WHAT?
More than magnetic levitation

HOW?
Strange pairing of electrons

WHY?
Technologies of the future?
Hello!

This magazine has been made by PhD students from the universities of Edinburgh, St Andrews and Heriot-Watt, as part of the “CM-CDT”, to explain a bit about the kinds of fun scientific research that interests them and that they are doing now. If you’re thinking that your next step might be going to university we hope this magazine will help you see science and, in particular, physics as something you would enjoy studying.

Following the success of Issue 1 of our magazine, we have produced a series of four issues, issues 2-5, each on a different theme. This is issue 5, the final issue in this series, but hopefully not the final issue ever! In this issue we will explain Superconductivity: what it is and where it comes from, as well as its interesting and powerful consequences for magnetism and electricity. Check out the previous issues too: issue 2 covers experiments at Extreme Pressure and what they tell us about the insides of planets. Issue 3 discusses Quantum Thinking: how we have to think about very small things in very strange ways! Finally, issue 4 talks about Soft Matter in its many guises: squishy things, goos, animals, and biomolecules to name a few!

What is the CM-CDT?

The Scottish Doctoral Training Centre in Condensed Matter Physics (CM-CDT) is a collaboration between the University of Edinburgh, Heriot-Watt University, and the University of St Andrews, to provide PhD students with a postgraduate education across a broad range of condensed matter physics. We have students from across the world, as well as across the UK, working on a range of topics including biological processes, quantum computing, materials in extreme conditions and superconductivity.

What is a PhD?

In the UK, a PhD, or Doctor of Philosophy, is a high level postgraduate academic degree typically carried out over 3-4 years. PhD students must undertake their own original research in their field, and submit a thesis or dissertation for examination at the end.

“Piled Higher and Deeper” by Jorge Cham. www.phdcomics.com
MEET THE TEAM

The University of St Andrews

Justin Whitehouse
completed his PhD in 2015 at the University of Edinburgh, using statistical mechanics to build mathematical models of mass transport processes. When not at his desk, he likes football, board games, and getting out to the highlands!

Chris Hooley is a Senior Lecturer in theoretical condensed matter physics at St Andrews, and also Operations Director of the Scottish Doctoral Training Centre in Condensed Matter Physics

The University of Edinburgh

Heriot-Watt University

Art is a 3rd year PhD student at Heriot-Watt University, where he uses lasers and optics to study atomically thin materials like graphene. Art is a munro-bagger, a TED and film enthusiast, and passionate about food - he cooks a lot.

Section Editors:
Pressure Mungo Frost
Soft Matter Toby Searle
Quantum Thinking Carole Addis
Superconductivity Calum Lithgow & Matt Neat

Meet the authors of this issue on pages 5 and 6

supported by:

Physics Scotland
WHAT IS CONDENSED MATTER PHYSICS?

Well, basically, condensed matter physics is the study of ‘stuff’. This stuff, this condensed matter, is everything you interact with in your daily life, and more.

There are the traditional hard materials such as metals and minerals, and the things you build cars and bridges out of. Normally scientists want to tinker with their atomic structures to make them, for example, harder or stronger, but they are also interested in how they behave under extremes of temperature and pressure, to find out what our own Earth is like on the inside, as well as distant moons and planets. (See: Extreme Pressure)

Then, there are more clever materials, like the ones your smartphone screen is made from, or the chips in your computer. For these, scientists start thinking about how to make them do things, like display your latest selfie in high resolution, or respond to your fingers swiping across their surface.

We can go deeper into the materials still, and try to harness their quantum properties - that mysterious weirdness which allows sub-atomic particles to be in two places at once - to try and build quantum computers and powerful superconducting magnets. (See: Quantum Thinking, Superconductivity)

The examples so far have been ‘hard’ stuff, but ‘soft’ stuff is just as interesting too. Scientists somewhere once had to figure out how to make toothpaste solid enough to stay on your toothbrush, but fluid enough to be spread around your mouth. Foodstuffs, such as chocolate and caramel, also get a surprising amount of scientific attention. How do you improve their texture, or make them flow into their moulds better?

The medical and pharmaceutical industries are also interested in soft stuff, like creams and gels, from the point of view of drug delivery and effectiveness. (See: Soft Matter) They are also interested in living things, such as bacteria. An important part of ‘soft’ condensed matter physics is learning how to control and manipulate bacterial colonies.

