The superconductor breakthrough that could mean an energy revolution

We've finally made a room-temperature superconductor, so materials that transport electricity without wasting any of it are within our grasp

THEY called it the "Woodstock of physics". The hastily convened evening session of the American Physical Society meeting in the New York Hilton hotel on 18 March 1987 was supposed to last for just a few hours. In the event, some 1800 physicists crammed into a space made for 1100, with thousands more watching on TV screens outside. The session eventually broke up at 3.15 am, with many people lingering until beyond dawn. The news made front pages around the world. In New York, meeting participants were feted on the street.

The reason for the unlikely euphoria was a sudden slew of breakthroughs in superconductivity. Superconductors are materials that can transport electrons, and therefore electrical power, entirely without resistance – unlike the lossy conducting metals that wire up our electrified society, or the semiconductors within our computers. Making a practical superconductor would presage a revolution in how we make, store and transport energy – just what we need in today's era of accelerating climate change.

"We might have made a superconductor that works at close to room temperature"

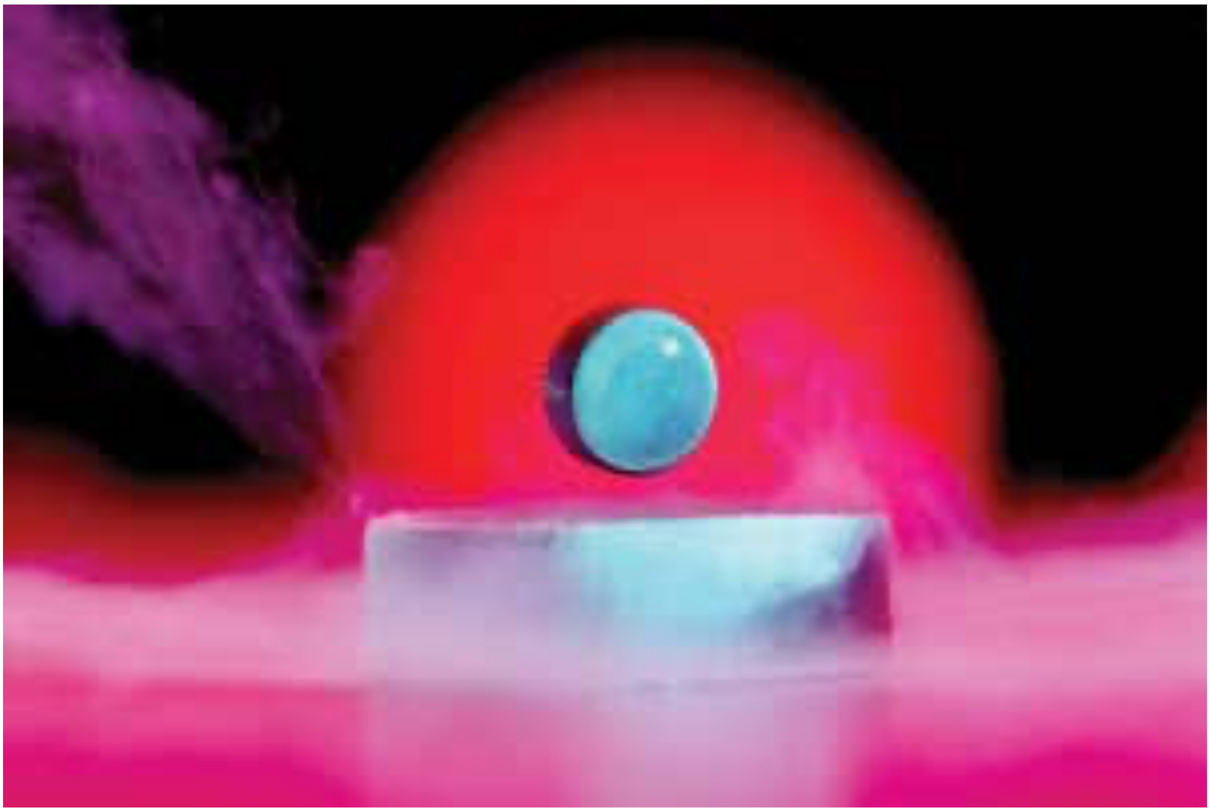
More than 33 years on, that revolution is still pending. Just lately, though, there have been rumblings of renewed optimism. Theory and experiment are coming together to provide new avenues towards superconductors. Not only that, it seems that we might already have made a superconductor that works at close to room temperature – the ultimate target of this realm of physics. Until now, we have been fumbling around in the dark in our search for working superconductors. Suddenly, we are seeing glimmers of light.

