A giant atomic slide-puzzle

Atoms crammed tightly together in metal crystal surfaces are surprisingly mobile.

Atoms in close-packed surfaces of metal crystals move around at surprisingly high rates, even though each atom is locked in tightly by its neighbours. Here we use a low density of indium atoms, embedded in the outermost atomic layer of a copper surface, as tracer particles for scanning tunnelling microscopy to reveal the high vacancy-assisted mobility of atoms in this surface. We believe that most close-packed surfaces of metals and other materials will exhibit a similar vacancy-assisted motion at room temperature, with such surfaces behaving like a gigantic atomic slide-puzzle.

We deposited indium on a clean Cu(001) surface, one of the naturally occurring facets on a copper crystal, in an ultrahigh vacuum system and then watched the diffusion of individual indium atoms at room temperature using a scanning tunnelling microscope[1] (STM). The surface consists of atomic 'steps' separating atomically flat copper 'terraces'. The indium atoms are rapidly incorporated in the outermost atomic layer, where each one replaces a single copper atom (refs 2,3; and R.v.G. *et al.*, manuscript submitted).

To our surprise, we found that the embedded indium atoms are mobile and that they 'jump' over distances larger than one lattice spacing, some of them as far as five lattice spacings. The root-mean-square jump length is 1.92 lattice spacings; these jumps are separated by relatively long intervals of about 100 seconds at room temperature. Neighbouring indium atoms show a strong tendency to jump simultaneously (Fig. 1 represents a typical sequence of STM images illustrating these observations).

We can explain this peculiar motion of the indium by assuming that it is assisted by a rapidly diffusing 'mystery particle' that remains invisible to the STM. During its fast two-dimensional random walk, there will be a high probability that this particle will encounter an indium atom several times, thereby displacing it over more than a single lattice spacing in a time that is too short to be resolved by the STM and giving rise to the long jumps. The mystery particle will also have a high probability of encountering other indium atoms in the direct vicinity, which explains the simultaneous jumps.

There are two naturally occurring particles that might act in the assisting role invoked here, namely adatoms (single copper atoms on top of the surface) and vacancies (atoms missing from the first layer). We have observed that the indium atoms, immediately after deposition on top of the surface, invade the first copper layer via the steps, which rules out the possibility that adatoms assist the indium motion by changing places with the indium — in that case, most indium atoms would have entered the copper layer at a point close to where they had landed, resulting in a homogeneous population of the terraces with indium. We conclude that surface vacancies are responsible for the diffusion of the indium atoms.

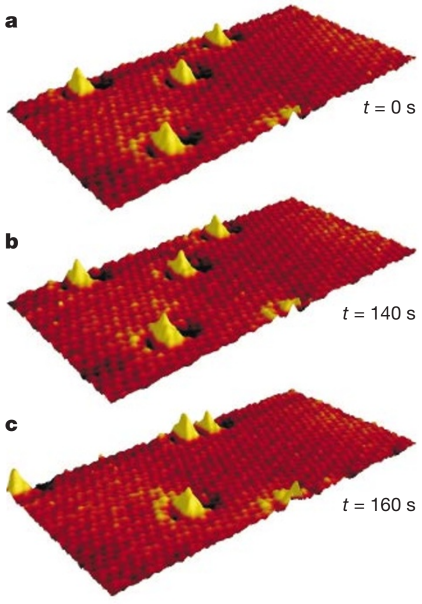

Figure 1 Images (14 × 7 nm^2) taken from a movie recorded by scanning tunnelling microscopy (see Supplementary Information), illustrating the diffusion of embedded indium atoms at room temperature. The fine corrugation is due to the atomic lattice of the Cu(001) surface. The four protrusions are individual indium atoms, each one replacing a single copper atom in the surface layer. **a,** Starting situation at $t = 0$ s; **b,** the positions of the four indium atoms are still identical to those in **a**, despite the fact that 140 s has passed; **c,** 20 s later, three of the four indium atoms have moved up to 5 atomic spacings. All motion exhibits this pattern of long waiting times followed by simultaneous displacements of several indium atoms over long distances.

