studies will be needed to corroborate this conclusion, as there are large uncertainties in the estimates of natural climate variability-derived from both models and observations[8].

Nonetheless, Stott and colleagues' work constitutes a breakthrough: it is the first successful attempt to detect man-made influence on a specific extreme climatic event. Such events are among the most notable features of a changing climate, not least given their impact on human affairs. Another article in this issue, by Allen and Lord (page 551)[10], discusses how refined analyses might lead to liability claims for costs incurred by climatic shifts. The advent of such 'attribution studies' might profoundly affect the course of international negotiations on ways to mitigate, adapt to and ultimately pay for the consequences of climate change. ■

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Information science

Quantum errors corrected

Andrew Steane

The phrase 'quantum error correction' might sound like a technical fix to a device that ought to be working better. But it is in fact a fascinating piece of fundamental physics with powerful implications.

Quantum error correction is a central concept of quantum information science and is almost the only thing a quantum computer would need to do if it is to work properly. It gives me great pleasure to say that it has now been implemented, in its most simple form, in a laboratory experiment reported by Chiaverini *et al.*[1] on page 602 of this issue.

It is surprising indeed that irreversible changes in quantum systems can be corrected. A correcting machine should first gather information from the faulty system, but for a quantum system this would cause the unavoidable disturbance associated with observation. We need to engineer an observation in such a way as to disturb the error, not the stored information, and to learn what the error is after the influence of our observation. Chiaverini and colleagues[1] have done exactly that.

Traditionally, 'Alice' is the protagonist in any quantum information story. Imagine that Alice wishes to preserve an atom's quantum state in the presence of noise. The state can be thought of as a spin, or rotation, about an axis oriented in three dimensions. (This is a short-hand for a pair of hyperfine levels in the electronic ground state of a $^9Be^+$ ion.) It is described by the notation $a\uparrow + b\downarrow$, where a and b are complex coefficients, and $\uparrow$ and $\downarrow$ are two spin directions. We assume that Alice does not know what state her atom is in, because if she did she could circumvent the whole problem by writing on a Post-it note — "Don't forget: *a* is 0.8, *b* is 0.6". Such cases are of no use for quantum computing.

Alice cannot examine the atom, because this would disturb its state. She cannot generate copies of it (that is, prepare further atoms in the same state) because no method to do that is physically possible (the 'no-cloning' theorem, which if broken would lead to various contradictions involving non-local correlations). However, Alice can cause her atom to interact with two others so that the group of three is now in a state described by $a\uparrow\uparrow\uparrow + b\downarrow\downarrow\downarrow$ (I have simplified things a little here, because Chiaverini *et al.*[1] in fact used an elegant, closely related, encoding, but this one is easier to describe). This is akin to radio operators' use of 'alpha' and 'bravo' for 'A' and 'B' to reduce errors: a longer symbol, here the three-atom state $\uparrow\uparrow\uparrow$ in which all atoms have spin-up, is used to encode a shorter one, the state $\uparrow$ (and similarly $\downarrow\downarrow\downarrow$ encodes $\downarrow$).

The atoms are now left alone for a while. Suppose the error processes mostly reverse the orientation of individual atoms. Then the state is likely to be corrupted into $(a\uparrow\uparrow\downarrow + b\downarrow\downarrow\uparrow)$ or $(a\uparrow\downarrow\uparrow + b\downarrow\uparrow\downarrow)$ or $(a\downarrow\uparrow\uparrow + b\uparrow\downarrow\downarrow)$, or any combination of these possibilities, through quantum superposition. In the experiment[1], to enable them to make a quantitative study, the team introduced an artificial error of known size, such that the probability of a spin-flip was p per atom. Alice's task is to manipulate the group so as to bring a given atom, say the first one, to the state originally stored $(a\uparrow + b\downarrow)$ — but she must not learn what that state was, or she will have disturbed it. Her operations must somehow reveal or react to the error, without learning the original message.

