonique et de Nanostructures, CNRS, France, Université Paris Diderot, and attocube systems AG, Munich demonstrate a significant step towards the practical realization of an array of single photon sources[2]. They have realized a semiconductor quantum dot (QD) single photon source that allows an electric field to be applied to the QD without impeding the path of single photons.

Self-assembled QDs have long been considered viable practical single photon sources. Each dot can be populated by an electron and a hole, and when these recombine to emit a photon, the QD empties and emits no further photons at the same wavelength until it gets populated again. Key to the success of QD technology is that a QD may be embedded in a distributed Bragg reflector (DBR) cavity structure that allows efficient out-coupling of the photons (Fig. 1). Etching a pillar structure in a DBR confines the light, via total internal reflection, to a small volume. In the past decade, improvements in pillar design and fabrication have allowed physicists to replicate in the solid state many of the cavity quantum electrodynamic effects observed first with atoms. Careful design and fabrication of QD pillars has led to a bright source of identical (indistinguishable) photons[3] and entangled photons[4] ready for integration into a quantum chip.

Further progress in micropillar design has been hampered by the significant difficulties in applying an electric field to the micropillar. Application of an electric field is an important functionality if QDs are to be a viable quantum technology. The self-assembly process produces QDs with almost-perfect quantum efficiency. But it is not possible to control the position at which the QDs form in the pillar, and even knowing the precise location of the QDs is challenging. This makes it difficult to fabricate a pillar with a QD placed in the middle of the cavity. Moreover, the QDs are not homogeneous in size, which means that the light emitted may not match the cavity wavelength exactly. An electric field can be used to fine-tune the photon wavelength, overcoming the problem of size inhomogeneity to produce an array of indistinguishable photon sources.

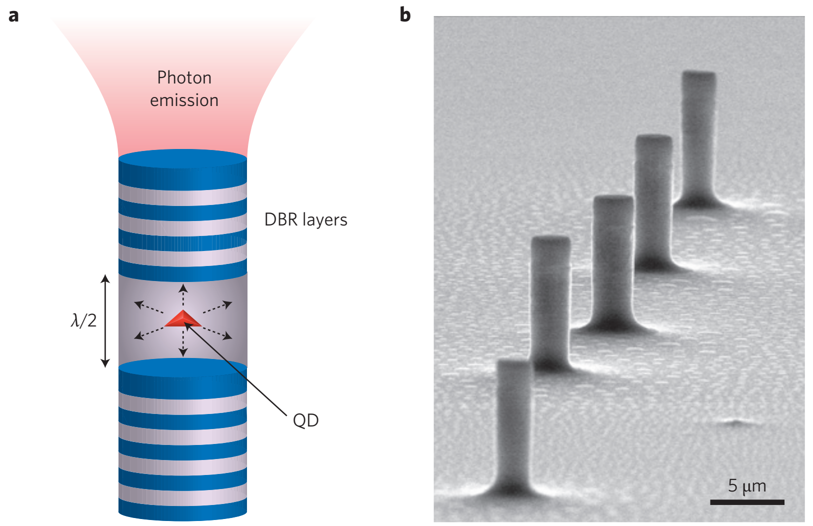

Figure 1 | Dot in a pillar. **a**, Schematic of a QD emitter embedded in the centre of a micropillar cavity. Alternating quarter-wavelength layers of GaAs/AlAs, known as DBRs, cause destructive interference, which allows them to effectively act as mirrors. A GaAs cavity of depth $\lambda/2$ allows confinement of light with wavelength λ, with further confinement achieved by etching the DBR into a pillar a few micrometres in diameter. Individual QDs incorporated in the centre of the cavity are identified spatially and spectrally using spectroscopy, allowing a pillar of a suitable mode wavelength and position to be fabricated. **b**, A scanning electron microscopy image of a set of fabricated micropillars. Panel **b** reproduced with permission from ref. 8, © 2009 AIP.