determines which Bell state was encoded, and discovers the message.

But how is this 'superdense' coding if two photons are needed to send the two classical bits? The answer is that all the information is carried by the second photon. In fact, when Bob sends the first photon to Alice, he might not even know which two-bit message he will send on the following day. If Alice measures the first photon alone, she will obtain no clue whatsoever as to what Bob's message is (or will be). She needs to perform a joint measurement on the entangled pair, because the message is encoded in their combined state.

To read the message, Alice must determine which of the four Bell states Bob sent. This requires the joint measurement of the two photons, and the measurement, in turn, requires an interaction between the photons. The photon–photon coupling could, in principle, be implemented with a nonlinear optical medium[2]. But the nonlinear coupling between single photons is very weak, rendering any such measurement device tremendously inefficient. Linear optics by itself can produce only a partial measurement at best, allowing Alice to identify no more than three out of the four states[4]. Therefore, in a linear-optics experiment, Bob can only send $\log_2 3 = 1.58$ bits to Alice, which is not enough to relay the entire two-bit message.

This type of setback has led to the development of a number of ingenious solutions, one of which is made possible by the nature of the photons themselves. In addition to polarization, photons possess additional physical properties, such as momentum and frequency. Indeed, it is possible to produce photons that are 'hyperentangled', that is, entangled in multiple degrees of freedom simultaneously[5]. In the case of superdense coding, one can use the extra entanglement to assist in the Bell-state measurement[6]. Barreiro *et al.*[3] harness this property in their experiment. They use a process known as spontaneous parametric down-conversion to produce pairs of photons that are entangled in two degrees of freedom — polarization and orbital angular momentum[7]. As in the example given above (Fig. 1a), the polarization state encodes the four Bell states, whereas the orbital angular momentum helps in the measurement of the polarization state. The first photon is sent to Alice (Fig. 1b), where it passes through its own analyser, a cleverly crafted arrangement of holographic plates, polarizing beam splitters and photodetectors. Bob encodes his two-bit message by rotating the polarization of the second photon using computer-controlled liquid crystals, and then sends it to Alice where it passes through an analyser similar to the first one. The analysers act on both the polarization and orbital angular momentum of each photon. Based on her joint detection results for both photons, Alice can identify all of the four different Bell states, which gives, ideally, a transmission rate of two bits of information per photon. But even with experimental noise and errors, Barreiro *et al.*[3] have succeeded in surpassing the linear-optics limit of 1.58 bits per photon.

One might think that the use of additional entanglement would nullify the communication advantage of superdense coding. But it is important to note that Bob manipulates only the polarization of the second photon, and thus the orbital angular momentum contains no information about the message Bob sends. The extra entanglement is used only to mediate the interaction between the polarization qubits, allowing a measurement that can be, in principle, 100% efficient. This experiment[3] demonstrates a considerable technical advantage as well. Because each photon is analysed separately, Alice does not need a quantum memory device to store the quantum state of the first photon while she waits for the second to arrive. Inventive schemes like these should help make quantum communication a future reality.

References

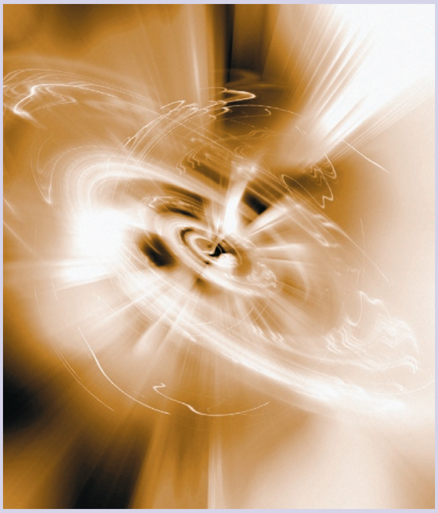
1. Bennett, C. H. & Wiesner, S. J. *Phys. Rev. Lett.* **69,** 2881–2884 (1992).
2. Kim, Y. H., Kulik S. P. & Shih, Y. *Phys. Rev. Lett.* **86,** 1370–1373 (2001).
3. Barreiro, J. T., Wei, T.-C. & Kwiat, P. G. *Nature Phys.* **4,** 282–286 (2008).
4. Mattle, K., Weinfurter, H., Kwiat, P. G. & Zeilinger, A. *Phys. Rev. Lett.* **76,** 4656–4659 (1996).
5. Barreiro, J. T., Langford, N. K., Peters, N. A. & Kwiat, P. G. *Phys. Rev. Lett.* **95,** 260501 (2005).
6. Kwiat, P. G. & Weinfurter, H. *Phys. Rev. A* **58,** R2623–R2626 (1998).
7. Molina-Terriza, G., Torres, J. P. & Torner, L. *Nature Phys.* **3,** 305–310 (2007).

ASTROPHYSICS

Black is black

In cosmology and astrophysics, it is the era of data. Measurements made using various telescopes and satellites are revealing the Universe and its history in a degree of detail few could have anticipated; the general theory of relativity that once seemed untestable is now under scrutiny.

All tests of general relativity so far have found no flaws in Einstein's logic. It is, at very least, a successful effective theory of gravity at the scales that can be probed at present. But what if it is only an effective theory, and there exists some more fundamental theory beyond it — how might that be detected? Writing in *Physical Review Letters*, Dimitrios Psaltis and colleagues consider what we might learn from those seemingly least informative of astrophysical objects — black holes (*Phys. Rev. Lett.* **100,** 091101; 2008).



MEHAU KULYK / SCIENCE PHOTO LIBRARY

Of the four exact black-hole solutions to Einstein's field equations, the Kerr metric corresponds to a black hole that is rotating (as may be expected from its formation following the collapse of a rotating star) and uncharged. Whether the Kerr metric does describe the external spacetime of an astrophysical black hole could soon be testable, using, for example, data collected in searching for gravitational waves or in high-energy observations.

However, Psaltis *et al.* show that several types of extension to the general theory — adding scalar, vector or tensor degrees of freedom, such as might exist in a theory of quantum gravity — still result in the Kerr metric. The exciting experimental possibility of proving the Kerr metric would, in fact, offer little scope for discrimination between approaches to a fundamental theory.

The flipside, of course, is that should any deviation from the Kerr metric be detected, then there's definitely something else out there.

Alison Wright