QUANTUM COMPUTING

# Snapshots of diamond spins

Defects in diamond crystals possess rare physical properties that can enable new forms of technology. Unlocking this potential requires rapid quantum-state measurement, a 'quantum snapshot', which has now been achieved.

John J. L. Morton and Simon C. Benjamin

When Nicéphore Niépce created the first photographic images in the 1820s, each frame required eight hours of exposure. Fifty years later, technology had advanced enough for Eadweard Muybridge's famous demonstration that horses become 'airborne' in mid-stride (see Fig. 1). Photography had become a tool to investigate timescales beyond human perception. Numerous devices now depend on swift measurement, but none more so than the emerging family of quantum technologies. These use measurement not only to read out, but also to prepare and entangle quantum states to create exotic new sensors, simulators and computers. A certain kind of defect that occurs in diamond, the so-called nitrogen–vacancy (NV) centre, is endowed with exceptional physical properties, making it particularly suitable for use in such technologies. But there has been a problem: making measurements on them takes too long. Muybridge's cameras recorded successive images on a timescale that was fast when compared with the horse's motion, but until now the devices monitoring NV centres have not achieved the same. Reporting in *Nature*, two research teams have now demonstrated the ability to take quantum 'snapshots' in rapid succession, thus recording the full state of the NV-centre complex more rapidly than it evolves[1,2].

In diamond, a nitrogen impurity and a vacancy — that is, an absent carbon atom — bind together and trap an additional electron to form the NV centre. It possesses an electron spin coupled to one or more nuclear spins (certainly one of nitrogen, as well as various carbon-13 spins). Having a number of nearby nuclear spins with well-resolved couplings to the electron spin creates a versatile quantum register of multiple interacting qubits (although the couplings to more distant carbon-13 spins become unresolved and contribute instead to line-broadening). NV centres in diamond are particularly exciting because it is possible to measure the electron spin of a single NV through optical methods[3]. This method involves crudely exciting the NV with an indiscriminate optical pulse, and using the fact that the emitted fluorescence intensity has some dependence on the electron-spin state. Although this highly successful technique has underpinned an explosion in research into NV centres, it requires substantial averaging of many experimental runs (or 'shots') to determine the electron-spin state. Achieving fast, high-fidelity measurements requires new approaches to single-spin measurement using NV centres.

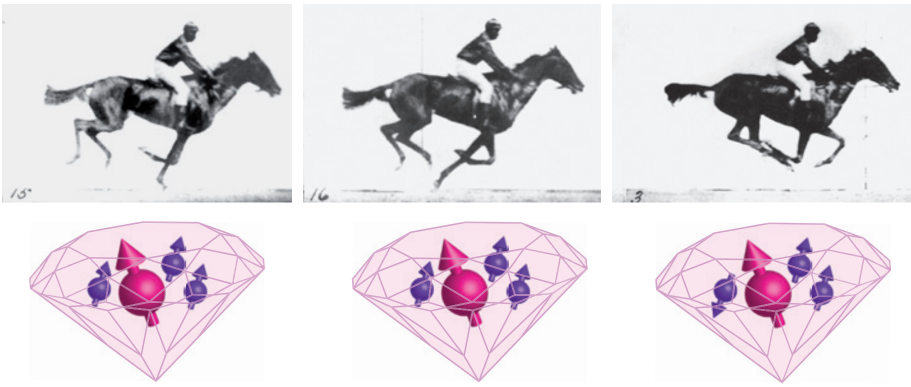

**Figure 1 |** Today, as in 1877 when Eadweard Muybridge photographed a horse in motion, it is crucial to be able to perform measurements that are fast on the timescale of the natural dynamics of an object. This is especially important in emerging quantum technologies given the unique power of quantum measurement. The nitrogen–vacancy defect in diamond consists of a collection of electron and nuclear spins, whose state can now be probed by fast, high-fidelity optical measurement in a single experimental snapshot[1,2]. (Image © Eadweard Muybridge Collection/Kingston Museum/Science Photo Library.)