All in all, condensed matter physics is the study of lot more different types of ‘stuff’ than there is space to mention here, and is a very exciting field of physics to be working in right now!
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Daniel recently finished his PhD research which involved conducting experiments on materials with exotic new phases that emerge under extreme conditions. That can mean ultra-low temperatures, high magnetic fields, or high pressures. He started out his research in St Andrews before moving to Dresden, Germany, where he not only had to struggle with some terribly complicated physics, but also the notoriously difficult German language. He spent a lot of his time preparing high quality crystal samples and measuring their properties using different cryogenic systems. Collaborating with theorists was also an essential part of his work, in order to interpret and make sense of the data he collected. Daniel is currently working as a patent attorney in the fields of electronics and engineering.

Matthew is a 3rd year PhD student at the University of St Andrews, investigating the magnetic ordering and superconductivity in heavy-fermion materials, using scanning tunnelling microscopy at temperatures close to absolute zero and in very high magnetic fields. He tells his mum and the research council that he is researching magnetic field induced quantum criticality as an excuse to break electronics and waste precious liquid helium.
Meet The Authors

Ferromagnetic Superconductivity

Calum completed his PhD at the University of St Andrews, working on ferromagnetic superconductors. He subjects his samples to extremely low temperatures, very high magnetic fields, and sometimes also high pressures, to measure their electrical and magnetic properties. He aims to find out how magnetic and superconducting states coexist in these materials by investigating what's known as quantum criticality, where the ferromagnetic transition temperature is suppressed to absolute zero by applying pressure or a magnetic field. He is now working as a postdoctoral researcher at the University of Edinburgh.

High Temperature Superconductivity

Steve is a 4th year PhD student at the University of St Andrews and visiting fellow at Cornell University, USA. He researches a family of high temperature superconducting materials known as the cuprates. Using a technique called scanning tunnelling spectroscopy he investigates the coexistence and interplay of superconductivity with density waves. He will begin a postdoctoral research position shared between St Andrews and Cornell later this year.

The Super Electric Generation

Duncan is an experimental physicist in the final year of his PhD at the University of Edinburgh. With a keen interest in material applications, he creates devices to induce and investigate superconductivity in a range of materials by use of electrostatic doping and hopes to explore this effect under high pressures as well.
A WHIRLWIND INTRODUCTION TO SUPERCONDUCTIVITY

Superconductivity could bring on a new technological revolution. But what exactly is superconductivity?

Dan Brodsky

Superconductivity is without a doubt one of the most exciting and strange physical phenomena ever discovered. Today, more than 100 years after its initial discovery, superconductivity is still the focus of a huge body of ongoing research, with physicists across the world working around the clock to unlock all of its secrets. So, what is superconductivity and why is it so fascinating?

If you take a look around you, chances are that you are surrounded by electrical appliances of all sorts, from simple light bulbs to radios or computers. These all consume energy in the form of electricity which is carried by metal wires - typically copper or aluminium. When electricity passes through these metals, they heat up and cause some of the transported energy to be lost. For example this is why computers need fans to evacuate the large amounts of heat they generate and keep them cool. Metals heat up when an electrical current passes through them because of their electrical resistance \( R \). The power \( P \) dissipated by a conductor in units of Watts is given by the formula \( P=I^2R \) (\( I \) is the electrical current passing through it). In fact close to 10% of the energy produced by power plants is lost in the power grid before it reaches the consumer because of the resistance of the transmission lines.

A superconductor is a material whose resistance drops to zero when it is cooled below a certain critical temperature. This means that it can carry large currents without dissipating any heat - in other words with 100% efficiency! Surprisingly, close to half of all the elements in the periodic table become superconducting under the right conditions. Another effect of superconductivity is the so-called Meissner effect. This causes a superconductor to expel any magnetic field which tries to pass through it, allowing one for instance to levitate a magnet over a superconductor. Common examples of superconductors are lead, mercury or lithium.