This has been a long time coming, even before the false dawn of 1987. It was in 1911 that Dutch physicist Heike Kamerlingh Onnes discovered that mercury wire lost all electrical resistance at an extremely frosty 4.2 kelvin, or 4.2 degrees above absolute zero (-273.15°C), the lowest temperature possible. The next year, tin and lead were discovered to become superconductors, at 3.8K and 7.2K, respectively, followed by other metals, often as alloys such as niobium-tin.

Onwards and upwards

This is known as low-temperature, or "conventional" superconductivity. As Nobel prizewinning research in the 1950s finally showed, it occurs because conducting electrons team up into so-called Cooper pairs, which use quantum properties to evade the normal barriers to their free movement through a solid. This pairing is caused by the influence of phonons – vibrations in the lattice of atoms that make up a solid. These vibrations get disrupted at higher temperatures. Until recently at least, conventional superconductors worked only below 40K or so, meaning they had to be cooled using expensive liquid helium.

What got the world so excited in 1987 was the discovery of materials that became superconducting at temperatures above 100K. This was a huge leap because they required only relatively cheap and accessible cooling with liquid nitrogen, which works down to 77K. Research teams quickly refined these new copper-oxide, or "cuprate", superconductors by experimenting with various recipes of elements in different proportions. By 1993, they had pushed their maximum superconducting temperature up to 133K or -140°C, a little under halfway from absolute zero to room temperature, which is typically taken as 293K or 20°C.


The strong magnetic fields from some superconductors can levitate objects

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Frustratingly, however, that was it. Unlike with conventional superconductors, we don't know what's going on inside these higher-temperature superconductors to make them lose their electrical resistance. We suspect that they form Cooper pairs directly, without phonons, but that is only an educated guess. Without knowing for sure, the only way to improve the recipes for these materials is by tinkering and crossing fingers.

There are also practical issues with the cuprate superconductors. They aren't ductile metals that you can draw out into thin wires, but brittle ceramics. They are expensive to manufacture, easily "poisoned" by contamination with stray elements and superconduct only within a single crystal. This means they are no good if you want, say, to make electricity transmission cables (see "How will superconductors change the world?"). "That means you have to try to make a crystal that is a kilometre long," says Susie Speller, who researches superconductor applications at the University of Oxford.

Cuprate wires of bismuth strontium calcium copper oxide, known as BSCCO (pronounced "bisco"), get round some of these problems. But this material is "prohibitively expensive" for most applications, says Speller. Besides only working below particular temperatures, other superconductors require high pressures or low intensity magnetic fields to function. Promising-looking iron-based superconductors discovered in 2008 also proved too brittle to easily turn into wires. "The materials science has held back the applications of these materials because they are so difficult to work with," says Speller.

The high density of the current in superconductors creates strong magnetic fields, so they have found niche applications. These include the magnets that steer particles at the Large Hadron Collider at the CERN particle physics laboratory near Geneva, Switzerland, and within hospital MRI scanners, which use the magnetic fields to look at tissue structures within the body. But these superconducting magnets typically use niobium-tin alloys cooled with liquid helium to 4K or lower. The lack of wider applications is disappointing, to say the least.

Today's fresh optimism comes courtesy of two breakthroughs. One concerns graphene, the much-feted supermaterial made of atom-thick sheets of carbon. In 2018, researchers led by Pablo Jarillo-Herrero at the Massachusetts Institute of Technology showed that putting two sheets of graphene together and introducing a twist makes it superconduct. That happens only at 1.7K, but, crucially, the superconductivity seems to mimic the way it works in cuprates.

In 2020, Artem Mishchenko at the University of Manchester, UK, revealed another carbon-based material that mimics cuprate superconductivity, rhombohedral graphite. "It's potentially interesting as a model system to help us understand high-temperature superconductors," says Mishchenko.

But it is a result published late last year that has provoked the most excitement. It too was a long time coming. Back in 1968, Neil Ashcroft at Cornell University in New York showed that if hydrogen could be turned into a solid, it should contain superconducting Cooper pairs. Ashcroft continued his theoretical studies for decades, and in 2004 showed the same should be true of hydrogen-containing compounds known as hydrides under conditions such as extreme pressures, perhaps even at room temperature.

That was a clue, but no more. To make a material superconduct "we've learned that you've got to have a number of different elements sitting in the right place in the crystal, in exactly the right proportions", says Speller. That means going through a whole periodic table of elements. "It's looking for a needle in a haystack – unless you've got a strategy for where to look."

That is where computing muscle comes in. In 2006, Chris Pickard, a materials scientist at the University of Cambridge, showed it was possible to speed the search by putting the theoretical frameworks for a range of materials – including the hydrides – into a free and easy-to-use software package called meta Ab initio Randomised Structure Searching, or AIRSS. This enables theorists to explore the internal structure of a solid, and analyse how its electrons would behave and what kind of electron-phonon coupling it would experience at particular temperatures, for instance. That won't tell you the best superconducting material, but it does tell you whether the material you are looking at could be a good one. "The computations are faster and less expensive than doing experiments," says Eva Zurek, a theorist at the State University of New York at Buffalo.

