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In retrospect

High-temperature superconductivity at 40

Inna Vishik & Warren Pickett

The first demonstration of superconductivity at 35 kelvin drove decades of materials research and introduced a puzzle about this strange state of matter.

Superconductors have captivated scientists for more than a century. These materials have zero electrical resistance, meaning that no energy is lost to heating when they conduct a current. However, this state generally only emerges at temperatures well below room temperature. Therefore, raising the maximum temperature of superconductors has been a focus of the field since the effect was first observed. An important step came in 1986 when Georg Bednorz and Alexander Müller reported[1] superconductivity at 35 kelvin (−238.15 °C) in *Zeitschrift für Physik B* – 50% higher than the previous record. Bednorz and Müller made their discovery in a type of copper-oxide compound called a cuprate. These materials ushered in the era of high-temperature superconductivity, and continue to confound scientists to this day.

Superconductivity was first discovered in 1911 by cooling mercury to 4.2 K using liquid helium as a cryogen[2]. Over time, this phenomenon was discovered in more metals, as well as in intermetallic compounds made from two or more elements. The temperature at which a material becomes superconducting is called the superconducting transition (critical) temperature, T_c. As the family of superconductors grew, the maximum T_c rose slowly. By 1973, superconductivity was achieved at 22.3 K in an intermetallic compound of niobium and germanium (Nb_3Ge; ref. 3). However, at this point, progress stalled for more than a decade.

Instead of seeking to increase the T_c of intermetallic compounds, Bednorz and Müller decided to investigate metal oxides. Mixtures of oxygen with metals are often magnetic insulators, and both oxygen and magnetism were thought to be antagonistic to superconductivity[4].

Bednorz and Müller eventually focused on mixtures of barium, lanthanum, copper and oxygen (BaLaCuO), which are cuprates. The researchers discovered that, at 35 K, a certain elemental ratio ($(Ba,La)_2CuO_4$) yielded the signatures of superconductivity – zero resistance and the expulsion of magnetic fields.

It should be no surprise that there was some initial scepticism. However, not only were other laboratories able to reproduce Bednorz and Müller's findings, but in less than a year, a group of researchers showed[5] that another cuprate, yttrium barium copper oxide (YBCO), superconducts at 93 K – almost one-third of the way to room temperature. Importantly, this was also above the boiling point of nitrogen (77 K), which is a much cheaper cryogen than helium. The magnitude of Bednorz and Müller's discovery was reflected in their receipt of the 1987 Nobel Prize in Physics. This was awarded just 16 months after they reported their discovery, when 'Nobel lag' is often measured in decades.

A few years after Bednorz and Müller's discovery, the maximum T_c for cuprates had been increased to above 100 K[6,7] and by 1993, it was pushed past 130 K – more than 40% of the way to room temperature[8]. Even more intriguingly, it became clear that the superconductivity of cuprates could not be explained using conventional theory. The Bardeen–Cooper–Schrieffer (BCS) theory, published in 1957, was the first complete theory of superconductivity[9], and has been incredibly successful for explaining the phenomenon in conventional metals and intermetallics. According to BCS theory, superconductivity arises from the exchange of quantized atomic vibrations called phonons between electrons in the material. However, atomic vibrations alone cannot explain the high T_c of cuprates.

The mechanism of cuprate superconductivity remains disputed, in part because cuprates are unconventional materials in many ways. First, the interactions between every electron

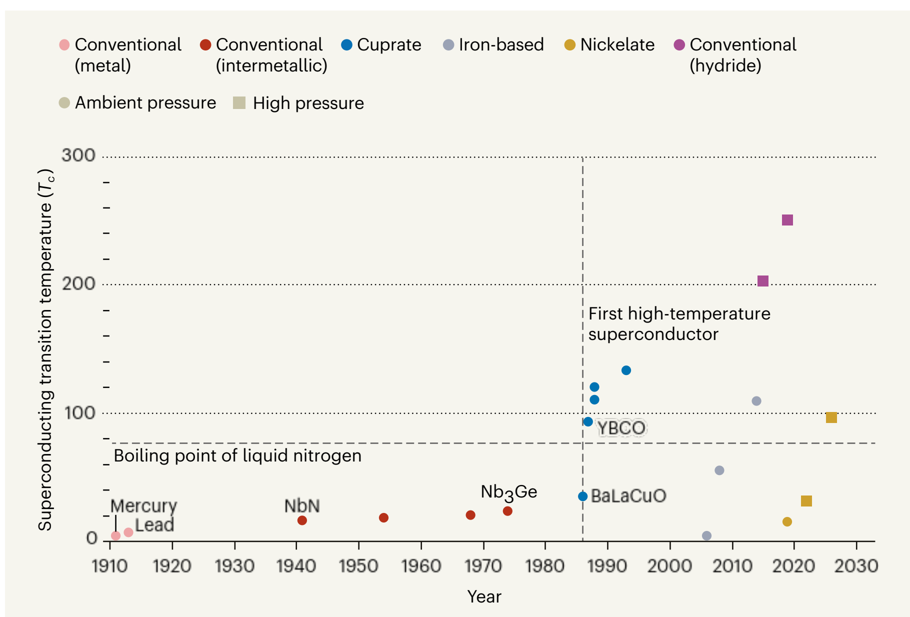

Figure 1 | Development of high-temperature superconductors. Superconductivity, first discovered in 1911, is a phase of some materials in which electricity is conducted with no resistance. This behaviour emerges at the superconducting critical temperature, T_c. In 1986, Georg Bednorz and Alexander Müller[1] reported that a certain ratio of barium, lanthanum, copper and oxygen (BaLaCuO) becomes superconducting at 35 kelvin. This was a jump of 12 K (50%) compared with the previous record and is considered the first high-temperature superconductor. BaLaCuO systems are cuprates, which are unconventional superconductors. The timeline shows a selection of demonstrations of superconductivity at various temperatures in different material classes, including yttrium barium copper oxide (YBCO).

