Currents without borders

Paul M. Grant

Following the discovery of superconductivity at liquid-nitrogen temperatures, the idea of making 'superwires' soon ran into problems. Structural impurities remain the main obstacle, but a high dose of calcium may be the answer.

In the 1960s, a solid-state physics researcher who studied a non-cubic compound that was made up of more than two chemical elements would be committing professional hara-kiri. Not even oxides were considered fashionable. Such materials were the province of the 'dirtier' derivatives of the field — metallurgy, geology, polymer chemistry and, at best, crystallography. But by the 1970s we purists had run out of simple structures. Much to our surprise, we found an even greater richness of physics in conducting organic materials, amorphous metals and semiconductors, and multi-element transition-metal oxides.

No event better illustrated this epiphany than the 1986 discovery of high-temperature superconductivity in barium-doped lanthanum copper oxide, $La_{2-x}Ba_xCuO_4$. The process of doping (replacing some La^{3+} by Ba^{2+}) introduces positive charge carriers (holes) into the material that can flow without resistance under certain conditions. The transition temperature at which this 'superconductivity' happens, T_c, is much higher in the copper oxides than in other compounds (as high as 135 K) — bringing closer to reality the dream of superconducting wires that operate at liquid-nitrogen temperature (77 K), rather than liquid-helium temperature (4 K). Nowadays, not just high-T_c superconductors, but also their offspring — magnetoresistive compounds used in computer hard drives — have taken centre stage.

The material described by Hammerl *et al.*[1] on page 162 of this issue continues this love affair with more complex compounds. The authors' samples contain five elements in unequal amounts, and, horror of horrors, are built from messy multilayer thin films. Such polycrystalline compounds usually consist of multiple grains whose boundaries reduce the supercurrent flow. Could anything be less 'fundamental'? Yet it was in a similar structure that Kirtley and Tsuei[2] discovered the underlying symmetry of the superconducting ground state, a critical clue to the mechanism behind high-T_c superconductivity. Could anything be more 'fundamental'? Nonetheless, insulating grain boundaries in superconducting films severely hinder the flow of supercurrents over any appreciable distance involving multiple grains. This is a serious obstacle to the production of longer wires and tapes for electric power devices. Hammerl *et al.* think they may have a clever structural solution.