The catch is that the critical temperatures of these

Physicists are working around the clock to unlock all of superconductivity's
superconductors are extremely low, for example that of lead is -266 °C. This makes using them for everyday life applications somewhat challenging, as they need to be cooled down using a cryogenic liquid. Normally, this needs liquid helium although in some special cases liquid nitrogen is sufficient. That said, there do already exist a number of technological applications where superconductors are widely used. For example, in Magnetic Resonance Imaging (MRI) scanners in hospitals, a superconducting coil is used to produce a very strong magnetic field. This allows doctors to take high quality images of their patients’ insides, giving them a valuable new tool for performing diagnostics. The first liquid-nitrogen-cooled superconducting power transmission cables are already being used in several cities, such as Essen in Germany. They turn out to be cheaper to use than conventional cables, and allow much more energy to be transported. Wilder applications that have been suggested include Maglev trains, which use superconducting magnets to levitate the train, or super-fast digital circuits. But for the moment the cost and technical difficulty of keeping superconductors cool has prevented a widespread use of them.

Superconductivity was first discovered by the Dutch physicist Heike Kamerlingh Onnes in 1911, a few years after he had succeeded in liquefying helium (helium’s boiling point is at -269 °C, just two degrees above the temperature of outer space!). He was measuring the resistance of mercury at low temperatures, and to his utmost surprise and bewilderment found that his sample’s resistance vanished altogether below -269 °C. Hastily checking all of the wires to make sure that there wasn’t a short-circuit anywhere, he quickly realized that he had discovered a new phenomenon. Following his discovery, a whole series of materials were tested and found to be
superconductors. Materials with higher and higher critical temperatures were being found, however none were higher than -250 °C, which was thought to be the theoretical limit.

Ever since Kamerlingh Onnes had reported his discovery, theoretical physicists puzzled over the origin of superconductivity in an attempt to explain this strange phenomenon. The problem was finally cracked (or so it seemed) in 1957 by John Bardeen, Leon Cooper and John Robert Schrieffer with the publication of their seminal paper “Theory of Superconductivity”, which won them the Nobel prize in physics in 1972. In this paper they describe how at the critical temperature, electrons enter a special quantum state in which they pair up to reduce their energy. In doing so they can waltz gracefully like a couple of dancers through the crystal lattice without bumping into anything, leading to the vanishing of all electrical resistance. This theory described beautifully all of the experimental data of the time, and it was thought that the superconductivity problem could be filed under “case closed”.

It therefore came as a big surprise when in 1986
Georg Bednorz and Alex Müller discovered the first “high-temperature” superconductor - a ceramic compound with a transition temperature of -238 °C. This led to an avalanche of new discoveries, with the highest reported transition temperature quickly climbing above -140 °C by 1990.

One huge advantage of these “high-temperature” superconductors is that they can be cooled by liquid nitrogen, whose boiling point is at -196 °C, and which is cheaper, more abundant and easier to use than liquid helium.

Suddenly the field of superconductivity was split wide open again, as none of the new superconductors followed Bardeen, Cooper and Schrieffer’s “Theory of Superconductivity”. Physicists quickly realized that they were dealing with materials with huge complexities, and that this was no trivial problem to solve. Today, 30 years after Bednorz and Müller’s breakthrough, the mechanisms driving high temperature superconductivity are still largely a mystery, and there exists no theory which can explain how superconductivity works in all of these materials. Yet understanding these materials is crucial if we wish to be able to design a superconductor that will work at room temperature - for that is in many ways the ultimate goal. There is no law of physics which says that superconductivity cannot exist at room temperature, and many physicists are convinced that it is only a matter of time and effort before a room-temperature superconductor is discovered. That would be truly revolutionary.

In the following articles we will learn more about superconductivity, starting with a deeper look at BCS theory, or “conventional superconductivity”, described by Matt Neat. Following this, Calum Lithgow will tell us why understanding the magnetism of these materials is important for superconducting technologies. Another significant technological difficulty is getting superconductors to work at high temperatures. Stephen Edkins will describe how high-temperature superconductors were discovered and why that was so surprising and exciting for physicists at the time, and finally Duncan McCann will explain how we can doping to create high-temperature superconductors to hopefully make some exciting potential technologies a reality!
CONVENTIONAL SUPERCONDUCTIVITY

How can we understand the strange behaviour of electrons in superconductors?

MATTHEW NEAT with thanks to EDMUND BENNETT

Ever since superconductivity was discovered by Kamerlingh Onnes in 1911, there have been great efforts to try and explain the phenomenon. If electrons are moving through metals with no dissipation of energy, something strange must be occurring for them to be seemingly unaffected by the structure of the material and other electrons.

