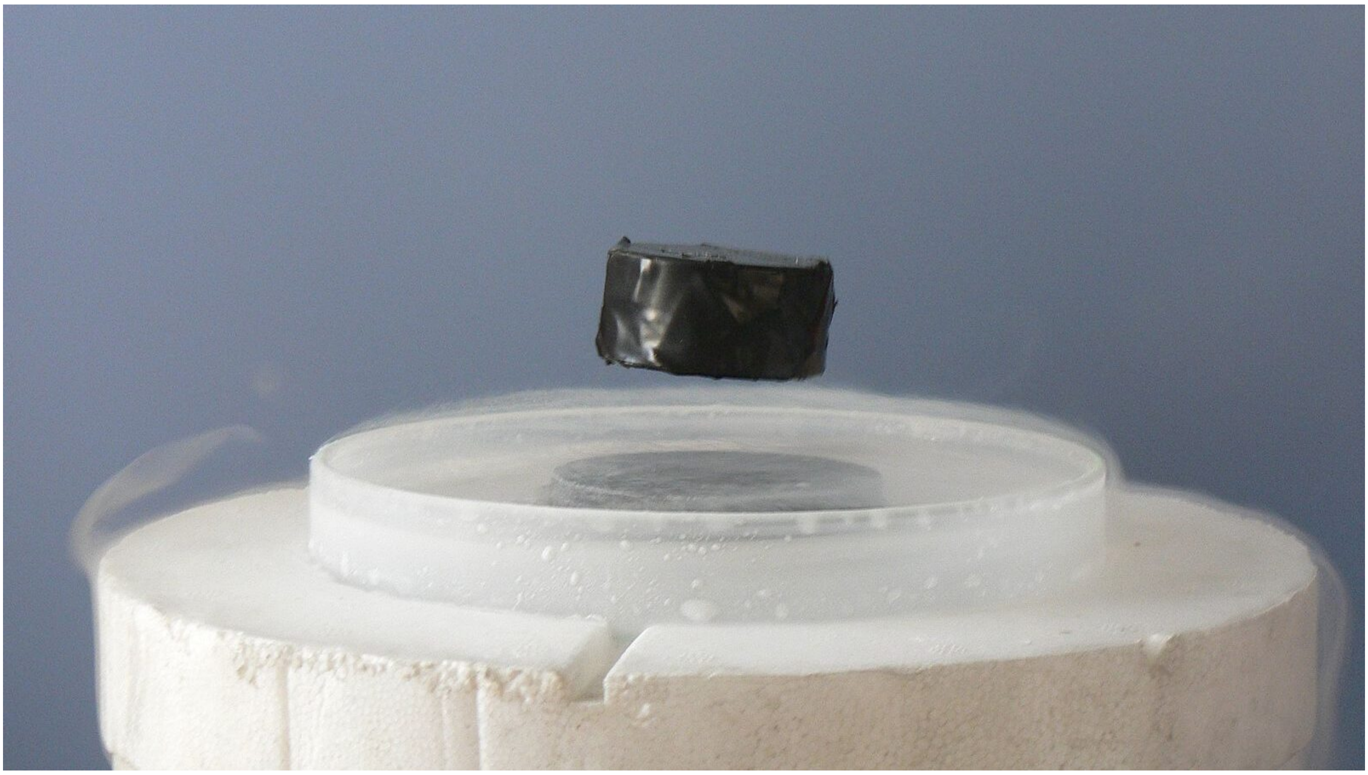
Room temperature superconductivity

In de serie 'Students on Science' presenteren we Engelstalige artikelen die zijn geschreven door studenten van het vak Wetenschapscommunicatie aan de UvA. Vandaag beschrijft Amber Visser de race om supergeleiding bij kamertemperatuur te realiseren.



The race towards room temperature superconductivity. The search for a material that conducts electricity without any resistance started over a century ago. Are we getting any closer to finding it? Image: Wikimedia Commons.

