

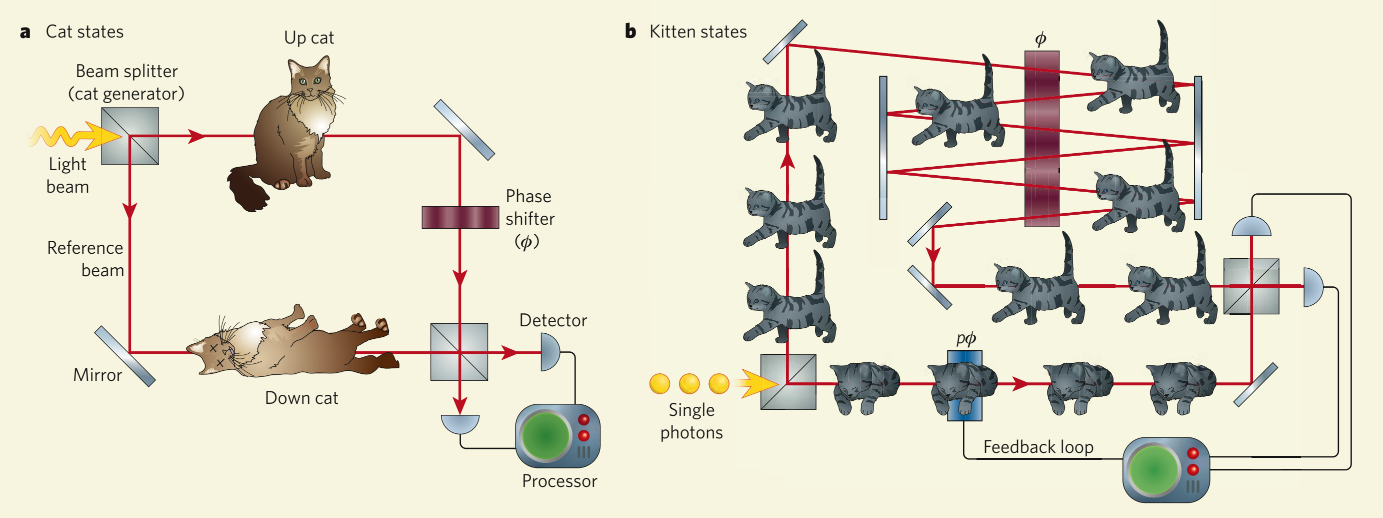

Figure 1 | Towards the Heisenberg limit. According to quantum theory, the accuracy possible in an interferometric measurement of a phase shift, ϕ, reaches a fundamental 'Heisenberg' limit that scales as the inverse of the number of photons involved in the measurement. But attempts to reach this gold standard experimentally have fallen short. **a**, A promising approach previously investigated[7] sent single Schrödinger's cat 'High-NOON' states consisting of large numbers of photons through the interferometer — all the photons went down one of two arms, but it was impossible to tell which (up cat indicates all photons in the upper path; down cat, all in the lower path). This approach effectively divided the wavelength of the light (and so its resolving power) by the number of photons in each state, but failed to deliver the hoped-for accuracy, owing to the difficulty of producing and caring for the large cat states. **b**, Higgins and colleagues[1] reach the Heisenberg limit by exploiting a series of smaller, 'kitten' states each involving just one photon. These states are easier to prepare, and are more robust against noise and loss; but the lower flux must be compensated by cycling the states through the interferometer many times and using a complex quantum feedback loop to adjust the phase shift, $p\phi$, of the reference beam.

rule is therefore called the Heisenberg limit.

This sounds all very well and good, and people continue to talk about putting squeezed light into LIGO some day. But the fact is that infinite squeezing is hard to come by, and the Heisenberg limit had until now never been realized in practice.

Enter, stage left, the weirdness of quantum entanglement, which occurs when the quantum states of remote particles become intertwined. In 1986, a way was proposed to get close to the Heisenberg limit not with squeezed light, but with quantum-entangled neutrons in a matter-wave interferometer[5]. The entanglement idea percolated along for a number of years, but really gained momentum in the past ten, when people realized that the entanglement approach to interferometry could be implemented using ideas from quantum computing such as error correction and quantum feedback[6].