The best known theory for how this happens is BCS theory, proposed by Bardeen, Cooper and Schrieffer in 1957. It describes how an effective attractive interaction between electrons in a crystal can lead to electrons pairing up and behaving as a collective fluid, producing the famous phenomena of persistent currents and magnetic levitation.

So the first question you might ask is, how can electrons attract each other? Surely two negative charges should normally repel each other? But that’s in empty space - these electrons, however, are inside a material (a lattice of positive ions), which can respond as they move through it. As one electron moves, it attracts the ions around it, and distorts the lattice. The electron moves on quickly, but the lattice relaxes back to its initial shape much more slowly. This means that, for a while, there’s an excess of positive ions where the first electron used to be - and this can attract a second electron. The trick, in other words, is that the attraction is delayed: the second electron is drawn to where the first one used to be, not where it is.

Something strange must be occurring for the electrons to be seemingly unaffected by the material's structure or other electrons.

How can electrons possibly attract each other?

Electrons can attract each other via the interaction with the lattice of ions.

Figure 3. The laws of electrostatics - repulsion and attraction.
For a more everyday analogy, you could imagine yourself sat in the bath with two rubber ducks and lying very still. If you were to carefully move rubber duck number one, through interaction with the bathwater, the second rubber duck would follow. So what all this means, is that electrons can attract each other via the interaction with the lattice of ions.

Now that we have an attractive interaction between electrons, what is the next step? Well just to add a bit more complication, there are a few extra conditions that need to be satisfied in this pairing of electrons. First, the net momentum of the pair of electrons has to be zero, so the pairing only occurs with electrons moving in opposite directions at the same speed. Secondly they need to have opposite ‘spin’ to each other. ‘Spin’ is a fundamental property of electrons which makes them act like little bar magnets, with a north and a south pole. For electrons, this internal bar magnet can point in one of two directions: ‘up’ or ‘down’. The electrons in a conventional superconductor always pair up such that one is ‘spin-up’ and the other is ‘spin-down’. In addition, since electrons are constantly attracted to other electrons and ions, these pairs don’t last very long and so they break and reform as frequently as the momentum of these electrons change. You could imagine this as a ceilidh, where partners are continuously swapping around the room.

These pairs of electrons are called Cooper pairs, after Leon Cooper, the physicist who predicted that they would form. But why does the formation of Cooper pairs lead to superconductivity? The answer to this is rather subtle, and it has to do with another fundamental property of particles: whether they are fermions or bosons. A fermion is a particle that will not go into a state if it is already occupied by another fermion: this is called the Pauli Exclusion Principle. (Roughly speaking, two particles in a conductor are in the same ‘state’ if they have the same momentum and the same spin direction.) For bosons, however, no such restriction applies.

Electrons are fermions; but when they pair up, the resulting Cooper pairs behave like bosons. At very low temperatures, all the Cooper pairs drop down to the same lowest-energy state. In that state they all interact with each other, constantly switching partners, and effectively become a single collective entity, known as a ‘condensate’. This is important, because it means that while the Cooper pairs survive, the superconductivity is very robust. It’s this
Figure 4. As one electron moves, it attracts the ions around it, and distorts the lattice. The electron moves on quickly, but the lattice relaxes back to its initial shape much more slowly. This means that, for a while, there's an excess of positive ions where the first electron used to be - and this can attract a second electron. The trick, in other words, is that the attraction is delayed: the second electron is drawn to where the first one used to be, not where it is now.
A technological milestone was to achieve superconductivity above -196°C, the boiling point of liquid nitrogen.

You could imagine this as a ceilidh, where partners are continually swapping around the room.

Figure 5. Just like at a ceilidh, the electrons are continually swapping partners.

collective behaviour of the electrons as a single entity which makes the superconductivity stable.