That approach has been a game changer, says experimentalist Mikhail Eremets at the Max Planck Institute for Chemistry in Mainz, Germany. "Just using intuition doesn't work: it's very difficult to predict which material will be favourable," he says. In 2015, Eremets took hints from the software to achieve superconductivity in hydrogen sulphide at 203.5K by squeezing it until it was at 155 gigapascals (GPa), more than 1.5 million times the atmospheric pressure at Earth's surface.

Following that lead, in October last year, Ranga Dias at the University of Rochester in New York and his colleagues created a material that superconducts at 287K, or 14°C. Assuming it is winter, and the central heating has been off, that is pretty much room temperature – the first time superconductivity has been achieved at anything like this temperature.

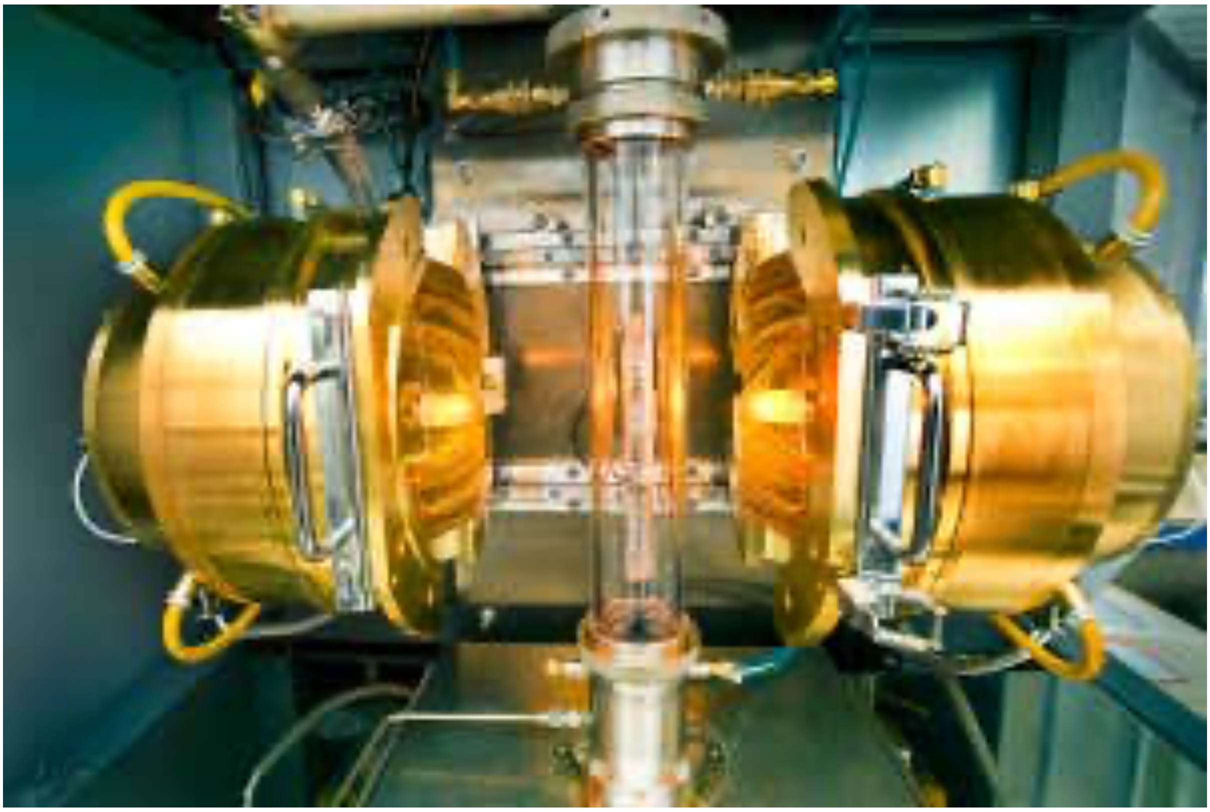
Dias and his team made their material superconduct by crushing it between two diamonds, achieving a pressure of 267 GPa – akin to that found near Earth's core. That is highly impractical. But crucially it seems likely, says Dias, that the material becomes a superconductor through the conventional Cooper pair mechanism.

Proof of principle

If so, it is the long-sought proof that conventional superconductivity is possible at room temperature, meaning we can use well-developed models to look for materials whose properties can tick all the boxes necessary to make a practical room-temperature superconductor. "Theory, computation and experiment all came together in the right place and at the right time for this breakthrough to happen," says Pickard. "These results demonstrate that we have the theoretical and computational tools to do that search."