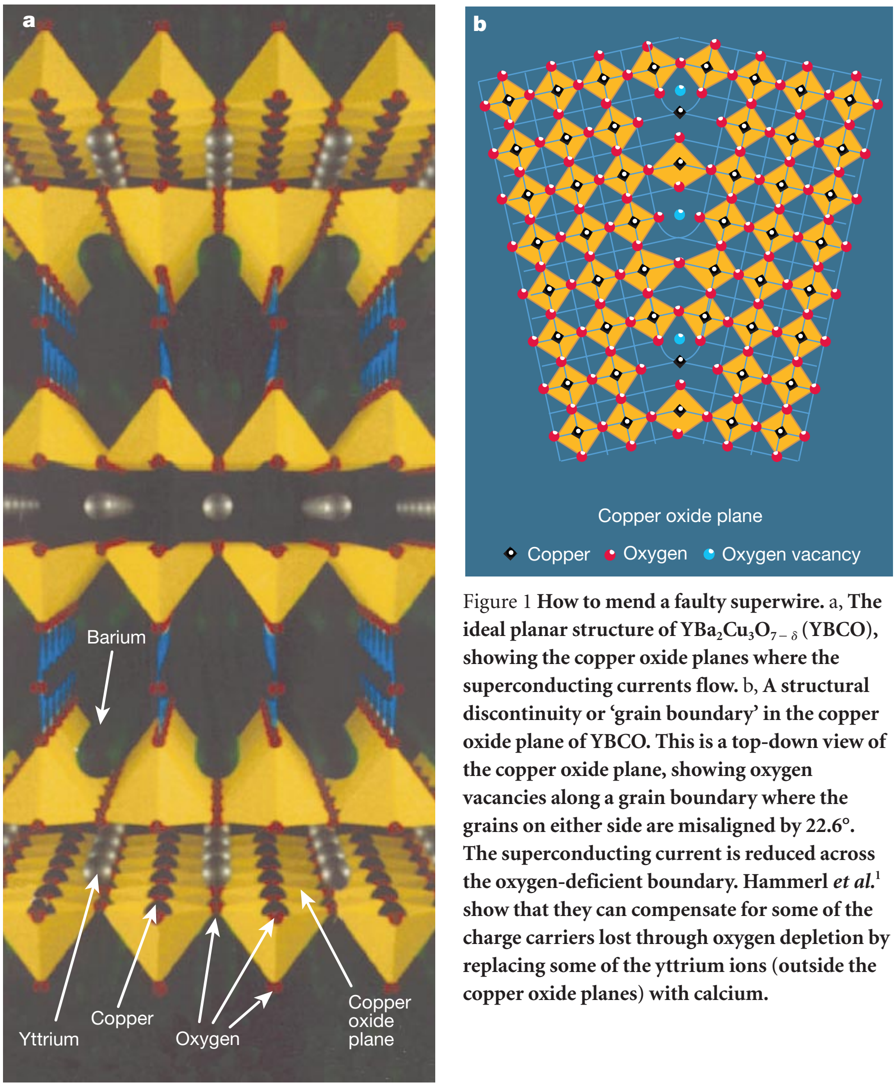


Figure 1 **How to mend a faulty superwire.** a, **The ideal planar structure of $YBa_2Cu_3O_{7-\delta}$ (YBCO), showing the copper oxide planes where the superconducting currents flow.** b, **A structural discontinuity or 'grain boundary' in the copper oxide plane of YBCO. This is a top-down view of the copper oxide plane, showing oxygen vacancies along a grain boundary where the grains on either side are misaligned by 22.6°. The superconducting current is reduced across the oxygen-deficient boundary. Hammerl *et al.*[1] show that they can compensate for some of the charge carriers lost through oxygen depletion by replacing some of the yttrium ions (outside the copper oxide planes) with calcium.**

All superconducting copper oxides have, without exception, highly anisotropic crystal structures (Fig. 1a). The superconducting state is most robust along the CuO_2 layers (the copper oxide planes), and it is relatively easy to grow polycrystalline thin films of the high-T_c compounds with these layers in the same plane as the film. Unfortunately, such films also contain a large number of grain boundaries where the grains on either side are misaligned by a large angle (more than 10°) (Fig. 1b). It has been shown that these large-angle grain boundaries form insulating 'Josephson junctions' — weak links that drastically reduce supercurrent flow between grains, especially in an applied magnetic field[3]. All high-T_c compounds suffer from this problem to some extent, but it is especially pernicious in one of the compounds best suited for making superconducting wire, $YBa_2Cu_3O_{7-\delta}$ (YBCO), which has a T_c of 91 K. Calculations indicate[4,5] that these grain boundaries have fewer charge-carrying holes, thereby reducing the ability of the boundary to conduct currents. Experimental data suggest[6,7] that this effect might result from oxygen ions being squeezed away from the boundary by compressive strain.

What can be done? One obvious way to 'heal' oxygen depletion at the boundary, by heating the films in an atmosphere of oxygen

NATURE

100 YEARS AGO

Another of those disastrous hurricanes which occasionally visit the West Indies and United States at this season of the year has to be recorded. On the 8th Inst. a storm of great violence struck the coasts of Louisiana and Texas, and, owing to the thickly populated districts over which it swept and to the high water wave which accompanied it, immense destruction to property and lamentable loss of life ensued. The fury of the storm is said to have been felt for at least a hundred miles inland, but up to the present time scarcely any details have arrived as to its character and the exact path that it followed. This part of America is one of the three regions referred to in the works of Prof. W. M. Davis from which tropical storms move into temperate latitudes in the northern hemisphere; but we must wait for further details before it can be stated whether the one in question was of the nature of a tornado, which differs from an ordinary hurricane chiefly in its excessive violence over a small, instead of a large, area. From the description so far given, and from its duration, the storm would appear to have been of the nature of the worst West India hurricanes.