Superconductors are known as conventional superconductors when they have properties that are accurately modelled by BCS theory as described above; where the superconductivity mechanism comes from the interaction with the ionic lattice (remember the ducks) involving spin-zero Cooper pairs. An example of a conventional superconductor is lead, which has a critical temperature, below which it becomes superconducting, of -265.95°C! BCS theory predicts superconductivity at temperatures below roughly -240°C. Since its development, superconductors have been found to operate at temperatures far too high for BCS theory to work. Others have been found to have strange properties such as Cooper pairs with non-zero spin and unlikely coexisting states such as ferromagnetism (like an iron bar-magnet). The first high temperature superconductor discovered was yttrium barium copper oxide (YBa$_2$Cu$_3$O$_{6+x}$), which was found to be superconducting at -181°C for a compound with x = 0.15 - above the boiling point of liquid nitrogen! Other strange superconductors include URhGe which is ferromagnetic and UPt$_3$ which is antiferromagnetic. These non-BCS superconductors are known as unconventional superconductors and will be discussed further next.●
Solving the Catch-22 of Superconductors

Calum Lithgow

There are two big challenges in developing superconductors to fulfil their immense potential and become a common feature of modern technology. The first of these is raising the temperature at which they work from far below any naturally occurring temperature on Earth to something more manageable, like the temperature of your living room. This would allow us to use superconducting circuits in electronic devices like computers and smartphones without needing to keep them in liquid nitrogen (inconvenient to say the least). Research into so-called ‘high temperature’ superconductivity is summarised in an article by Stephen Edkins on page 18 of this magazine.

The second challenge facing superconductors is increasing the magnetic field up to which they work, called the upper critical field. This isn’t so important for your superconductor-filled laptop or phone, but it’s very important if you want to make big, powerful magnets. The unfortunate thing is that currently the main use of superconductors is to do just that. There are many applications for strong magnets in modern technology: electric motors (for use in electric cars, for example, a clear case where the superconductors would need to work to fairly high temperatures), power generators (like those in wind turbines for instance), medical brain imaging devices, and the magnets that direct proton beams in particle accelerators like those based at CERN.

So how do we get around this awkward (and somewhat ironic) problem, that superconductors are mainly used to make strong magnets but strong magnetic fields stop them from working? An interesting idea is to start with materials that themselves are magnetic, the logic being that if we can make a superconductor out of a magnetic material it surely can’t mind magnetism all that much, can it? In fact that’s exactly what we do find with a particular recently discovered ferromagnetic superconductor, URhGe: it stays superconducting up to and beyond the highest continuous magnetic fields the
world can currently produce. We don’t know how high the field has to be to break it, since we can’t actually produce a field that powerful! A promising start, but with one major issue: we don’t really know how ferromagnetic superconductivity manages to exist. We’ve discovered an exceptionally interesting material, which is fortunate, but we’re yet to understand exactly how it works.

Before we discuss ferromagnetic superconductivity any further we need to understand what ‘ferromagnetism’ is and thus why it’s so surprising that it should coexist with superconductivity. In general, magnetism arises due to the motion of charge, or in other words moving charges create magnetic fields. This is essentially how we make powerful magnets: we wind a coil of wire and pass an electric current through it, and the movement of the charged particles that constitute that current, the electrons in the wire, gives rise to a magnetic field. This is called an electromagnet. But we also have things called permanent magnets, which you’ll probably be familiar with from having them stuck to your fridge. These magnets are made from permanently magnetised material. The question is then, where does the magnetism come from in this case?

It actually also comes from the electrons in the material. As we saw above, each electron has a ‘spin’: a little bar magnet that can point up or down. The magnetic field generated by each of these spins is tiny. However, there are about a million billion billion spins in something the size of a fridge magnet, so if all the little bar magnets point in the same direction then the total magnetic field can add up to something pretty substantial. The combined force is big enough for a fridge magnet to overcome gravity, the force of the entire mass of the Earth pulling it down, and stick to your fridge.

So that’s ferromagnetism: when all the magnetic moments point in the same direction and set up a permanent magnetic field. We understand that pretty well. Ferromagnetic superconductivity, however, is another story.

Conventional superconductivity (as discussed in Matt Neat’s article on page 11) requires pairs of electrons with spins pointing in opposite directions. Let’s name these opposite directions ‘up’ and ‘down’ so that it’s easier to talk about them. In a ferromagnet the spins have to either all be pointing up, or they all have to be pointing down (which is the same thing really, depending how you look at it), such that all the moments add up. The
conventional theory of superconductivity, however, has half the electrons spin-up and half spin-down, which would give us a non-magnetic state, since all the magnetic moments would cancel each other out.