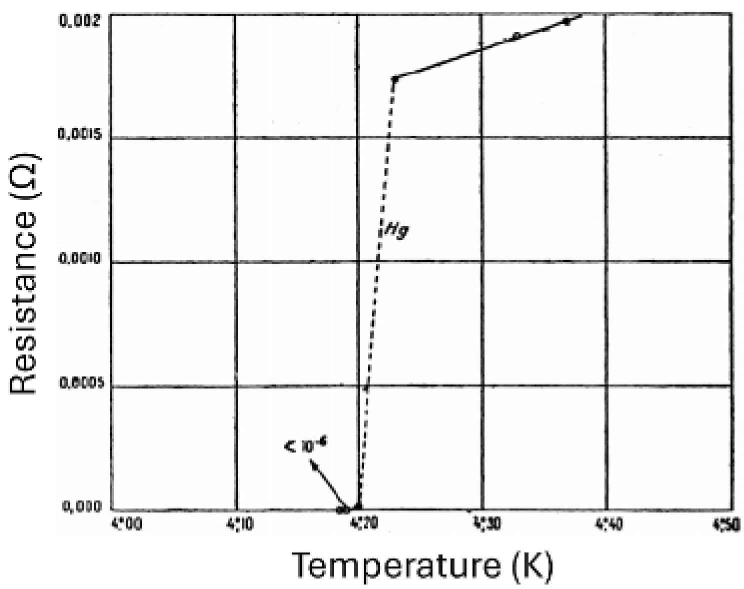
Electricity is all around us. We use it to charge our phones, make light in the dark and to power our trains. Perhaps you have noticed that when you use your computer it gets warm. This is because the materials through which electricity is transported have a resistance. You can picture resistance as trying to ride a bike into the wind. A lot of energy is just lost without moving forward. This energy turns into heat and is thus useless in powering anything, but there is a solution on the horizon. Materials that can conduct electricity without any electrical resistance are called superconductors. These materials were discovered all the way back in 1911, by Heike Kamerlingh Onnes. In the future, superconductors might allow you to do your commute on a floating magnet train or let you get highly accurate medical tests wherever you are. However, there is one problem: all of the superconducting materials we currently have only superconduct at extremely low temperatures, which makes it difficult to use them. The search for a material that superconducts at room temperature has been going on for over a century, but it is yet to be found. The race towards room temperature superconductivity is turning out to be a marathon rather than a sprint.

The experiment that started it all

Superconductivity was discovered by Heike Kamerlingh Onnes in his dimly lit laboratory in the physics building in Leiden. There, he was working on low-temperature physics, trying to reach temperatures as close to absolute zero as possible, closer than anyone had ever gotten before. Cooling stuff down is not as easy as you might think. Kamerlingh Onnes spent day and night thinking up complicated diagrams of special fridges that could cool below -269°C, because at this temperature even helium turns from a gas into liquid, as was already predicted from calculations. These fridges did not look like the one in your kitchen. They were complicated networks of shiny cold stainless steel chambers, tubes and pumps, sometimes with huge balloons attached to store gases and they towered over even the tallest of students. Not only did they look impressive, the sounds these machines produced when working were deafening. A deep, rumbly, mechanical noise was constant in these old laboratories. This might not sound very attractive, but it was Kamerlingh Onnes' passion. After working perilously on his special fridges, in 1908, he finally built one that could go all the way down to -269°C and so he became the very first person on earth to turn helium from a gas into a liquid. However, this did not mean his work was done. Kamerlingh Onnes wanted to cool other materials, and his next target was not a gas like helium; he wanted to cool metals.

Metals are not inherently more interesting when they are cold. After all, most metals are already solid at room temperature, so cooling them will not bring them to another phase. Kamerlingh Onnes' interest, however, was not in the phase of the metals but in their conductivity. The theory of conductivity at the time treated electrons (tiny, negatively charged particles) in materials as miniscule marbles that move quicker at higher temperatures and are slowed down by bumping into the metal atoms. Slower electrons can transport current less efficiently and thus there is a higher resistance. Physicists therefore did not know whether an *extremely* low temperature would lead to extremely slow electrons and as a consequence high resistance, *or* that the slower movement would reduce the number of collisions such that the resistance of the material would decrease.

To test this, Kamerlingh Onnes measured the resistance of several metals, while decreasing the temperature to unprecedented lows. In platinum and gold, nothing interesting happened at the temperatures he could reach. The resistance smoothly when he decreased the temperature, as it typically does in metals. However, when he placed a mercury sample in his fridge on April 8th 1911, he made the crucial observation that started our story. The resistance did not just smoothly increase or decrease when Kamerlingh Onnes was decreasing the temperature; it sharply dropped to zero at 4.18 K (that is -268,97 C) and stayed there. The figure from the original publication where he first published this, is shown in the picture below. The temperature decreases from right to left on the horizontal axis and the vertical axis shows the resistance. The temperature at which a drop to zero resistance occurs in a material was later named the *critical temperature*. In 1913, soon after his discovery, Heike Kamerlingh Onnes was awarded the Nobel Prize in Physics for his work.