There is a way to do this: measure pairs of atoms, to determine whether their spins are aligned, without allowing information about any individual atom to be revealed. A general method for this, using quantum logic gates, was discovered in 1995. Such measurements 'project' the state, so that instead of a superposition of the possibilities listed above, the atoms must adopt just one of those possibilities. This is the unavoidable disturbance associated with the act of observation, but in this case it is engineered to make the state better defined and thus easier to correct. Furthermore, the correction can now be completed, because Alice can deduce from her measurements which, if any, atom has an inverted spin.

In Chiaverini and colleagues' experiment[1], these operations were performed by moving atoms in ultra-high vacuum along a segmented array of ion traps, each 100 micrometres in dimension. To control the rotations of the atoms, the team extended a technique of their own invention: a pair of laser beams with a precise frequency difference between them to drive the oscillations of the atoms. In this new work, the laser pulse was made to act on three atoms simultaneously, such that the force cancelled when all spins were aligned, and had the same magnitude for all states in which the spins were not all aligned. This performed most of the encoding or decoding in one step, greatly simplifying the (nevertheless still very demanding) experiment.

Although other experiments in liquid-state nuclear magnetic resonance[2,3] have demonstrated encoding and correcting operations for this and larger codes (more atoms), in these the signal was halved for each further spin introduced, and the fundamental ingredient of either individually measuring, or else reinitializing, the state of the extra spins was not available. Chiaverini *et al.*, however, have demonstrated all of the ingredients of quantum error correction in a single experiment. Their results are summarized by the formula $P \approx q + 2.6p^2|ab|^2$, where P is the probability that the final state was wrong, and $q \approx 0.22$ is the contribution from imperfection of the apparatus. For technical reasons, only a small range of initial spin states could be prepared, but this does not diminish the main achievement. It is also notable that for $p > 0.25$ a net suppression of noise (that is, $P < p$) was attained.

There are several natural steps to take next. One is to replace the rotation by a fundamentally irreversible decoherence process, induced for example by scattering a photon from the atoms. As long as this projects the spin state without relaxing it, it could be corrected by the same code. Another is to achieve repetitive correction, something not available in the experiments so far. It would also be very valuable to see a five-atom or a similar code in action, correcting general errors, including relaxation, rather than only rotation about a known axis. ■

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NATURE

50 YEARS AGO

One hundred, or even fifty, years ago there was far less to understand… but certainly it becomes every day more difficult to find scientists whose interests are wide enough to assist the advance by helping the specialists to understand one another. There is in the Library of Trinity College, Cambridge, a collection of letters illustrating the value of such help. They were written between the years 1830 and 1860 by… Michael Faraday and William Whewell, the great discoverer seeking advice from the most learned scholar of his day. Faraday was in difficulties with his experiments on electrolysis. He needed new terms to describe what he was doing… Whewell…, in a letter dated May 5, 1834, strongly advises the terms 'Anode' and 'Cathode'. The letter continues: "If you take *Anode* and *Cathode* I would prefer for the two elements resulting from electrolysis the terms *Anion* and *Cation*, which are neuter participles signifying *that which goes up* and *that which goes down*; and for the two together you might use the term *ions* instead of *Zetodes* or *Stechions*." And Faraday replies ten days later to say that he has taken Whewell's advice and ends his letter: "I am quite delighted with the facility of expression which the new terms give me and I shall ever be your debtor for the kind assistance you have given me."
From *Nature* 4 December 1954.

Archaeology

Greater expectations

Peter W. Stahl

Evidence of unexpected complexity in an ancient community in Uruguay is a further blow to the conventional view of prehistoric development in marginal areas of lowland South America.

Archaeological research often reveals unexpected results. This is common in South America, especially when archaeologists venture off the beaten track to explore unfamiliar areas. However, our surprise is also a product of our preconceptions. Recent work in the lowlands of tropical South America clearly bears this out, with discoveries of prehistoric complexity in unforeseen places and/or times[1–6]. On page 614 of this issue, Iriarte *et al.*[7] present another example of precocious development in a hitherto little-explored and under-appreciated area. The authors refer humbly to their results as unexpected; but given the profusion of surprises elsewhere, why would they be unexpected in the first place?