Our interpretation that each long jump reflects the passage of a single assisting entity — in this case a vacancy — is corroborated by the measured distribution of jump lengths. The shape of this distribution is described well by a modified Bessel function, as expected for this type of diffusion (ref. 4; and R.v.G. *et al.*, manuscript submitted), rather than the ordinary Gauss function expected for an unassisted random walk of the indium. The distribution of waiting times between successive jumps is purely exponential, which shows that subsequent (long) jumps are the effect of the passage of different vacancies.

The indium atoms should be regarded merely as tracer particles — the observed motion of the indium reflects the diffusion of all copper atoms in the surface layer. Model calculations show, however, that the width of the measured jump-length distribution implies a noticeable short-range attraction between the indium and the vacancies, which makes the average jump length of the indium atoms somewhat larger than that of the copper atoms (without affecting the average jump frequency). The mechanism by which surface vacancies allow the diffusion of atoms in the surface is like a slide-puzzle, in which a set of square tiles can be rearranged completely by sliding a single missing tile through the puzzle.

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Supplementary information is available on *Nature*'s World-Wide Web site (http://www.nature.com).

Psychology

An electoral butterfly effect

Part of the controversy surrounding this year's presidential election in the United States concerns the potential for systematic bias in the ballot-card format — could the butterfly ballot used in Palm Beach County, Florida, have led to confusion and caused people who had intended to vote for Al Gore to vote for Pat Buchanan by mistake? Here we show that not only is the double-column butterfly ballot more confusing than a single-column ballot, but that it also appears to cause systematic errors in voting which call into question the validity of the results from Palm Beach County in the 2000 United States presidential election.

To test whether the butterfly ballot format is likely to confuse voters, we asked Canadian college students to vote for a prime minister of Canada on the day after the presidential election in the United States, using either a single-column ballot or a dual-column (butterfly) ballot like the one used in Palm Beach County (fortuitously, there was a Canadian federal election on 27 November 2000).

The ballots contained the names of leaders of ten Canadian political parties and space for a write-in-candidate. The dual-column butterfly ballot was designed so that the leaders of the two dominant parties appeared in the first and second positions in the first column (Fig. 1). Stockwell Day, leader of the Canadian Alliance Party, was in the first position, corresponding to the position occupied by George W. Bush's name in the Palm Beach County butterfly ballot, and Jean Chrétien, leader of the Liberal Party, was in the second position, corresponding to the position of Gore's name. The leader of another party, expected to receive few votes, was the first name to appear in the second column. Specifically, Joe Clark, leader of the Progressive Conservative Party, was in the position corresponding to that of Buchanan in the Palm Beach County ballot. The remaining candidates were from parties that were expected to receive only a few votes.

Participants ($n = 324$) randomly received one of the two types of ballot (single- or double-column) and voted for a prime minister by darkening the circle beside their preferred candidate's name; they then evaluated any confusion caused by the ballot format (calculated using the mean, M, of two items on 7-point scales, with high scores indicating greater confusion; Cronbach's $\alpha = 0.96$) and reported the name for whom they had intended to vote.

The results showed that the butterfly ballot ($M = 3.69$, $n = 161$) was more confusing than the single-column format ($M = 2.14$, $n = 163$; $t(322) = 8.23$, $P < 0.0001$); however, none of the students made any errors. Although greater confusion might be expected to lead to higher error rates, we were not surprised by the lack of error in this sample because it involved students skilled at completing complex scoring sheets. We therefore decided to collect data off campus from a sample more representative of the general population.

The design of these ballots was similar to the ones used by the students, except that by 9 November 2000 we were able to modify the butterfly ballot to resemble exactly the format used in Palm Beach County (but without punch holes; Fig. 1). Participants (51 males, 62 females and 3 respondents who failed to report their gender; mean age was 51.10 years, s.d. = 19.19; range, 19–86 years) were approached individually at a mock polling station in the Bonnie Doon Shopping Centre in Edmonton, Alberta, and were randomly assigned to one of the two ballots; they were then directed to one of two polling booths to vote for a prime minister. We subsequently asked the participants to evaluate ballot confusion in the same way as the student sample had (Cronbach's $\alpha = 0.82$), to report for whom they had intended to vote, and to give their gender, age and ethnic background, and finally to place their ballots in a ballot box.