Now we begin to see why high magnetic fields usually destroy superconductivity. The magnetic moments of the electrons all want to swivel around to line up with the external field (this is what makes a compass needle, a ferromagnet, point towards the Earth's North pole) and this influence disrupts the equal spin-up/spin-down balance required for conventional electron pairing, breaking the superconductor.

But in a ferromagnet all of our spins are already pointed in the same direction, so an applied magnetic field won't really bother them; they don't need to preserve this spin-up/spin-down pairing. In general the spins in a ferromagnet will just swivel around like a compass needle and nothing much about the physical state will change. This is good news, this is why we observe such extraordinarily high upper critical fields in the aforementioned ferromagnetic superconductor, which if we properly understood it would hopefully allow us to one day make extraordinarily powerful magnets. The bad news is that we don't have an established theory of how we can have a superconductor when all the electron spins point in the same direction. Something similar happens in liquid

The conventional theory of superconductivity, however, has half the electrons spin-up and half spin-down, which would give us a non-magnetic state.

The bad news is that we don't have an established theory of how we can have a superconductor when all the electron spins point in the same direction.

Figure 7. In a ferromagnetic lattice, all the magnetic moments point in the same direction.
helium-3, but adapting the theory to deal with these metals is proving a challenge!

We’re not giving up any time soon though. Ferromagnetic superconductors have only been discovered this side of the new millennium, relatively recently compared to conventional superconductors which were discovered in 1911, and it wasn’t until the 1950s that we eventually found a theory to explain them. So we’ve still got a few decades to go before we miss out on the chance of beating that record! Research into unconventional superconductivity continues all over the world to find answers and we understand a little bit more every day. Hopefully we’ll have the complete picture soon!

Figure 8. In ferromagnetic superconductors, the pair of electrons have spin pointing in the same direction.

HIGH TEMPERATURE SUPERCONDUCTIVITY

Bringing superconductivity out of the cold.

STEPHEN EDKINS

The field of superconductivity is littered with serendipitous discovery and this has never been more applicable than to “high temperature” superconductivity. By the 1980s physicists believed that they had a good understanding of superconductivity based upon the Nobel Prize winning BCS theory by Bardeen, Cooper and Schrieffer. It was widely accepted that an upper limit on the critical temperature, \( T_c \), for “conventional” superconductivity with electron pairs glued together by lattice vibrations was \(-248^\circ C\) to \(-243^\circ C\). Berndt Matthias, a prolific discoverer of superconducting materials, went so far as to give a set of rules for the kinds of materials to look for superconductivity in. In particular he recommended trying materials with crystal structures with a large amount of rotational symmetry, as well as materials that are electrical conductors, non-magnetic and not oxides.

Despite these rules, in 1986 two researchers at IBM, Bednorz and Müller, made waves by discovering
superconductivity at around -238°C. In addition to exceeding previous estimates of the maximum possible temperature for superconductivity, the material was formed from a magnetic insulator and consisted of two-dimensional planes of copper and oxygen atoms, meaning it had a lower symmetry structure than the mostly three-dimensional “conventional” superconductors. This represented such a huge violation of the amassed wisdom of physicists at the time that it breathed new life into a field that many thought was on its last legs. The subsequent discovery of superconductivity above the boiling point of liquid nitrogen in Yttrium Barium Copper Oxide (YBCO) led to widespread hope of realising technological applications without the use of expensive liquid helium.

The family of superconductors containing copper and oxygen atoms, of which YBCO is a member, is known as the cuprates. The highest $T_c$ observed in a cuprate material to date is -135°C and such high transition temperatures have led an army of researchers and technologists to develop technologies that exploit the properties of high temperature superconductors. Equally, these materials reveal a failure of many of the models of condensed matter physics that were built up over the twentieth century and have spawned a revolution in theory and experiments designed to understand them.

The obvious application of high temperature superconductors is to transmit power over long distances without wasting any energy as heat. However, the difficulty and expense of fabricating and cooling these

These materials reveal a failure of many of the models of condensed matter physics that were built up over the twentieth century.

