must be metals. This observation, made shortly after the development of quantum mechanics, helped to explain the electronic properties of many solids. But copper oxide compounds with an odd number of electrons per copper atom are insulators. Their charge transport is blocked because the energy cost of moving an electron from one atom to a second, where it experiences repulsion from existing electrons, is too large. Insulators of this type — including the copper oxide material studied by Schön and colleagues — are known as Mott insulators.

Electrons in a Mott insulator are localized on atoms, and their magnetic moments, or 'spins', prefer to have an ordered arrangement in which neighbouring spins point in opposite directions, producing an antiferromagnetic state. Such electrons cannot move independently; a theorist trying to understand the rules of their correlated motion is like an outsider trying to follow the steps of a charming but unfamiliar country dance. Everyone finds their place, but how? The Mott-like behaviour of copper oxide superconductors suggests[4] that understanding their electronic correlations is essential to understanding their superconductivity.

Superconductivity in copper oxides occurs when the number of electrons per copper atom differs slightly from the integer value that gives rise to a Mott insulator. It can be fractionally larger if it has been doped with atoms that add electrons to the CuO_2 planes (electron doped) or smaller if it is doped with atoms that remove electrons from the CuO_2 planes (hole doped). The superconducting state in 'underdoped' copper oxides — those with relatively low levels of doping — has proved particularly difficult to understand. For example, angle-resolved photoemission experiments[5,6] have shown that characteristic excitation energies in underdoped copper oxides do not drop to zero at the superconducting transition temperature, as they do in conventional superconductors. Moreover, experiments using neutrons and scanning-tunnelling microscopes have established that charges in a doped Mott insulator have a tendency to cluster[7], separating themselves from the antiferromagnetic background into which they have been introduced and sometimes forming charged 'stripes'. These stripes have been studied both experimentally[8] and theoretically[9], but the role they play in the superconducting state remains unclear.

The lack of a clear consensus on the mechanism behind high-temperature superconductivity is due, at least in part, to the difficulty of growing high-quality crystals with electron densities that vary smoothly across the range of interest. Chemically doped materials with different electron densities also have varying amounts of disorder, greatly complicating the interpretation of experiments that try to compare the properties of systems with different doping levels. The role of disorder in the underdoped copper oxides is especially strong, perhaps because of the tendency for charge separation[10].

The achievement of Schön *et al.*[3] appears to remove these problems simultaneously, by making it possible to vary electron density continuously and reversibly, without introducing any external sources of disorder. They achieved this by building a simple[11] electronic device known as a field-effect transistor on top of a particularly simple layered copper oxide crystal. By establishing a voltage difference between a metallic electrode and the crystal, they can add or remove charge from the CuO_2 layers: positive voltage injects electrons, and a negative voltage injects holes. This allows them to vary both electron and hole charge densities over the full range of interest. The success of this technique relies on the high-quality copper oxide crystals they can grow using a technique known as molecular-beam epitaxy, and on the quality of the interfaces between the copper oxide material and the metallic electrode.

So, at the flick of a switch, Schön *et al.* can convert an insulating copper oxide compound into a superconductor. They find maximum superconducting-transition temperatures of 89 K for the hole-doped copper oxide and 34 K for the electron-doped one. These transition temperatures are not particularly high, but they demonstrate that the CuO_2 layers are similar to those generated by chemical doping. However, because the mobile electrons exist in a single two-dimensional layer, it will be difficult to use many of the experimental techniques used to study bulk samples of copper oxide superconductors, such as angle-resolved photoemission and neutron scattering. Conversely, the geometry of these samples may be better suited to other techniques. Tunnelling experiments should work easily, for example, and we should look for further inspiration from studies of two-dimensional semiconductors, where the ability to tune electron density using electrodes has been exploited for nearly 40 years. The challenge will be to design experiments that exploit the geometry of these tunable single-layer superconductors, opening the way to disorder-free observations probing the nature of superconductivity in the copper oxides. ■

Allan Hugh MacDonald is in the Department of Physics, University of Texas at Austin, Austin, Texas 78712, USA.

e-mail: macd@physics.utexas.edu

1. Bednorz, J. G. & Muller, K. A. *Z. Phys. B* **64,** 189–193 (1986).
2. Orenstein, J. & Millis, A. J. *Science* **288,** 468–474 (2000).
3. Schön, J. H. *et al. Nature* **414,** 434–436 (2001).
4. Anderson, P. W. *Science* **235,** 1196–1198 (1987).
5. Shen, Z. X. & Dessau, D. S. *Phys. Rep.* **253,** 2–162 (1995).
6. Ding, H. *et al. Nature* **382,** 51–54 (1996).
7. Emery, V. J. *et al. Phys. Rev. Lett.* **64,** 475–478 (1990).
8. Tranquada, J. *et al. Nature* **375,** 561–563 (1995).
9. Zaanen, J. *Science* **286,** 251–252 (1999).
10. Pan, S. H. *et al. Nature* **413** 282–285 (2001).
11. Sigrist, T. *et al. Nature* **334,** 389–394 (1998).

Daedalus

Corrosive water

Marine creatures often make their shells or skeletons from calcium carbonate, yet the sea floor under deep water sees very little of it. In their long fall from the surface, the shells of these creatures lose carbonate to deep, high-pressure water, which dissolves much more carbon dioxide than surface water. This gives soluble calcium bicarbonate. Similarly, deep sea water dissolves much more oxygen than surface water, and high-pressure oxygen solution dissolves organic matter very efficiently.

All this implies that deep seawater is actually quite a corrosive medium, although rather slow in its action. This might explain the delayed failure of deep-sea cables, and the lack of organic detritus on the ocean floor as a whole. Over the aeons it has simply been dissolved in the water. The hydrogen sulphide of 'black smoker' springs must also have played its part.

It struck Daedalus that the mass of human rubbish now piled into landfills or inefficiently burnt could instead be dumped at sea. Even modern mariners have learnt that "over the side is over", so new ships strive to be self-contained. The rumour that the path of the great liners from Sydney to Tilbury could be traced by the crockery and cutlery they left on the ocean floor, to avoid washing it up, will never now be verified.

So DREADCO oceanographers are lowering assorted human rubbish in stout wire baskets to the ocean floor, to judge the rate of its decomposition. With luck, many food residues and organic nasties will be swiftly dissolved. So will some ceramics and plastics. The workers will closely study the way water penetrates into each object. The crucial components may be the metals themselves — do they dissolve or stay coherent? Many of the wooden ships sunk in numerous wars seem not to have left much metal behind them; cannon extracted from centuries-old sunken frigates are claimed to ignite when exposed at last to air. This suggests that metals undergo remarkable chemical changes when kept for centuries under water.

The DREADCO researchers hope to show that much of the world's rubbish — food, cans, bottles, paper and plastics — can be safely disposed of on the deep ocean floor. It would also be fitting that Greenpeace, which forced Shell to beach an outmoded oil platform instead of dumping it on the ocean floor, should be shown to be precisely wrong. David Jones