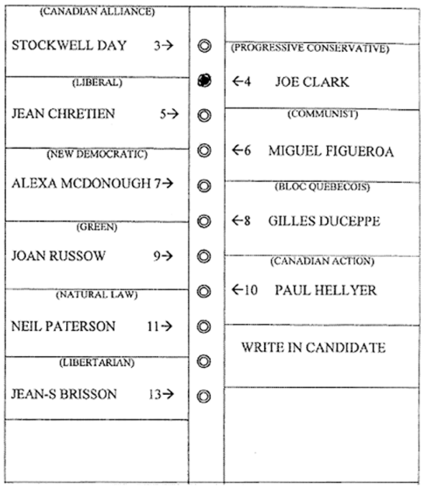

Figure 1 The arrangement of candidates on the butterfly ballot in a mock election for the Canadian prime minister. The card shows the entry made by an individual who intended to cast a vote for Chrétien and instead erroneously cast a vote for Clark (this error is directly comparable to a Gore–Buchanan voting mistake because their names occupied similar positions on the butterfly ballot). Note that the design of the ballot could lead a person to commit such an error because Chrétien is in the second position in the first column, yet the circle corresponding to Chrétien's name is in the third position on the ballot; this type of error would appear to be less likely for Day (or Bush on the US ballot).

Four people failed to complete both confusion items. The results indicated that the butterfly ballot was more confusing ($M = 3.52$, $n = 53$) than the single-column ballot ($M = 2.30$, $n = 59$; $t(110) = 3.32$, $P < 0.002$). There were four errors, all of which occurred on the butterfly ballot (that is, a 7.55% (4/53) error rate on the butterfly ballot compared with 0% on the single-column ballot; likelihood ratio $\chi^2(1) = 5.47$, $P < 0.02$). Three of the four errors occurred against the candidate who occupied the same position on our butterfly ballot as Gore on the Palm Beach County ballot — this candidate's votes were unintentionally given to the candidate who was in the same position as presidential candidate Buchanan (that is, of the 15 people who intended to vote for Chrétien, 20% erroneously voted for Clark instead, which corresponds to a Gore–Buchanan error on the Palm Beach County ballot). Thus, the butterfly ballot appears to cause systematic errors in the casting of votes.

Considering only those participants exposed to the butterfly ballot, there was no relation between age and errors ($r = 0.05$, n.s.), or between the amount of confusion and errors ($r = 0.07$, n.s.). Furthermore, participants who made errors ($M = 4.00$, $n = 4$) did not differ in their confusion from those who did not commit errors ($M = 3.45$, $n = 49$; $t(51) = 0.53$, n.s.).

We asked participants after voting whether they were aware of the butterfly ballot controversy in Palm Beach County, as it might have influenced their responses. In the student study, no one was suspicious of the ballot format; in the second study, only three voters were hypothesis suspicious and none of these made errors. If anything, then, it appears that awareness of the ballot issue was associated with careful voting.

The results from these two studies indicate that the butterfly ballot is more confusing than a single-column ballot. Our study on the second group of voters suggests that the butterfly ballot may cause systematic errors in voting which could cast doubt on the validity of the results from the Palm Beach County vote. With the butterfly ballot, vote counts systematically vary from the intention of the electorate.

It is unclear whether a biasing ballot format does or should have legal standing in adjudicating disputes after an election. But given the centrality of elections to the democratic process, it is remarkable that biasing formats continue to be used. Low-cost application of social science theory and methods would help to prevent such controversy in the future.

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Geophysics

Timing of the Martian dynamo

On Mars, the strong magnetization in the highland crust of the southern hemisphere and the absence of magnetic anomalies at the Hellas and Argyre impact basins have been taken as signs that the core dynamo that once drove the planet's magnetic field turned off more than 4 billion years (Gyr) ago. Here, we argue instead that the Martian dynamo turned on less than 4 Gyr ago and turned off at an unknown time since then. High spatial resolution magnetometry in both Martian hemispheres is needed to reveal the true history of the Martian dynamo.

The discovery by Mars Global Surveyor of remanent crustal magnetization was strong evidence that Mars — which now has no magnetic field — once had a core dynamo[1]. The onset and duration of dynamo action place strong constraints on a planet's thermal evolution. The persistence of the Earth's dynamo for the past 3 Gyr is attributed to the solidifying of the