Figure 9. Trials of superconducting power cables have begun in the US.
wires has thus far precluded such an application on a large scale. The ability of superconducting transmission lines to carry very large currents compared to the same volume of a normal conductor such as copper has led to their use in dense urban environments. In places where more power is needed but creating more space for underground wires is prohibitively expensive, high temperature superconducting transmission lines have come to the fore. Another property exploited to great effect is the large change in resistance between the superconducting and normal (non-superconducting) state of the material. This can be used as a fast switch that responds to a current surge and protects one part of a power distribution network from a fault in another.

From the point of view of fundamental physics, the cuprate high temperature superconductors present many questions. It is widely accepted that their superconductivity is unconventional and is not caused by lattice vibrations. Whilst great progress has been made towards determining what binds charges into pairs at such high temperatures, no consensus has yet emerged.

In 2006 the first of a new generation of high temperature superconductors were serendipitously discovered whilst searching for a transparent semiconductor to be used in display technologies. These materials share the property that they contain iron and also exhibit both superconductivity and magnetism. The highest critical temperature in these materials found so
far is -217°C. Like the cuprates, these compounds are thought to be unconventional superconductors. These materials are providing more clues about unconventional superconductivity and what conditions foster high $T_c$. Despite their transition temperatures being relatively small compared to those of some cuprates, the iron based superconductors are technologically attractive because, unlike the cuprates, they are easily made into wires.

The pleasing combination of fundamental scientific mystery and technological applications make the high $T_c$ superconductors such an interesting and attractive area of research for scientists and engineers. For society at large, high temperature superconductors are not the technology of tomorrow, they are the technology of today and look set to play a continued role in our energy production, infrastructure and security. With the discovery of a second family of high $T_c$ materials we can hope that high $T_c$ superconductivity is perhaps not so rare amongst materials and that yet more families of high temperature superconductors will be discovered and exploited for our benefit.

**THE SUPER ELECTRIC GENERATION**

Jump starting the superconducting technology revolution

**DUNCAN MCCANN**

Imagine a world where ultra-fast magnetically levitating transport is everywhere, where electricity is transmitted with almost no wastage whatsoever and all power lines are simply gone, replaced by a single thin wire buried underground. This is the world of tomorrow, a world filled with superconductors, the world of the super electric generation.

When a superconducting material is cooled below the critical temperature its resistance drops to zero, meaning electricity can run through a material without heating it up. In other words none of that electricity will be lost through heat like it usually is in, for example, regular power lines, thus allowing them to become 100% efficient. Without resistance such a material could carry even more electricity and be used to create extremely strong magnetic fields, ones that can be used in
magnetically levitating transportation or medical imaging devices. In fact almost all MRI machines in hospitals use superconducting wires to create the high magnetic fields they need. A world where superconductors are commonplace is potentially just around the corner!

But what materials are superconductors? It turns out most elements in the periodic table can become superconductors but only at extremely cold temperatures (typically -263°C and below). Such low temperatures are impractical for most of the applications we wish to use superconductors for but luckily many compounds of these various elements become superconductors at much higher temperatures. The most promising compounds are the High Temperature Superconductors, the best of which becomes a superconductor at -135°C, which while still very cold is a temperature we can readily achieve with refrigeration technology.

So how do we create such a high temperature superconductor? In general we take a starting compound, usually an insulator, and try to incorporate a certain amount of a particular element into it through a chemical process known as doping. The more of an element we incorporate the more we change how that compound behaves until it reaches a point where it becomes a superconductor! In fact as we can see in Figure 11 the amount of the element we incorporate even controls the temperature at which a compound becomes a superconductor. If we incorporate just the right amount of an element we can produce a compound that goes superconducting at its highest possible temperature, $T_{c,\text{max}}$.

So if we can already create materials with the highest possible superconducting temperatures (that we know of) then why are we not already living in our world of the super electric generation? Unfortunately creating large amounts of superconductors through this chemical process is still fairly complicated. Incorporating just the right amount of an element into our starting compound requires a significant amount of equipment and strict control of all the conditions. Even a tiny variation in this process could cause our material to have a lower superconducting temperature than the maximum we wish. We are also unable to reverse this process, so if the amount of the element we have incorporated is slightly off then that is the amount we have in our material permanently. Surely there must be a better way? If only we could simply flip a switch and make a material go
superconducting at the maximum temperature we wish. Well in fact there is a way to do precisely that!