The focus of theorists now is on directing experimentalists towards similar materials with a structure that means they will superconduct at low enough pressures and high enough temperatures, while having desirable physical properties such as ductility or malleability. Only a few research groups can achieve the kinds of pressures that Dias managed, but attaining pressures below around 100 GPa doesn't need the specialised equipment he used. If theorists can point to structures that might superconduct at 100 GPa or lower, "we suddenly open it up to a much wider experimental community that can test and refine and optimise the materials", says Pickard. He already has a paper out that predicts a 0°C superconducting transition temperature for a material that requires just 100 GPa of pressure.

There is a further stumbling block to feeding the results of Dias's experiments back into the models, though: nobody knows quite what his team made.



Superconducting crystals are grown in an infrared furnace at Brookhaven National Laboratory in New York state

Brookhaven National Laboratory/Science Photo Library

Dias aped Eremets's techniques – he says that if there is a Nobel prize for this work, Eremets should get it – but squeezed together a witch's brew of carbon, hydrogen and sulphur. No one can tell exactly how those atoms bonded together at high pressure, and the material doesn't respond to the usual X-ray diffraction imaging technique used to see what is going on inside at the atomic level: hydrogen is such a light element that its diffraction is too small to see. "We're trying to develop new techniques," says Dias. "As of now, we are sort of blind."

If we can understand the structure and the mechanics of how high pressures might create a Cooper-pair interaction, we may be able to start doing it at lower pressure. One hope is that the material is "metastable" and won't fall apart when the pressure is released. Diamond is an example of a metastable material: it is created when carbon atoms are subjected to extremely high pressures, but once it has formed you can remove the pressure and it doesn't revert to its previous form.

Cool ideas

Metastability isn't easy to check: the experiments to squeeze materials to induce superconductivity generally crank up the pressure until the diamond breaks, mixing with the sample, and you can't just reverse the process. David Johnston, who researches superconductivity at Iowa State University, isn't convinced that any Cooper-pair interaction present would survive a return to low pressures. "I don't see any hope of room-temperature superconductivity from that interaction at ambient pressure," he says.

Zurek reckons further developments might need to be led by a theory that starts with mathematics, not a compound that just happens to have some of the properties we are looking for. That might lead us in a completely different direction. If we can understand what allowed superconductivity to exist at room temperature in Dias's experiment, we could apply that insight to conventional superconductors such as niobium-titanium and magnesium diboride.

"Theory, computation and experiments all came together to make the breakthrough"

These are useful, useable materials, and we don't necessarily need to lift their transition temperature above that of liquid nitrogen. That is a point people often miss, says Pickard. "Sometimes it can be hard to get people excited about that – they want to get to room temperature," he says. But to start the superconducting revolution, we just need a "good enough" material that is relatively cheap, can easily be drawn out to form wires and works at liquid-nitrogen temperatures.

That would be enough, for instance, to make cheaper MRI scanners, widening their availability for medical diagnostics and studies of the human brain. The same is true of using superconductors in electricity transmission. "Needing to cool using liquid nitrogen is not a showstopper for power lines," says Speller. The current within superconducting wires is so dense that high-voltage transmission cables could be much thinner than normal. It is "pretty easy", she says, to make vacuum-flask-style jackets for them to stop liquid nitrogen from boiling off too fast.

What has changed in the past couple of years is that we have theory, computation and experiment feeding off each other to find a material that ticks those boxes. That can only be good, says Pickard. "The more people that can have different ideas, the more chance that someone, somewhere, will find the needle in the haystack." This time round there may not be Woodstock-style euphoria, but with the hard graft now becoming easier, the superconducting revolution really could be within our grasp.

How will superconductors change the world?

Being able to conduct electricity without resistance at room temperature would be a game changer in everyday life. Something like 10 per cent of electrical power is lost in long-distance, high-voltage cables, so making them out of superconductors would be an immediate big win. We would also be able to store energy in superconducting circuits, allowing us to keep cheaply generated power from renewable sources until it is needed.

By making our energy systems more efficient, superconductors would reduce greenhouse gas emissions, helping slow climate change. In applications such as motors and generators, they would offer a significant improvement in the power-to-weight ratio, boosting the efficiency of electric vehicles, for example. And the strong magnetic fields that will be needed to confine the hot plasma in future nuclear fusion reactors will only be sustainable with the high current density that superconductors provide.

What about magnetically levitating trains, you might ask? These have been a much-vaunted application of the strong magnetic fields that superconductors provide. In truth, though, you can get a train to float above its tracks, and hurtle along friction-free, using standard magnets. The infrastructure costs for this kind of track are already eye-watering enough for most governments to demur, without adding expensive superconductors.