The conventional view suggests that little of archaeological importance can be expected of 'marginal' areas — those areas geographically distant from a great Andean "center of inventiveness and social development"[8]. Although the origin of this idea can be traced directly to the *Handbook of South American Indians* (*HSAI*), conceived in 1939, and published between 1946 and 1950, its roots are certainly deeper. With state-of-the-art knowledge at his disposal, *HSAI* editor Julian Steward[8,9] cobbled together a summary of cultural history in South America that used a now-outmoded belief in cultural evolution, culture areas and trait diffusion; environmental determinism; a sketchy archaeological record; and an underestimation of the effects of European conquest on native populations.

How does one understand the bewildering complexity of the humans of pre-Columbian South America? In his tentative historical summary, Steward subsumed indigenous South America under a ranked scheme based on sociopolitical and religious patterns, and shared or missing cultural elements. He sketched out the historical–developmental implications of his classification, putting Central Andean civilizations at the top, and descending through circum-Caribbean/sub-Andean, to tropical forest peoples, and with 'marginal' tribes at the bottom. Steward proposed an Andean centre of development with unlimited agricultural potential (a factor considered essential for establishing large, sedentary populations), from which cultural traits had diffused into other portions of the continent. According to the theory, in recipient areas, cultural elements were varyingly adopted or lost for historical or ecological reasons. In particular, marginal areas fared poorly — some areas were so far removed from the Andean centre that little was passed on. Besides, local environmental conditions were supposed not to be conducive to prehistoric agriculture in these marginal areas, thus necessitating a constant nomadic quest for subsistence.

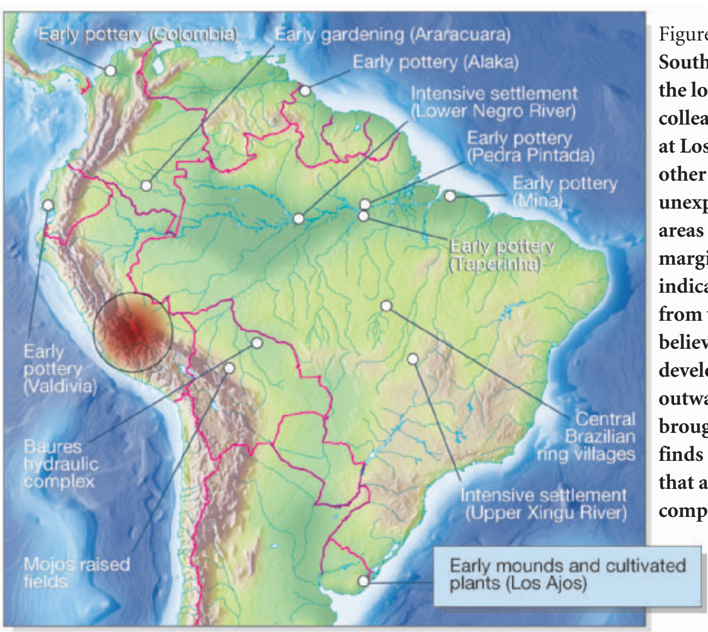

Figure 1 **Marginal or not? South America showing the location of Iriarte and colleagues' investigations at Los Ajos[7] and some other examples[1–6] of unexpected discoveries in areas once considered marginal. The red circle indicates the general area from which Steward[8,9] believed cultural developments spread outwards — a view brought into question by finds in 'marginal' areas that are earlier or more complex than expected.**

Although few would buy into these ideas today, Steward's culture history has had an enormous impact on archaeological interpretation, both academic and popular. Using this perspective, 'traditional Indians' are conceptualized as having made ancient ecological adaptations that allowed them to survive relatively unchanged since deep time. In areas or periods where archaeological facts