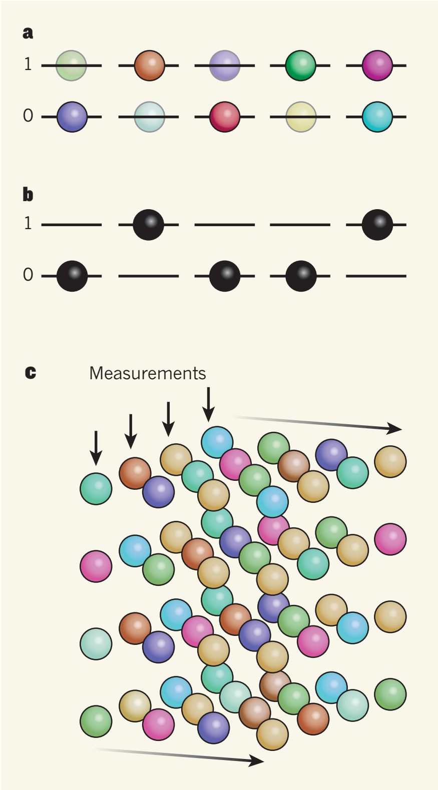


**Figure 1 | Measuring quantum bits.** **a**, Five qubits represented by the energy levels of five atoms (spheres). The ground state encodes the logical value '0', whereas the excited state encodes the value '1'. Because of their quantum nature, the atoms can be in both states simultaneously. The intensity of the spheres' colour denotes the probability that an energy level is occupied, and the colours indicate the phase of the oscillating probability amplitude associated with the energy level. **b**, After a measurement, the qubits collapse to classical states with a specific value of 0 or 1, and the phase information is destroyed, as illustrated by the black colour. **c**, A three-dimensional array of qubits can be used to implement topological error correction, which reduces the sensitivity of quantum computing to errors. The calculation consists of a series of measurements that proceeds from all of the qubits in the plane that forms the left side of the array through the adjacent planes to the right. Yao *et al.*[1] demonstrated topological error correction using an ensemble of eight qubits.

probability amplitudes. According to quantum mechanics, the probability amplitudes of both the 0 and 1 states have wave-like properties, and their relative position in an oscillatory cycle corresponds to an additional degree of freedom known as their phase. In addition, the qubits can be entangled with one another in many different ways. Thus a qubit can contain much more information than a classical bit, which can have only a specific value of 0 or 1.

Measuring the value of a qubit causes it to collapse to a specific value of 0 or 1, reducing it to a classical bit (Fig. 1b). Because measuring a qubit destroys its quantum-mechanical properties, it was not initially apparent whether there was any way to correct for errors in qubits without destroying them. It was subsequently shown[2] that error correction was possible if a 'logical' qubit was constructed from a combination of multiple physical qubits (Fig. 1a). For example, the value of the logical qubit can be taken to be the parity of the ensemble of physical qubits, where parity is defined to be 0 if the sum of the qubit values is even and 1 if the sum is odd. But there are more efficient ways of encoding the logical information. Quantum logic operations on the qubit ensemble can be used to correct the errors in the individual qubits without measuring the value of the logical qubit, and thus without destroying the information it encodes. This allows the errors in a quantum computer to be made arbitrarily small — although additional errors will be introduced during the error-correction process itself, so the average error rate must be below a threshold on the order of $10^{-4}$ for conventional error-correction techniques.

In the type of topological error correction[3,4] used by Yao *et al.*[1], the logical qubits are distributed over a lattice of physical qubits in such a way that the information is automatically protected against most forms of error. This type of error correction is theoretically expected to increase the tolerance for errors to above 1%. The authors[1] demonstrated topological error correction by combining topological techniques with cluster-state quantum computing[5], in which a three-dimensional array, or cluster, of qubits is prepared with a carefully chosen form of entanglement between nearest neighbours in the array.

Their approach begins with measurement of all the qubits in the plane that forms the left side of the array (Fig. 1c). The results of those measurements are then used to decide what kind of measurements to perform on the next layer of adjacent qubits. No active logic operations are performed — instead, the calculation depends on choosing the measurements in such a way that the collapse of the quantum state produces the desired logical operations[6,7]. The calculation proceeds until the final layer of qubits on the far right side of the array — the values of which give the desired output of the calculation — is reached. The authors reduced the sensitivity of the calculations to environmental noise and small errors in the logical operations by optimizing the spatial arrangement, or topology, of the qubits and the measurements.

Yao and colleagues[1] performed their experiment using an eight-qubit cluster, in which the value of each qubit (0 or 1) was represented by the polarization of a single photon (the direction of the photon's electric field). An optical route to quantum computing has the advantage that optical fibres can be readily used to transfer qubits from one location to another. The greatest challenge of an optical approach

NATURE

## 50 Years Ago

Although the annual figures for carriage-rates of all pathogenic staphylococci follow no particular course, evidence from many sources in industrialized countries shows that this is not the case with regard to the proportions of penicillin-resistant organisms … These findings raise many questions about the origin and spread of resistant strains. They are certainly consistent with the general impression of a relationship between the increased use of penicillin and the growth of resistant strains … It has to be borne in mind that penicillin, with other antibiotics, is being used on a large scale for preserving food and controlling animal diseases in many countries. It is increasingly present in milk and cheese, and quite large numbers of hospital, veterinary and farm workers are intermittently or continuously exposed to small concentrations of the antibiotic. These are all factors likely to promote the emergence of resistant strains in man.

**From *Nature* 24 February 1962**

## 100 Years Ago

By the death of Lord Lister, the world has lost one of its greatest men … it was his work which gave the main impulse to the development of the great science of bacteriology, a science which bids fair to occupy the most prominent place in medical work … Until Pasteur's time the existence of bacteria and their life-history had been looked on as only an interesting but not very important study … As soon as Lister showed that the exclusion of these organisms from wounds meant the disappearance of a variety of diseases to which man had been previously subject, the study of these organisms naturally advanced with great rapidity.

**From *Nature* 22 February 1912**