The first measurements of superconductivity.
The resistance of mercury as a function of temperature that Kamerlingh Onnes published in

1911. The graph shows that a clear, sudden drop when read from right to left (high temperature to low temperature), was measured.

The Meissner–Ochsenfeld Effect

In the following decades, researchers discovered several other superconducting materials, but nobody could explain their lack of resistance. The properties of the superconducting materials did become clearer in 1933 when Walter Meissner and Robert Ochsenfeld wondered what would happen if you put a superconductor in a magnetic field. They decided to try it out and discovered that if you cool a superconducting material down to below the critical temperature and place it into a magnetic field, the magnetic field inside the material vanishes. A current is generated on the surface of the superconductor that induces a magnetic field that exactly cancels the one applied to it. As a consequence of the Meissner–Ochsenfeld effect, a magnet and a superconductor will always repel each other, which means that a superconductor can float above a magnet (or vice versa) – see the image at the top of this article for a nice example. This floatation is a slightly more complicated version of something you have probably experienced: trying to push two magnets together from the “wrong side” and feeling them push your hands apart instead. The Meissner–Ochsenfeld effect would later become the primary criterion for testing superconductivity, as it is much easier to measure than the vanishing of resistance.

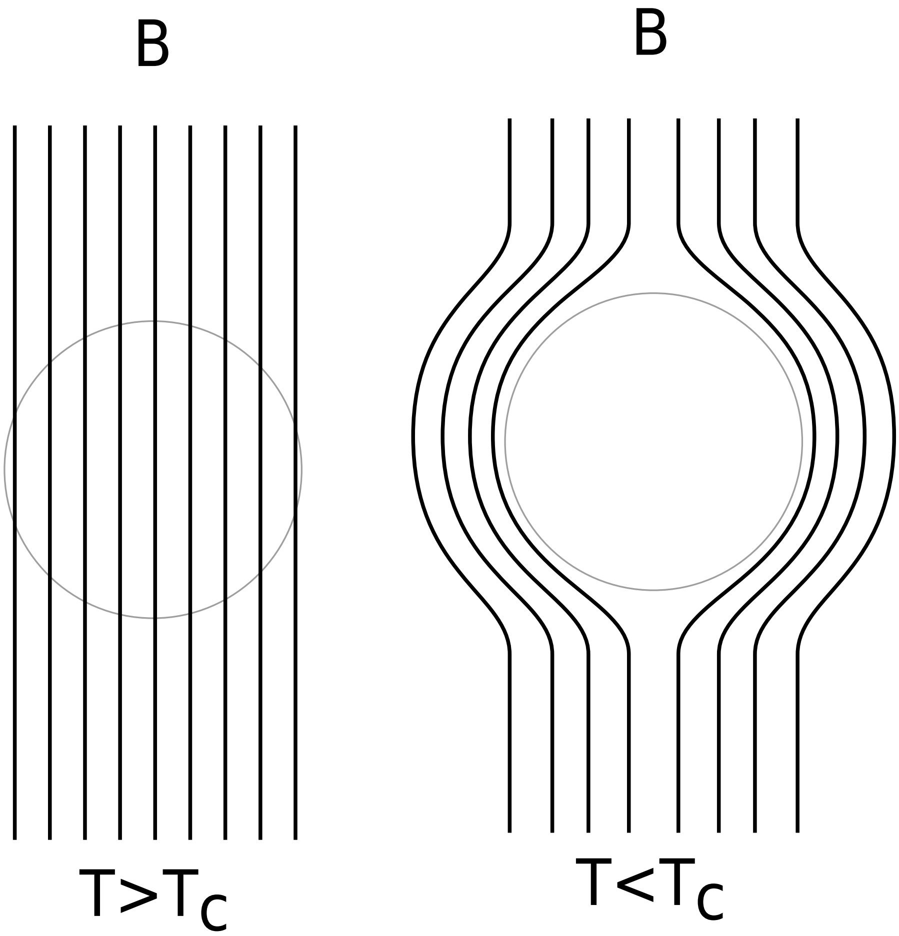
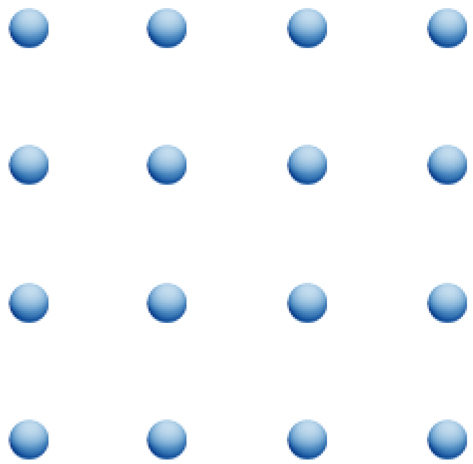


