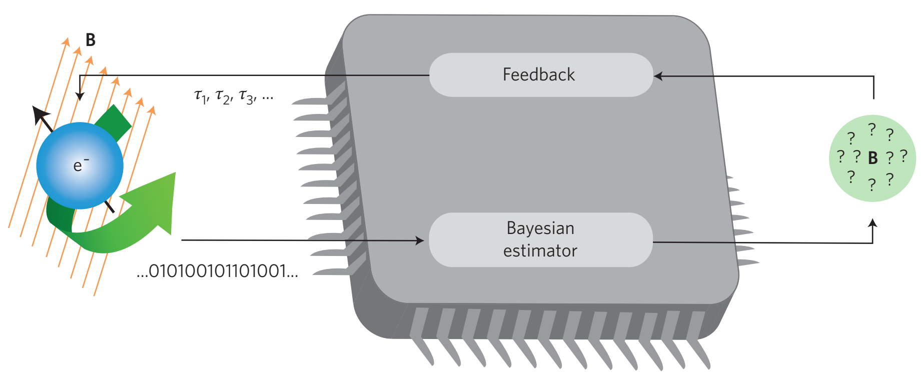


Figure 1 | Sketch of the adaptive protocol. The electron senses the magnetic field, **B**, for some time *t* and acquires a quantum phase. The outcomes of the spin measurements are sent to a microprocessor, which estimates the strength of the magnetic field in real time using a Bayesian estimation algorithm. This estimate is used in a feedback step to calculate the optimal sensing time for the next round (τ_1, τ_2, τ_3). This adaptive process is then repeated several times to improve the estimate of the magnetic field strength.

the spin — to acquire the most amount of information about the field[4]. In a standard procedure, the sequence would be programmed in advance, and the experiment run in one go. The use of a quantum algorithm to optimize the sequence during the experiment itself can be beneficial in this respect. More specifically, the information obtained from early measurements performed on the electron spin can be used to adapt the sensing times for subsequent repetitions to improve sensitivity. Such adaptivity is technically challenging and involves careful scheduling of each step throughout the measuring process. In practice, the outcome of the spin measurement is fed into an algorithm that calculates a Bayesian estimate for the field strength and then uses this estimate to choose a sensing time for the next step (Fig. 1). In the meantime, the electronic spin state must be initialized for this next step, ready to go when needed. By using a dedicated microprocessor to perform the calculation in real time, these two tasks can be processed simultaneously within a fraction of a millisecond, so that the electron is not left waiting idle for its next sensing run.

Hanson and colleagues benchmarked the performance of their sensing protocol both in terms of its scaling with the number of measurements — thus proving that the scheme outperforms any classical protocol that does not exploit quantum behaviour — and also against the best-known non-adaptive schemes. Their adaptive protocol is a clear winner, offering outstanding magnetic field sensitivity.

This work is yet another confirmation that quantum probes can be used for precision metrology. But perhaps the key innovation here is the use of previous measurements to achieve fast, adaptive classical control of the electron's dynamics. Control processes such as this are now ripe for applications in quantum technologies beyond just metrology. In particular, fast adaptive electronics will be needed to perform the quantum error correction believed to be necessary for quantum computers to function. Given that most candidates for quantum technologies operate best at temperatures close to absolute zero, they will require the development of fast and powerful cryogenic electronics integrated closely with compatible, controllable quantum systems[5]. ❐

Stephen D. Bartlett is at the Centre for Engineered Quantum Systems, School of Physics, The University of Sydney, Sydney 2006, Australia.
e-mail: stephen.bartlett@sydney.edu.au

References

1. Maze, J. R. *et al. Nature* **455,** 644–647 (2008).
2. Balasubramanian, G. *et al. Nature* **455,** 648–651 (2008).
3. Bonato, C. *et al. Nature Nanotech.* **11,** 247–252 (2016).
4. Berry, D. W. *et al. Phys. Rev. A* **80,** 052114 (2009).
5. Hornibrook, J. M. *et al. Phys. Rev. Appl.* **3,** 024010 (2015).

Published online: 16 November 2015

QUANTUM INFORMATION

Violation of Bell's inequality in Si

An entangled state of two spin qubits in silicon has been prepared and measured, yielding a violation of Bell's inequality that is the largest achieved in the solid state so far.