From *Nature* 13 September 1900.

50 YEARS AGO

Publication of the Report of the Royal Commission on Population has been followed by a series of papers, and the fifth volume… contains an important contribution on "The Economic Position of the Family"… The authors of this paper, after discussing the various ways in which parents meet the extra cost of bringing up children, by comparing their expenditure with that of childless couples having the same income, conclude, first, that at all income-levels parents have to make considerable economic sacrifices to maintain their children, and, secondly, that children in large families have a lower standard of living than children in smaller families… It would seem that, despite the large increase of prices and incomes, the actual money cost of a child to its parents, at a low working-class level of income, is substantially unchanged as compared with the pre-war figure. The burden of two children, which at this income-level was about a third of a childless couple's income, has now fallen to one-sixth. The raising of the school-leaving age, however, has meant that the burden lasts a year longer.

From *Nature* 16 September 1950.

(annealing), does not seem to work well, even under high pressure. But replacing oxygen ions is not the only way to introduce holes into high-T_c compounds. For example, because yttrium ions (Y^{3+}) and calcium ions (Ca^{2+}) are almost identical in size, it is possible to introduce holes into YBCO by replacing some of the Y^{3+} by Ca^{2+}.

Now imagine that you could balance the number of holes lost at the grain boundary through oxygen depletion with holes from an appropriate number of Ca^{2+} ions substituted for Y^{3+} in the same region. You might be able to 'repair' the weak link with a low-resistance — and hopefully superconducting — bridge. This is what Hammerel *et al.* have done. Their first attempt[8] at this approach led to the grains themselves, as well as the boundaries, receiving the same amount of Ca^{2+}, so the former became 'over-doped' (too many holes) and T_c dropped from 91 K to 77 K. Not so impressive if you want to use liquid nitrogen for a coolant, because a superconductor needs to be well below its transition temperature to carry a useful amount of current. In their latest work, Hammerel *et al.*[1] have grown a calcium-doped YBCO film over an undoped one, and found that some of the Ca^{2+} appears to migrate into the grain boundaries, partially 'healing' them. This improves superconducting current flow between grains three- to sixfold, without degrading current flow within grains or adversely reducing T_c. The authors suggest that their result could have profound consequences for future developments of high-T_c technology. I agree.

Present high-T_c wires — or more precisely, tapes — are based on lead-stabilized $Bi_2Sr_2Ca_2Cu_3O_x$ (BSCCO) drawn into a series of long, fine filaments enclosed in silver[9]. It is now possible to produce kilometre lengths of such tape that carry supercurrents in excess of 100 amperes (A) at 77 K. The main barrier to wider use of this 'first generation' technology is cost (principally of the silver). The price-to-performance ratio of superconducting wire is measured in US dollars per unit of supercurrent per unit of length. For example, the performance of Nb_3Sn, used in many high-field laboratory research magnets, is about \$5–6 $kA^{-1}\ m^{-1}$, and NbTi, the mainstay of MRI and particle-collider magnets, is roughly \$0.90 $kA^{-1}\ m^{-1}$. For comparison, several companies offer BSCCO tape at \$300 $kA^{-1}\ m^{-1}$, with estimates that this figure may drop to \$50 $kA^{-1}\ m^{-1}$ with mass production. But this is still too high. Fortunately, a second-generation technology is being developed, and the findings of Hammerel *et al.* may mean that much cheaper alternatives are not far off.

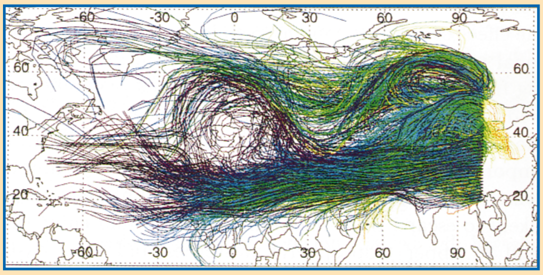
This second-generation technology is based on 'coated conductors' — films of

Atmospheric physics

Sky-high Asian imports

The Tragedy of the Commons has long been seen to apply to air pollution. Many nations freely dispose of their emissions, but others — downwind, and maybe far away — will be most affected by the consequences.