The past few years have seen significant advances in understanding the nature of the excited state of the NV centre[4], laying the groundwork for more sophisticated optical control. By picking particular NV centres with a low strain and working at liquid-helium temperatures, it is possible to exploit resonant optical techniques to selectively excite the centre only when the electron spin is in a particular state[5]. This form of measurement can be made much faster and more efficient than the previous technique. This has now allowed Lucio Robledo *et al.*[1] to measure the NV electron spin in a single shot for the first time. With their approach they could, also in a single shot, read out the state of up to three nuclear spins in the immediate vicinity of the NV centre. Emre Togan *et al.*[2] borrowed a further technique from the toolbox of trapped atoms, exploiting a phenomenon known as coherent population trapping[6]. In this method, if the magnetic field at the NV centre is precisely zero, the energy levels of the electron spin possess a symmetry that causes them to fall into a 'dark state', which scatters no photons. This measurement is also fast, providing a glimpse of the environment of the NV centre in real time, by monitoring the fluctuating magnetic field created by a bath of more distant carbon-13 nuclear spins.

High-fidelity quantum measurements can do more than just probe the state of a system; they can also be used to initialize it into a given state. Although the result of the measurement may be intrinsically random, the system could then, in principle, be manipulated conditionally on the result of this measurement. This would ensure that the desired initial state is created every time. In practice, such conditional manipulation is technically demanding, and so, instead, typically post-selection of data is used: the same experiment is performed each time but only certain results are kept, corresponding to those attempts where the initial measurement heralded the desired initial state. This powerful technique, termed conditional preparation, has been extensively used, especially in quantum optics[7]. The fast measurements demonstrated by Robledo *et al.*[1] and Togan *et al.*[2] allowed them to conditionally prepare the state of the nuclear spins in the vicinity of the NV centre. There are limitations associated with scaling up such preparation to multiple systems, as the more unlikely the desired input state is, the more experimental runs one has to discard before performing a successful experiment. However, introducing the act of conditional manipulation into a measurement cycle should be feasible for NV spins in future experiments, providing a route to deterministic preparation of spin states.

With the achievement of fast measurement, platforms based on NV centres further establish themselves as a promising building block for quantum technologies. A single NV centre has only a limited capacity for storing and processing information (in the work of Robledo *et al.*[1], there are four quantum bits). This is already sufficient for applications such as sensing magnetic fields. But the more ambitious tasks of simulation, and ultimately general computation, will require far greater capacity. Fortunately, there are emerging ideas for connecting multiple NV centres together within a single crystal[8,9], or resorting once again to the power of quantum measurement to project two distant devices into a mutually entangled state[10]. This profound effect has already been demonstrated for atomic systems[11] and the great progress being made using NV centres[12] indicates that entangling remote centres — perhaps the last key ingredient to enable quantum technologies — now lies within grasp. ❐

*John J. L. Morton and Simon C. Benjamin are in the Department of Materials, University of Oxford, Oxford, OX1 3PH, UK.*
*e-mail: john.morton@materials.ox.ac.uk or simon.benjamin@materials.ox.ac.uk*

## References

1. Robledo, L. *et al. Nature* **477,** 574–578 (2011).
2. Togan, E., Chu, Y., Imamoglu, A. & Lukin, M. D. *Nature* **478,** 497–501 (2011).
3. Jelezko, F. *et al. Appl. Phys. Lett.* **81,** 2160–2162 (2002).
4. Tamarat, P. *et al. New J. Phys.* **10,** 045004 (2008).
5. Togan, E. *et al. Nature* **466,** 730–734 (2010).
6. Santori, C. *et al. Phys. Rev. Lett.* **97,** 247401 (2006).
7. Grangier, P., Roger, G. & Aspect, A. *Europhys. Lett.* **1,** 173–179 (1986).
8. Yao, N. Y. *et al. Phys. Rev. Lett.* **106,** 040505 (2011).
9. Bermudez, A., Jelezko, F., Plenio, M. B. & Retzker, A. *Phys. Rev. Lett.* **107,** 150503 (2011).
10. Benjamin, S. C., Lovett, B. W. & Smith, J. M. *Laser Photon. Rev.* **3,** 556574 (2009).
11. Moehring D. L. *et al. Nature* **449,** 68–71 (2007).
12. Bernien H. *et al.* Preprint at http://arxiv.org/abs/1110.3329 (2011).

Published online: 30 October 2011