Illustration of the Meissner–Ochsenfeld effect. On the left a non-superconducting material in a magnetic field (shown by the arrows and indicated by the letter B) is shown, and on the right a superconducting material expelling a magnetic field. T signifies the temperature of the system and T_c the critical temperature of the ball. Image: [Wikimedia Commons].

The discovery of the Meissner–Ochsenfeld effect[1] led to the first mathematical formulas that could describe some of the behaviour of superconductors[2]: the London equations. The brothers Heinz and Fritz London showed that if a material carries some amount of current with zero resistance, this material would “expel” a magnetic field from its interior to lower its energy. However, these equations still did nothing to explain why currents could propagate without encountering any resistance. That was still a huge open question.

Superconducting electrons work together

In fact, no one found an explanation for the lack of resistance in superconductors until 1957, despite many people looking for it. Eventually, it was only found due to a collaboration between three giants of theoretical physics: John Bardeen, Leon Cooper and John Robert Schrieffer. Cooper could show that if there was some attraction between electrons that pulled them into pairs, this would result in the Meissner–Ochsenfeld effect. An attraction between electrons seems counterintuitive, as all electrons carry a negative charge and so they repel each other. To see how electrons might still interact attractively, it is necessary to take into account the lattice of atoms that makes up the material. A simplified picture of pair formation is as follows: an electron moves the nearby positively charged atoms in the lattice slightly towards it, locally making that region positively charged. This locally positively charged region then attracts an electron at a long distance, resulting in a coupling between two electrons. To see how this pairing leads to superconductivity, you need a few pages of equations. However, you can picture that the electrons are so strongly paired that small disruptions cannot break the pairing and so, together, they become almost untouchable, which enables superconductivity.



Cooper pair formation. Illustration of the mechanism that allows electrons to form Cooper pairs by deforming the lattice. Animation: Wikimedia Commons.

One crucial consequence of the pairing interaction between the electrons being mediated by the atoms on the lattice is that the mass of these atoms affects how easily a material becomes superconducting. The heavier the atom, the harder it is to move and so the harder it is for a material to become superconducting. The easiest way to test this is by comparing the properties of a material to the properties of that same material but with atoms with slightly different masses (i.e., compare different *isotopes*). In this way, you have two identical materials, the only difference between which is in the masses of the atoms on the lattice. It is harder for electrons to move the heavier atoms in much the same way that it is harder for you to pick up an elephant than it is to pick up a feather. Thus, it becomes harder for the electrons to form pairs, which makes the superconductivity weaker and so causes the critical temperature to decrease. C.A. Reynolds and E. Maxwell observed this phenomenon in an experiment back in 1950. It indicated that Bardeen, Cooper, and Schrieffer were on the right track.

It turns out that the vast majority of superconducting materials follow the predictions of Bardeen–Cooper–Schriefer theory, so the problem of superconductivity seemed solved. Sadly, one of the theory's predictions imposed an upper limit on the critical temperature, at slightly above 40 K (or -230 °C), which would limit applications to high-tech facilities where liquid helium could be used to cool down the materials. Liquid nitrogen, which is a much more commonly available coolant, has a boiling point of 77K and freezes into a solid material at 63K, and is thus not cold enough in its liquid state. Liquid helium is much more expensive and so it is less accessible for everyday use.