in the material cannot be treated in an average manner, making them strongly correlated electron materials. This makes the cuprates' properties difficult to predict. Second, the best pre-1986 superconductors had 3D cubic crystal structures, whereas cuprates are made from 2D sheets of copper and oxygen atoms, arranged into stacks. This structure results in superconducting behaviour and in mechanical properties that are highly anisotropic.

Finally, cuprates exhibit other phenomena when factors such as composition, temperature, magnetic field and pressure are varied. This includes a magnetic insulating phase; a 'strange metal' phase[10]; a mysterious precursor phase to superconductivity called the pseudogap; and a phase in which superconductivity emerges from a more conventional state called a Fermi liquid metal. It is thought that these phases might hold the clues to solving the mystery of cuprate superconductivity.

Over the past 20 years, the research landscape of superconductivity has broadened substantially (Fig. 1). In 2008, iron-based superconductors were discovered, showing that high T_c superconductivity could manifest in a material that is structurally unrelated to cuprates[11]. The discovery of low T_c superconductivity in a material called magic-angle twisted bilayer graphene in 2018 revealed another example of superconductivity close to an insulating phase in a material with strongly interacting electrons[12]. Nickel oxide superconductors, discovered in 2019, revealed yet another family of high T_c superconductors, this time with structural motifs similar to those in cuprates[13]. Moreover, it was reported in 2015 that, when compressed to pressures of almost two million atmospheres, conventional superconductors based on metal hydrides can superconduct at 200 K (ref. 14), which was raised to 250–260 K in 2019 (refs 15, 16) – near the temperature of a household freezer.

Technological development over the past 40 years means that cuprate-based superconducting magnets, tapes and cables now exist on the market. However, they are not yet widely used – magnetic resonance imaging machines, particle accelerators and the tiny superconducting circuits that power quantum computers all still use conventional superconductors. One reason for this is that some technologies, such as superconducting quantum computers, do not benefit from high-temperature operation. Furthermore, some potential applications would not save money by replacing existing infrastructure with high-temperature superconductors.

In the wake of Bednorz and Müller's discovery, researchers with applications in mind began to predict a future in which magnetic-levitation trains and lossless power transmission lines would become commonplace. This has yet to be realized, but a lag is not unprecedented. Existing technologies that use conventional superconducting materials came to fruition decades after the initial discoveries.

The work that began in 1986 is still rich with intriguingly unexplained physics and potential breakthroughs. There is hope that superconductors that operate at the temperature of liquid nitrogen could be incorporated into the electrical grid, or facilitate technological advances such as fusion energy[17].

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Sustainability

How mineral demand is causing deforestation

Brent Sohngen

An analysis of the extent to which mining caused deforestation between 2001 and 2020 in areas near mines in sub-Saharan Africa could help conservation efforts. **See p.971**

For the past century and a half, agricultural expansion has been the main driver of deforestation[1]. Now, however, factors including slowing population growth, improvements in crop yields and policy innovations such as the growing adoption of community forest management and advances in the detection of illegal logging and land conversion, are helping to lessen the agricultural footprint in tropical forests. Unfortunately, new concerns about deforestation have emerged regarding mineral scarcities, which are underlying commodity price increases that greatly exceed trends in the economy more generally. With these higher prices, the scramble for resources from tropical forests has intensified. So far, policymakers have been mainly in the dark about the effects of mining on deforestation, but on page 971, Morton *et al.*[2] present work that resolves many limitations of earlier approaches used to identify and quantify mining-related deforestation effects.

According to the Food and Agricultural Organization of the United Nations, 66 million hectares of forest were lost in sub-Saharan Africa from 2000 to 2020 (ref. 3). Using modern techniques that capture both direct and indirect (those associated with roads and other infrastructure) losses, Morton and colleagues show that 10% of the deforestation in sub-Saharan Africa between 2001 and 2020 was caused by mining (Fig. 1) and mining-related activities.

Morton and colleagues' key contribution is their identification of mining operations' effects outside the boundaries of the operations themselves. When mines are developed in remote tropical forests, deforestation will not be limited just to the location of the mine. Roads must be built and workers housed – and crops might need to be grown to feed them. Processing facilities might be set up. However, attributing these activities to mining is complex, to say the least.

The authors used detailed information on the location and timing of mining, along with high-resolution spatial data on forest losses over time. Using a database of mines established in sub-Saharan Africa between 2001 and 2020, the authors examined a series of concentric circles centred on each mine. They identified the deforestation effects of a given mining operation by comparing forest loss in the surrounding buffer area with deforestation