lium ions in a Paul trap can be coupled spectroscopically to phonons (not photons) — vibrational quanta of the trapped ions. Their work, inspired by a theoretical proposal by Cirac and Zoller[3], demonstrated the successful operation of a quantum exclusive-or or controlled-NOT gate, which flips one qubit conditionally on the state of another qubit, with an overall reliability in the initial experiments of about 80 per cent. In another experiment reported at the Turin meeting (Q. A. Turchette, California Institute of Technology), the roles of the quantum information carriers are reversed: cavity quantum electrodynamic systems are studied in which the interaction between different photon states is mediated by an atomic state (in this case, of a caesium atom in a beam passing through a high-finesse optical cavity). The group have determined indirectly that this set-up would provide an atomic-state dependent phase-shift (up to 16° in one experiment), from which logic gates like the exclusive-or could be built up.

These last few examples are illustrative of a general theme that pervaded both theoretical and experimental discussions at Turin (and elsewhere): a lot can be done in systems where quantum states can be controllably interconverted from one physical form to another. Fundamentally new approaches to experiments involving the Einstein–Podolsky–Rosen (EPR) paradox, which have implications for real quantum cryptography, may come out of these discussions. An EPR pair (made out of two photons, say) is usually a fleeting thing, lasting as long as it takes the constituents to traverse an experimental apparatus to a detector. Suppose, instead, that the photon quantum state could be 'swapped' using dark-state spectroscopy into a long-lived quantum state like the Zeeman sublevels of an atomic ground state; such a state is potentially some six orders of magnitude longer-lived than the original photon state. This capability of storing two halves of an EPR pair for a long time is a prerequisite for many novel forms of quantum information transmission.

One interesting protocol introduced at Turin is a 'purification' process. Suppose a collection of particles, each of which is half of an EPR pair, is received and stored, but that some corruption of the quantum state (losses, say, or decoherence) occurs during transmission or storage. In purification (outlined below), this collection of particles is processed so as to leave a smaller number of particles, each of which is a member of a now nearly perfect EPR pair. Such a technology would open up a variety of possibilities. It would, for instance, make possible the separation of EPR pairs by much greater distances, permitting quantum cryptography and teleportation[4] to be practised over distances much farther than a typical photon can travel through an optical fibre without loss.

The actual processing involved in purification is a sequence of quantum-coherent exclusive-or gates supplemented by classical messages between the two parties; thus, purification is itself a kind of quantum computation. Workers at Turin were encouraged that other quantum computations of fundamental interest exist besides the famous algorithm suggested by Peter Shor for factorization of integers. It is also heartening that purification and other error-reduction schemes, in particular a very recent technique described by Shor[5], as well as schemes for quantum data compression, become useful at scales far below quantum factorization: Shor's algorithm surpasses classical factorization methods only for quantum computations involving perhaps millions of quantum gate operations, whereas for purification the number of gates may only be in the tens. Workers in the field see even tens of gates as a monumentally difficult job experimentally, and no one has any idea when the 'engineering' era will be entered even for so simple a computation. Needless to say, Shor factoring is much, much more remote. Still, when Shor offered a wager during his seminar at Turin that the first factoring of a 500-digit number would be accomplished on a quantum computer, there were no takers on the other side.

Although Rolf Landauer was not in attendance at Turin, his work[6] throughout the 'visionary era' of quantum computing exercised an influence over much of the present work. He has constantly challenged the 'visionaries' to show a workable path to the future, sceptically pointing out that abstract Turing-machine Hamiltonians do not make an apparatus, that dissipation and disorder are inherent in physical systems and cannot be ignored, and that computers would not be what they are without error correction. As a result, Landauer's points now serve as accepted terms of admission to the 'experimental era'. The serious workers in the field may not yet be conclusively demonstrating success, but they are proposing real apparatus, not abstraction; they are worrying about and calculating the effects of dissipation and disorder; and they are struggling with the meaning of error correction in a quantum-coherent system. ☐

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1. Pellizzari, T. *et al.* Decoherence, continuous observation and quantum computing: a cavity QED model (preprint, Univ. Innsbruck, June, 1995).
2. Monroe, C., Meekhof, D. M., King, B. E., Itano, W. M. & Wineland, D. J. Demonstration of a fundamental quantum logic gate (preprint, NIST, Boulder, 1995).
3. Cirac, J. I. & Zoller, P. *Phys. Rev. Lett.* **74**, 4091 (1995).
4. Sudbery, T. *Nature* (News and Views) **362**, 586 (1993).
5. Shor, P. *Phys. Rev. A* (in the press).
6. Landauer, R. *Trans. R. Soc. Lond.* (in the press).

DAEDALUS

Air craft

SOME migrating birds fly thousands of kilometres, often over water without insects to feed them or atmospheric thermals to lift them. Where do they get the energy? Daedalus reckons that they extract it from the air.

The wind, he points out, blows in turbulent flow; it is full of eddies. A clever enough bird could pick a path through just those regions where the air happened to be rising, and moving in the direction it wanted to go. It could even exploit eddies smaller than itself. A bird's feathers are all coupled fairly independently to its frame. A feather meeting a local updraught may curve to trap it, while one experiencing a downdraught bends out of its way. Indeed, says Daedalus, that's why birds have feathers. They form an 'active wing' far more efficient than any static aerofoil. Birds migrate at fairly low altitudes to exploit the greater turbulence there.

So Daedalus is designing an eddy-powered flying-machine. The hang-glider principle seems appealing, but Daedalus needs something flatter and bigger, with an area large enough to capture the dilute energy of the eddies all around it. His new 'Aerosail' will spread a wide aerofoil out on bifurcating ribs from a central spine, like a leaf. Cunningly, it is a thin film of a piezoelectric polymer, such as PVDF. A dense pattern of flaps and holes all over the surface is connected by conducting paths to a central computer.

Each flap senses the local air flow, sends a signal to the computer, and receives back a voltage that bends it into or out of the slipstream. Each leading-edge element will sample its bit of atmosphere, and set up the regions behind to exploit it. Over each patch of wing, an updraught will be captured, holes will open to let out a downdraught, elements of tailwind will be caught and headwind dodged. Surplus energy captured by the piezoelectric elements will 'flap' the wing ripple-fashion, like a flatfish, and angle it to steer the craft.

The software for all this will be daunting. The Aerosail may even have to learn to fly by neural-net optimization, as a bird does. But then a wonderful new flying-machine will take the air. Silent, simple and elegant, the Aerosail will swoop and soar endlessly, its hundreds of square metres of film glittering in the sunlight. It will live in the air as a fish lives in the sea. Remote-controlled Aerosails could carry airmail or light freight; the largest feasible sizes could just lift a human pilot. A new sport will be born — or maybe not so new. Daedalus may have stumbled on the secret of the magic carpet. David Jones