Susan Coppersmith

In addition to being the host material of most current electronics, silicon has been demonstrated over the past several years to have excellent properties for quantum information processing devices. Electron spins in silicon that has been isotopically enriched to reduce the fraction of nuclei with non-zero spins to less than 50 parts per million have been measured to have coherence times longer than a second[1]. Over the past few years, single qubits constructed from dopants in silicon with process fidelities exceeding 99.9% have been demonstrated for both electrons associated with phosphorus dopants and from phosphorus nuclei[2,3], which means that the desired quantum transformations are implemented by the gate operations to within 0.1%.

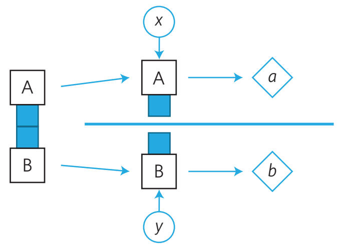
In addition to high-fidelity single-qubit gates, a quantum information processor requires high-fidelity two-qubit gates as well as accurate qubit measurement and initialization. Now writing in *Nature Nanotechnology*, Andrea Morello and colleagues from the University of New South Wales and Keio University report the construction and characterization of a two-qubit device consisting of a single electron spin and single nuclear spin pair, achieving a new record in the amount of quantum nonlocality that is measured[4].

Quantum nonlocality is a key difference between quantum mechanics and classical mechanics[5]. Originally formulated by Bell[6], a relatively intuitive explanation of its remarkable nature is in terms of a game[7] in which two agents, conventionally called Alice and Bob, can consult with each other beforehand, but are then separated and not allowed to communicate during the game. The game starts when Alice is given a number x and Bob is given a number y, each of which is either 1 or 0, and they wish to collectively determine the quantity xy by having Alice report a number a and Bob report a number b that satisfy the equation $a + b = xy$. In the classical world, Alice and Bob can do no better than to output $a = 0$ and $b = 0$ for every x and y, winning the game 75% of the time (which one can check by trying all deterministic strategies). But in the quantum world, Alice and Bob can each take half of an 'entangled Bell pair of qubits' (specifically, spins in the quantum state $(|00\rangle + |11\rangle)/\sqrt{2}$) before they separate, and they can win the game with probability $\cos^2(\pi/8) \approx 0.85$.

Box 1 illustrates the protocol and shows explicitly that it enables the game to be won with higher probability than with classical rules because the result of Alice's measurement depends on Bob's choice of rotation and vice versa. The remarkable nature of quantum nonlocality as predicted by quantum mechanics is well verified by experiments[8–13], including recent loophole-free demonstrations in which Alice and Bob are separated by a time small enough and distance large enough to forbid intercommunication between their measurements[14–16].

Alice and Bob's strategy yields the largest probability of winning, or, equivalently, the largest nonlocality, when they share a perfect Bell state and do all rotations and measurements without error. Experimental imperfection in any of the steps of the protocol reduces the probability of winning. The work reported by Morello and colleagues is performed on a proximate electron–nuclear spin pair. While it does not explicitly demonstrate nonlocality, it achieves a new record in the winning probability, without relying on any assumptions about whether detected events are typical, because the detection efficiency of the experiment is very close to unity. Their result is reported as the value of a quantity S, which is related to the probability of winning, p_{win}, by $S = 4(2p_{win} - 1)$. The largest value of S obeying locality is 2, and the largest value of S achievable within quantum mechanics is $2\sqrt{2} \approx 2.83$. Morello and colleagues report $S = 2.70 \pm 0.09$, which is substantially larger than previous reports in the literature, which all yielded values less than 2.5 (refs 8–16). Morello and colleagues' success in optimizing their experiment to achieve this impressive value is yet another piece of evidence that silicon spin quits are an extremely promising platform for the development of quantum information processing devices. ❐

Box 1 | Using a Bell pair to help win a nonlocal game.



Inputs x	Inputs y	Desired $a + b$
0	0	0
1	0	0
0	1	0
1	1	1

Alice (A) and Bob (B) can share information before the start of the game (above diagram), but they are then separated and cannot communicate (horizontal line). Alice is then given x and Bob is given y. Alice outputs a and Bob outputs b. Alice and Bob win the game if $xy = a + b$ (above table). The best classical strategy is for Alice and Bob to output $a = 0$ and $b = 0$, winning the game with probability 0.75.