MRI machines and floating magnet trains

Nevertheless, let's take a moment to envision possible applications. Because superconductors have no electrical resistance, they can carry incredibly high currents. If you make a coil out of a superconducting wire and send a high current through it, you will create an extremely strong magnetic field. Hospitals are using these coils in MRI machines right now, despite the high cost of cooling with liquid helium. These extremely strong magnets can also be used for magnetic levitation (or maglev) trains. Maglev trains float above the track due to magnetic repulsion, getting rid of friction between the train and the track. These trains could be incredibly energy efficient due to this lack of friction, because overcoming friction costs a lot of energy. The first maglev train became operational in 1984 and floated only 15 millimeters above the track. The fastest maglev train is the L0 SCMaglev in Japan, reaching top speeds of over 600 kilometers per hour, five times the speed of a car on a Dutch highway. Imagine getting on a train in Amsterdam and getting out in Paris less than an hour later. Unfortunately, this technology has not been widely implemented, in part because it costs a lot of energy, and is very expensive, to keep the strong superconducting magnets cold enough.

In addition to the above applications, superconductors can be used to build extremely sensitive circuits that can be used in all kinds of detectors. Right now, these are restricted to laboratory applications but if superconductors were to function at higher temperatures they could work in all kinds of devices. People are even considering how they could be used to easily detect the presence of certain molecules in the body to see if a person has specific illnesses. You could go to a doctor's office and have them immediately tell you whether or not you have the flu.

Transrapid 09 maglev train at a testing facility in north west Germany. Image: Wikimedia Commons.

New materials raise the critical temperature

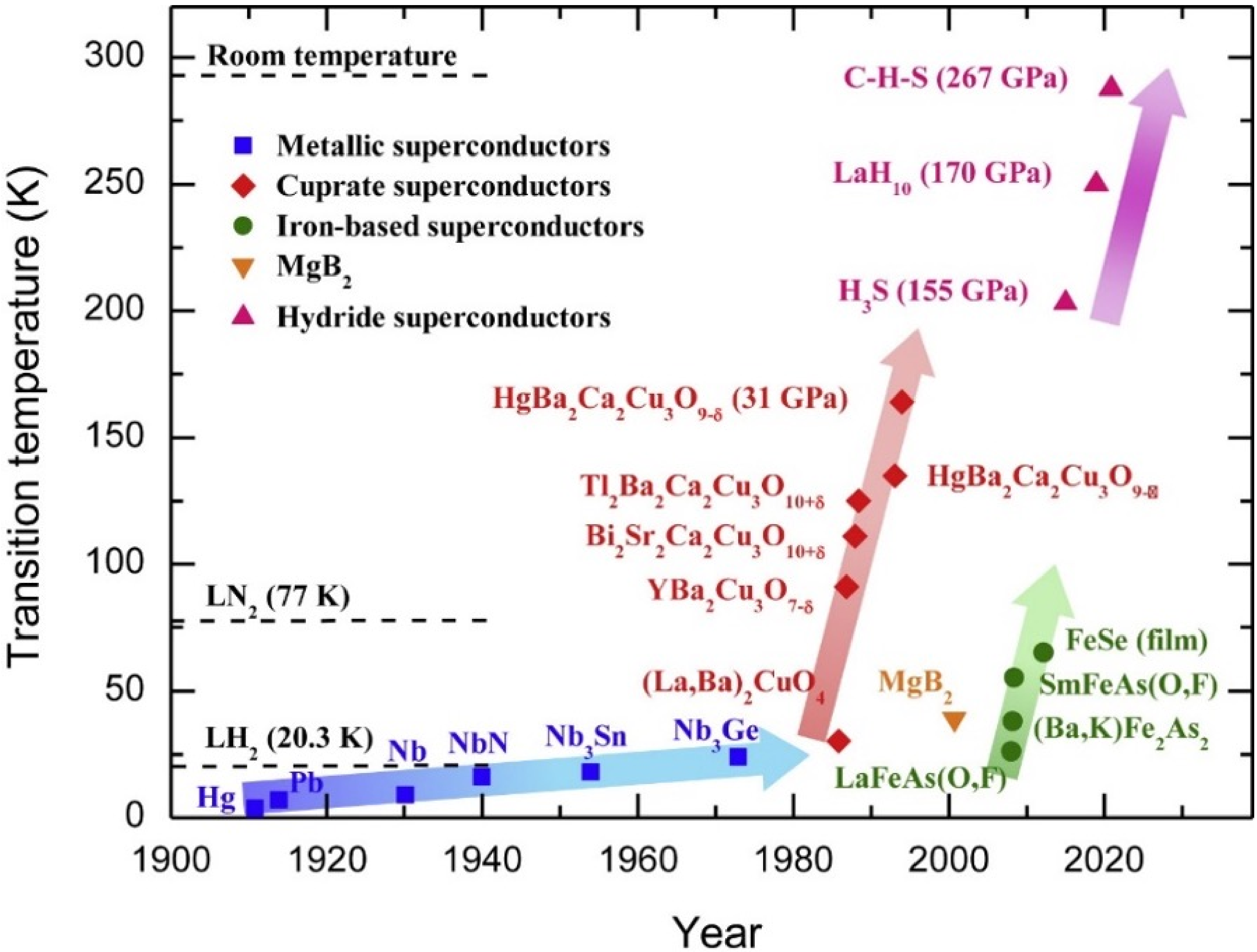
Clearly, the limiting factor in expanding the application of superconducting materials is the upper limit of the critical temperature, but as the title of the article suggests, this upper limit turned out not to be as strict as expected. In 1979, researchers developed superconductors that showed behaviours that could not be explained by Bardeen–Cooper–Schrieffer theory. For example, their critical temperatures did not decrease as quickly as expected when heavier atoms were used in the lattice. These materials were dubbed *“unconventional superconductors”*. Although the first unconventional superconductors still had very low critical temperatures, their existence suggested that there might be other unconventional superconductors with very high critical temperatures, since there was no reason they should satisfy the upper limit from Bardeen–Cooper–Schrieffer theory.