‘Electrostatic doping’ is another method by which we can alter a compound to the point where it becomes a superconductor. Instead of incorporating another element into it chemically we simply apply a very strong electric field. Such an electric field causes the same effect as adding an element: the stronger the field applied to our starting compound the more its behaviour is changed, by essentially altering the concentration of electrons at its surface. This changes it from being an insulator to a superconductor if we apply a strong enough field. If we vary the strength of this electric field then we can also choose the temperature at which the material becomes a superconductor. We can control precisely what level of doping we want and settle on the maximum possible temperature for superconductivity! And if we turn off the field the material simply returns to its initial state; we are not locked to one particular level of doping such as with the chemical process. The only hitch? Generally you can’t create a strong enough electric field through conventional means to induce superconductivity in most materials, which leads us to an unconventional solution: the Electric Double Layer.

The Electric Double Layer is a novel means of creating extremely strong electric fields. The essential set up behind it can be seen in Figure 12. We have one metallic plate (labelled “Pt gate”) separated from the
We can change a compound from an insulator to a superconductor if we apply a strong enough electric field.

If we vary the strength of this electric field then we can also choose the temperature at which the material becomes a superconductor.

Figure 12. An Electric Double Layer Transistor where an applied voltage effectively creates a small separation between charge layers and hence an extremely high electric field. The material we are attempting to dope, LaSrCuO (LSCO) in this instance, by an electrolyte: a liquid of positive and negatively charged ions (invisible in the figure). When a voltage is applied between these plates it attracts the ions within the electrolyte to each plate, positive ions at one and negative ions at the other. This layer of ions effectively causes electrons in our material to accumulate on the other side of interface; the separation between these two layers of charges is only about one billionth of a metre and hence creates an extremely strong electric field at the interface. If the voltage is increased, more ions accumulate at the plates and the field becomes even stronger. Thus this Electric Double Layer (EDL) can generate high enough electric fields to dope a material into its superconducting state and we can alter the associated superconducting temperature merely by varying the voltage applied.

Many devices can be designed to take advantage of the Electric Double Layer, allowing superconductivity to be established more easily than by chemical means in a wide range of materials as well as having their superconducting temperature continuously modified if necessary. Such devices will allow applications of superconducting technology to become more commonplace and help catapult us forward into the super electric generation.
IMAGE CREDITS

On the Covers


Back - Calum Lithgow, 2015
"A dilution refrigerator in the foreground, ready to go into the liquid helium filled cryostat in the background, which can cool materials down to 0.01 K (-273 °C) while applying magnetic fields up to 17 T”

Inside Cover

See below

1 Hello!


3 What is Condensed Matter?


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7 A Whirlwind Introduction to Superconductivity

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Figure 2 – "Sc history" by Department of Energy (Transferred by RJBl/originally uploaded by Materialscientist) - http://www.ccas-web.org/superconductivity/#image1 (Originally uploaded on en.wikipedia). Licensed under Public Domain via Commons - https://commons.wikimedia.org/wiki/File:Sc_history.gif#/media/File:Sc_history.gif

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Figure 3 - Repulsion and Attraction - Justin Whitehouse, 2015


Figure 4 - BCS Lattice - Justin Whitehouse, 2016

Figure 5 - Ceilidh, by Frederique Bellec http://frederiquebellпечography.com/c eilidh/#24
Retrieved 1st April 2015
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Figure 6 - École Polytechnique Montréal, Laboratoire de Spectroscopie des Matériaux et des Nanostructures, http://lsmn.polymtl.ca/index.php?SOC - modified, retrieved May 2015 (see also: http://www.polymtl.ca/lsmn/)

Figure 7 - Justin Whitehouse, 2015

Figure 8 - Calum Lithgow, 2014

18 High Temperature Superconductivity


Figure 10 – “Comparison of power equivalents of overhead power lines, copper underground cables, and HTS underground cables,” American Superconductor Corporation. https://www.bnl.gov/cmpmsd/AdvancedEnergyMaterials/AppSupcon/

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Figure 11 - Phase Diagram

Figure 12 - LaSrCuO-based electric double layer

http://rstas.royalsocietypublishing.org/content/370/1977/4890

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25 Image Credits

On the covers:
Front: Levitation of a magnet on top of a superconductor.
Back: A dilution refrigerator which can cool materials down to 0.01 K (273 °C).
(credits page 25)