By sharing a Bell pair before the start of the game, Alice and Bob can win a nonlocal game with higher probability than the 75% that is achievable classically. Their optimal strategy is:

For Alice
If $x = 0$, measure qubit and report a = result of the measurement.
If $x = 1$, rotate qubit by $\pi/4$ (a rotation by θ transforms the state $|0\rangle \rightarrow \cos\theta|0\rangle + \sin\theta|1\rangle$ and the state $|1\rangle \rightarrow -\sin\theta|0\rangle + \cos\theta|1\rangle$), measure it, and report a = result of the measurement.

For Bob
If $y = 0$, rotate qubit by $-\pi/8$, measure it, and report b = result of the measurement.
If $y = 1$, rotate qubit by $+\pi/8$, measure it, and report b = result of the measurement.

This quantum strategy yields the results shown below; Alice and Bob win the game with probability $\cos^2(\pi/8) \approx 0.85$. The nonlocality is manifest by the dependence of the result of a measurement by Alice on Bob's choice of measurement axis and vice versa.

Inputs		Probability of output				Probability that $a + b = xy$
x	y	$a = 0, b = 0$	$a = 1, b = 0$	$a = 0, b = 1$	$a = 1, b = 1$	
0	0	$\cos^2(\pi/8)/2$	$\sin^2(\pi/8)/2$	$\sin^2(\pi/8)/2$	$\cos^2(\pi/8)/2$	$\cos^2(\pi/8) \approx 0.85$
1	0	$\cos^2(\pi/8)/2$	$\sin^2(\pi/8)/2$	$\sin^2(\pi/8)/2$	$\cos^2(\pi/8)/2$	$\cos^2(\pi/8) \approx 0.85$
0	1	$\cos^2(\pi/8)/2$	$\sin^2(\pi/8)/2$	$\sin^2(\pi/8)/2$	$\cos^2(\pi/8)/2$	$\cos^2(\pi/8) \approx 0.85$
1	1	$\sin^2(\pi/8)/2$	$\cos^2(\pi/8)/2$	$\cos^2(\pi/8)/2$	$\sin^2(\pi/8)/2$	$\cos^2(\pi/8) \approx 0.85$

Susan Coppersmith is in the Department of Physics, University of Wisconsin, Madison, 1150 University Avenue, Madison, Wisconsin 53706, USA.
e-mail: snc@physics.wisc.edu

References

1. Tyryshkin, A. M. *et al. Nature Mater.* **11,** 143–147 (2012).
2. Muhonen, J. T. *et al. Nature Nanotech.* **9,** 986–991 (2014).
3. Muhonen, J. T. *et al. J. Phys. Condens. Matter* **27,** 154205 (2015).
4. Dehollain, J. P. *et al. Nature Nanotech.* **11,** 242–246 (2016).
5. Brunner, N. *et al. Rev. Mod. Phys.* **86,** 419–478 (2014).
6. Bell, J. *Physics* **1,** 195–200 (1964).
7. Cleve, R. *et al.* in *Proc. 19th IEEE Annu. Conf. Computational Complexity* 236–249 (IEEE, 2004).
8. Freedman, S. J. & Clauser, J. F. *Phys. Rev. Lett.* **28,** 938–941 (1972).
9. Rowe, M. A. *et al. Nature* **409,** 791–794 (2001).
10. Matsukevich, D. N., Maunz, P., Moehring, D. L., Olmschenk, S. & Monroe, C. *Phys. Rev. Lett.* **100,** 150404 (2008).
11. Ansmann, M. *et al. Nature* **461,** 504–506 (2009).
12. Hofman, J. *et al. Science* **337,** 72–75 (2012).
13. Pfaff, W. *et al. Nature Phys.* **9,** 29–33 (2013).
14. Hensen, B. *et al. Nature* **526,** 682–686 (2015).
15. Shalm, L. K. *et al. Phys. Rev. Lett.* **115,** 250402 (2015).
16. Giustina, M. *et al. Phys. Rev. Lett.* **115,** 250401 (2015).