In 1986, J. Georg Bednorz and K. Alexander Mueller found the first unconventional superconductor with a high critical temperature. This had an at the time record-setting critical temperature of 35 K and won them the Nobel prize. After that, for a while, it seemed that the sky was the limit. Everybody was looking for other materials that might have higher critical temperatures. Researchers who were inspired by Bednorz and Mueller’s compound, synthesized the superconductor YBCO (Ytrium Barium Copper Oxide). YBCO was discovered to have a critical temperature of 92 K. This means YBCO can be cooled to superconducting temperatures using just liquid nitrogen. This discovery left just the holy grail: a material that is superconducting at room temperature, so no cooling whatsoever is necessary.

The class of materials that was found by Bednorz and Mueler and that also contains YBCO is called the *cuprates*. The cuprates seem promising, and many more similar compounds were synthesized. Some cuprates have critical temperatures above 100 K, but none of them have critical temperatures anywhere close to room temperature (298 K). What does not help in the search for a room temperature superconductor, is that these unconventional materials do not follow Bardeen–Cooper–Schrieffer theory, so it is unclear what determines their critical temperatures. This makes it difficult to predict which materials will have higher critical temperatures. Other classes of unconventional superconductors with high critical temperatures have been found, but none of them come close to room temperature either.

The future of superconductivity

Recently, physicists found a new avenue by placing superconductors under pressure, to strengthen the pairing mechanism and raise the critical temperature. This works very well, and under high pressure, some materials even superconduct at room temperature. Researchers are considering what interactions lead to this transition to superconductivity at high pressures and whether interactions could be present at ambient pressure in other materials. Even if this is not the case, understanding why these materials superconduct at high pressures would bring us closer to understanding unconventional superconductivity as a whole. Furthermore, the high-pressure superconductors are another option that might be useful in applications where low temperatures are not feasible, although such high pressures are, of course, also difficult to achieve.



Critical temperatures of various superconductors over the years. The colours indicate the class of material. Note that all superconductors with a critical temperature above 150 K require some level of high pressure. Image: C. Yao, Y. Ma, Superconducting materials: Challenges and opportunities for large-scale applications, iScience 24, 102541 (2021).

In summary, superconductivity is a complex phenomenon of which our understanding has grown steadily over the past century. It started out from a question about conductivity at low temperatures, but turned into research around a much larger question about interactions in materials under extreme conditions. We might not have a room temperature superconductor yet, but all across the world, many research groups are still looking—more than a century after the discovery of the first superconductor—because a room temperature superconductor might be hard to find, but finding it would be well worth the effort.

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[1] This is commonly referred to as the Meissner effect, possibly to Ochsenfeld's dismay.

[2] Note that we are already 20 years removed from Kamerlingh Onnes' original discovery.