In this context, the paths of emissions from Asia across the Pacific Ocean, and their potential effects on air quality in the United States, have been well investigated. Reginald Newell and Mathew Evans of the Massachusetts Institute of Technology have taken a different perspective, as they report in *Geophysical Research Letters* (**16,** 2509–2512; 2000). They have investigated the question of how much pollution reaches Asia from sources elsewhere.



Newell and Evans set up particles along an imaginary wall, extending meridionally from north of Bangkok to Siberia. Data on wind strengths and directions allowed them to reconstruct the particles' possible routes through the atmosphere. The picture here shows the resulting 'spaghetti plot', with each line representing a path that would have taken an air parcel, starting at an altitude of 2.5 km or more, to the imaginary wall within five days.

A detailed analysis of the complete data set reveals that in January and February, 30–40% of the air that arrives at longitude 100° E has passed over Europe. Considering European emission levels, and the tendency of winter storms to swirl pollution up through the atmosphere, European air up to a height of about 10 km is likely to be far from pristine. So, in winter, Europe may contribute significantly to Asian pollution.

So much for the dynamics. At this point, the researchers hand over to the atmospheric chemists, who will have to measure the composition of the atmosphere above Asia to confirm or disprove the point. **Heike Langenberg**

YBCO deposited on specially prepared metal tapes[10]. Such films have grain boundaries at angles of 5–10° within the CuO_2 planes and supercurrent densities (J_c) bordering on 10^6 A cm^{-2} over metre lengths. Even though the average grain boundary angles are relatively small, the main impediment to making longer high-quality wires (even a few metres) remains the low J_c between grains. Calcium doping may be the answer.

It has been estimated that if the performance of coated conductors at the metre-level could be scaled to kilometre lengths, the basic manufacturing cost of coated-conductor tape would approach \$1 kA^{-1} m^{-1}. Successful commercialization of coated conductors is considered so essential to future electricity infrastructure and use that major government-sponsored efforts have been launched in Japan and the United States to assist private industry in its development.

Much remains to be understood about what really happens within calcium-doped grain boundary junctions in YBCO. How does the calcium get there? Are there other, and possibly simpler and more efficient, methods of inserting Ca^{2+} into the boundary? There is also the issue of the relationship of the grain-boundary J_c, as measured by Hammerl *et al.*, to the macroscopic J_c relevant to wire performance, especially the degree to which the 'weak link' nature of the boundary — that is, its sensitivity to external magnetic fields — remains unchanged despite the improvement of J_c in an internal field. A forthcoming paper[11] will report a 30% improvement in J_c between grains in high magnetic fields as a result of Ca^{2+} doping of a bicrystal boundary (at a rotation angle of 5° commonly found in coated conductors). Although these data were measured at 44 K because the entire sample was overdoped with holes, thus reducing overall T_c, the same improvement might be expected in samples at 77 K in which only the boundary region is doped.

The use of preferential calcium doping of YBCO grain boundaries to improve the properties of coated conductors, as supported by the data of Hammerl *et al.*, is the best idea that's come along in the five years since coated conductors first emerged. As they say in the adverts, a diet high in calcium is good for you — and maybe for high-T_c wire as well. ■

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Neurobiology

Bundling up excitement

Jeffrey D. Rothstein

Glutamate is a ubiquitous amino acid; every cell in our body is packed full of it. But in the brain it functions in a unique way — as a neurotransmitter. In nerve cells, glutamate is bundled into tiny, membrane-encased spheres called synaptic vesicles. When a neuron is stimulated, these vesicles rush to its outer membrane, releasing glutamate outside the cell. Glutamate then rapidly excites other neurons. Neurons are usually defined by the neurotransmitter they release; most release glutamate (they are 'glutamatergic'). As such, glutamate forms the basis for most of the brain's activity. It is responsible for your ability to see this journal, and to read and understand the words on this page. Over the past decade we have learned much about how glutamate excites neurons, but we know little about what gives a neuron the ability to release glutamate. On page 189 of this issue[1] Takamori and colleagues provide the answer, in the shape of the protein responsible for packing glutamate into synaptic vesicles.