A quantum computer is, in essence, a big machine filled with quantum-entangled qubits. A quantum interferometer is also a big machine filled with quantum-entangled particles, and these can be treated as qubits. A popular approach to the phase-estimation problem exploits whacky beasts such as the Schrödinger's cat 'High-NOON' state[7], in which all the photons are either in one arm of the interferometer or the other, but you can't tell which arm is which (Fig. 1a). In this case, a NOON state of n photons, each of wavelength λ, acts like a single high-frequency photon of wavelength λ/n. Hence, if one has ten red photons of 500 nm wavelength in an $n = 10$ NOON state, the result is an entangled red-photon state, but one with the resolving power of an X-ray photon of wavelength 50 nm. The shorter the wavelength, the more accurate the phase estimation. Much progress was made with such states on both the theoretical and experimental front, and they have got closer to the Heisenberg limit than have squeezed states. But owing to losses in the interferometer and the fragile nature of these states, they have never quite reached the mythical Heisenberg limit[8].

Until Higgins and colleagues came along[1]. In January 2007, in a theoretical talk at the Physics of Quantum Electronics workshop in Snowbird, Utah, Howard Wiseman from Griffith University in Brisbane, a co-author on the paper, made the remarkable claim that you could get to the ultimate uncertainty limit by sending not Schrödinger's cat through the interferometer, but a bunch of Schrödinger's kittens — single photons. You then compensate for the lower flux and apparent lack of quantum entanglement with an elaborate quantum feedback loop (Fig. 1b). Good luck with that, I remember thinking to myself: applying a feedback loop to single photons at light speed would be technologically impossible any time soon. I am now forced to eat my hat. The authors' optical interferometer, operating at the Heisenberg limit, involves no squeezing, minimal entanglement, and no Schrödinger's cat; the quantum weirdness is in the feedback loop.

This loopy demonstration in fact implements an ingenious phase-estimation algorithm based on quantum computing[9] that uses simple optics to recycle photons through the phase shift to be measured. Although the solution is too low in intensity to be of use in LIGO anytime soon — the largest number of photons the authors used was 378, whereas LIGO has a circulating power of 10^{14} photons per second — the work breaks new ground. It could have other, more immediate applications in areas such as quantum metrology, quantum imaging and quantum sensing.

So what is the immediate lesson to be learned? That tricks from quantum computing will find their practical near-term implementation in spooky gizmos with scientific and practical importance, but nothing to do with computers at all. Bravo! ■

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1. Higgins, B. L., Berry, D. W., Bartlett, S. D., Wiseman, H. M. & Pryde, G. J. *Nature* **450,** 393–396 (2007).
2. Michelson, A. A. & Morley, E. W. *Phil. Mag.* **24,** 449–463 (1887).
3. www.ligo-la.caltech.edu
4. Caves, C. M. *Phys. Rev. D* **23,** 1693–1708 (1981).
5. Yurke, B. *Phys. Rev. Lett.* **56,** 1515–1517 (1986).
6. Lee, H., Kok, P. & Dowling, J. P. *J. Mod. Opt.* **49,** 2325–2338 (2002).
7. Bouwmeester, D. *Nature* **429,** 139–141 (2004).
8. Nagata, T., Okamoto, R., O'Brien, J. L., Sasaki, K. & Takeuchi, S. *Science* **316,** 726–729 (2007).
9. Kitaev, A. Y. *Electr. Coll. Comput. Complex.* **3,** article 3 (1996).

Clarification

"Environmental science: Nutrients in synergy" by Eric A. Davidson and Robert W. Howarth (*Nature* **449,** 1000–1001; 2007).

This News & Views article discussed a paper in *Ecology Letters* (doi: 10.1111/j.1461-0248.2007.01113.x; 2007), and included the comment that the results in the paper support the rule-of-thumb that the biological response to phosphorus addition is greater than that to nitrogen addition in freshwater ecosystems. That is true for lake benthos, but not for lake ecosystems as a whole, where the responses to nitrogen and phosphorus are similar.