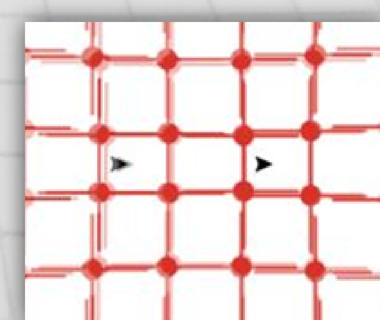
Superconductivity

An Introduction For High School Students



Shawn Liner

Acknowledgements

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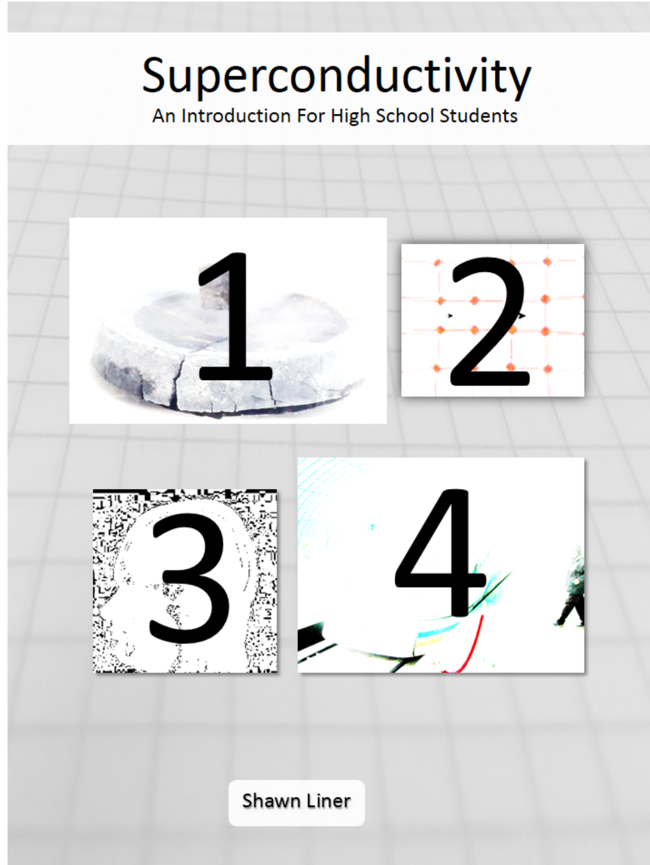
Superconductivity
An Introduction For High School Students
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Shawn Liner

How to Use This Ebook

This Book was written as an introduction to individuals curious about superconductivity. It was born from a frustration in getting a clear idea about superconductivity without getting frustrated on currently available webpages. The target audience is high school students with some science background. However, the casual adult might find it interesting as well. It does not attempt to teach detailed, merely to introduce the topic and hopefully pique curiosity.

Pictures in this book are usually clickable. At the least, clicking a picture will open a larger/ zoomable version of that picture. Some pictures have been enhanced with callouts that allow you to get information on the picture itself.

Video demos have been included which show you a demo that may be done in a classroom. These are labeled "video demos" and are accessed through the table of contents or by clicking the still frame link in the text. It should be noted that videos always stream. Even if you've downloaded the book, you will need internet access to access the videos.

A **Glossary** has been included to help with some introductory words. Words like " **resistance** " have been defined for you. Clicking the bubble to the right of a word will bring up its definition in the glossary. In addition the glossary can be accessed by taping the search button on the table of contents area.

What is a Superconductor

Simply put, a superconductor is material that has zero resistance to electricity.