A neurotransmitter itself is defined in part by the molecular mechanisms that make it, release it and mop it up from the extracellular environment after it has done its job. Over the past 30 years we have come a long way towards understanding how glutamate is made and cleared up. Now it is the turn of the release mechanisms to face the glare of the researchers' spotlight.

When packets of glutamate are released from a stimulated neuron (Fig. 1), the neurotransmitter diffuses across the 'synaptic cleft' to the receiving neuron. There, it activates a series of receptors, leading to stimulation of that neuron, too. The glutamate then needs to be cleared up, and transmembrane glutamate transporters found on the surface of nearby astroglial (supporting) cells are the major synaptic vacuum cleaner. Finally, within the signalling (presynaptic) neuron, more glutamate has to be bundled into synaptic vesicles, ready for another round of stimulation.

It turns out that most of the new glutamate is synthesized from another amino acid, glutamine, which is released from astroglial cells and taken up by the presynaptic neuron. An enzyme called phosphate-activated glutaminase converts the glutamine to glutamate, which is then bundled into synaptic vesicles. Biochemical studies indicated that a unique transporter was involved in the repackaging, but, until now, the molecular nature of this transporter has eluded researchers. In fact, the repackaging is one of the critical steps in the overall process of glutamate release, so the expression of the molecule required for this process might be what makes a neuron able to release glutamate.

Two years ago, it was discovered that the brain-specific, sodium-dependent phosphate transporter (BNPI) is found mainly in the presynaptic terminals of glutamatergic neurons[2]. Moreover, electron microscopy showed that BNPI localizes specifically to the synaptic vesicles in those neurons[2]. But it was not clear whether BNPI has a function in neurotransmitter physiology. Intriguingly, though, a protein called EAT-4 — a relative of BNPI in the nematode worm *Caenorhabditis elegans* — has an essential role in glutamate transmission[3]. So it was suspected that BNPI might have a similar function in mammals.

In an elegant series of studies, Takamori

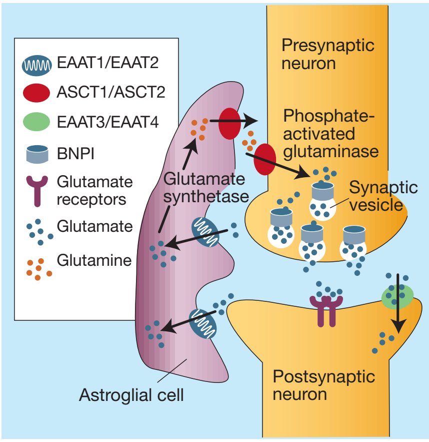

Figure 1 **What gives a glutamate-releasing neuron its identity? Most of the neurons in the mammalian brain release glutamate as a neurotransmitter. When the presynaptic neuron is stimulated, synaptic vesicles containing glutamate merge with the neuron's plasma membrane and release their contents outside the cell. Glutamate diffuses to the postsynaptic neuron and binds to receptors there, activating the postsynaptic cell. The released glutamate then needs to be cleared away. This is achieved mainly by the glutamate transporters EAAT1 and EAAT2 (found on astroglial — support — cells), and to a lesser extent by transporters on the postsynaptic neuron (EAAT3 and EAAT4). In astroglial cells, glutamate is enzymatically degraded to glutamine. Glutamine may then be supplied to neurons, through the neutral-amino-acid transporters ASCT1 and ASCT2. Once in the neuron, glutamine is converted to glutamate. Takamori *et al.*[1] and Bellocchio *et al.*[4] show that glutamate is then repackaged into vesicles by a protein called BNPI. Expression of BNPI in neurons that do not normally release glutamate is sufficient to make them do so[1].**