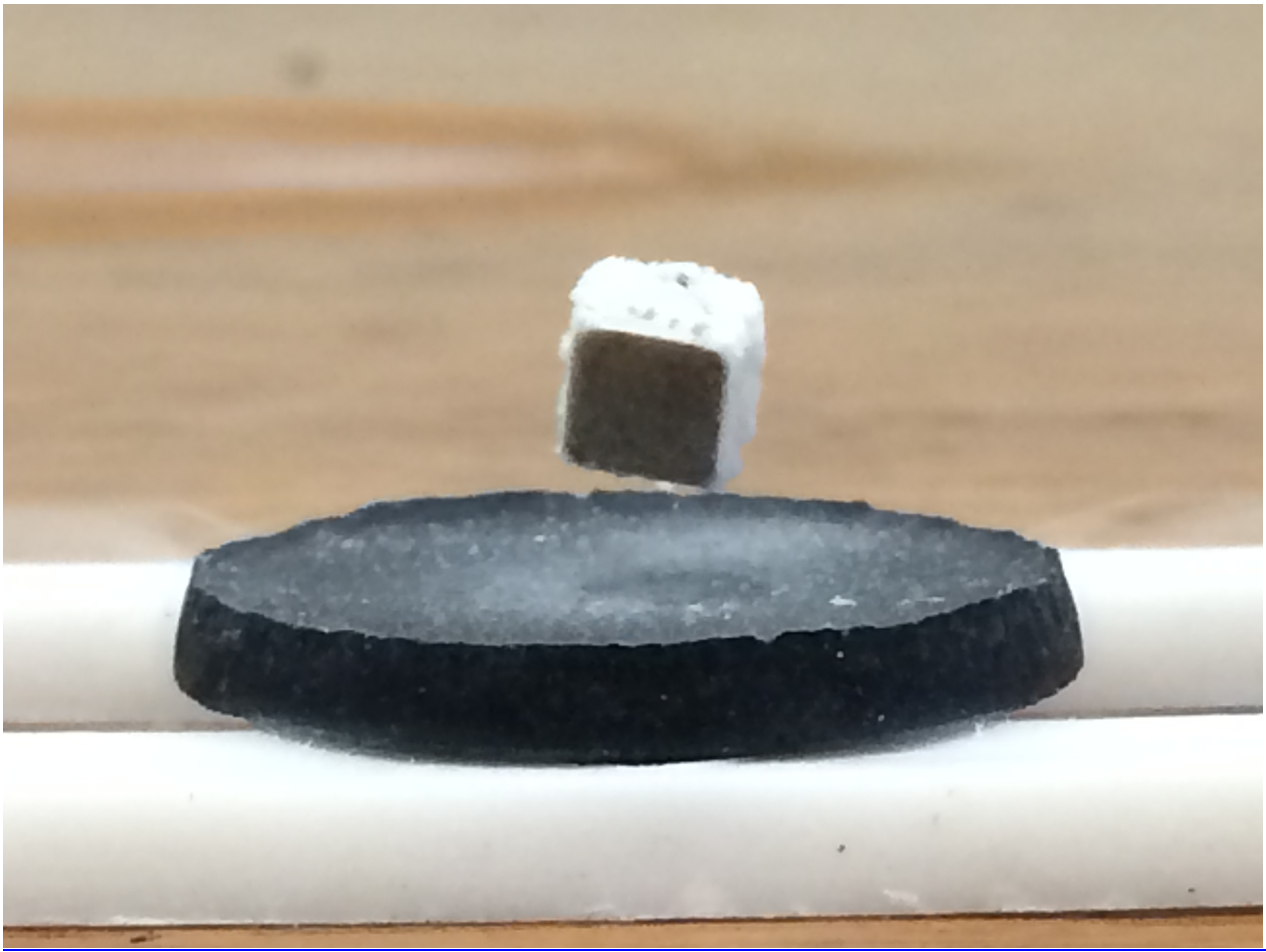


Figure 0 A magnet levitates above a superconducting disk. Shawn Liner

Chapter Objectives

1. State the Electrical Characteristics of a Superconductor.
2. State the Magnetic Properties of a Superconductor.

W

hat is a superconductor? Simply put, a superconductor is material that has zero resistance to electricity. However, that hardly taps the amazing properties of superconductors. They also float above magnets, allow for the detection of very weak magnetic fields, and have the possibility of speeding up our computers.

Even though the physics behind superconductors is not fully understood, superconductors have huge potential in medicine, electricity transmission, transportation, and electronics. Part of what makes superconductors so interesting is how little we know about how they work. If we can apply this technology despite our limited knowledge, image what will come from it with better understanding.

Section 1.1 Electrical Characteristics of Superconductors

Electrical Resistance

Superconductors show zero resistance to electricity. Electrical resistance can be thought of as a materials opposition to the flow of electrical current. It is measured in ohms(). In order to understand why this is so important, it is necessary to understand a little about resistance.

Some materials, such as rubber and plastics, have very large electrical resistance. These materials are called insulators and are used to prevent the flow of electricity. You will see an insulator on the outside of a wire that you use to charge your electronic device. The wire will be coated in a heavy plastic that is designed to protect you from the electric current in the wire. This heavy plastic is the insulator. However, inside the wire is a conductor. Conductors, such as copper and other metals, have very little electrical resistance and are used for wiring in electronics and for electrical transmission.

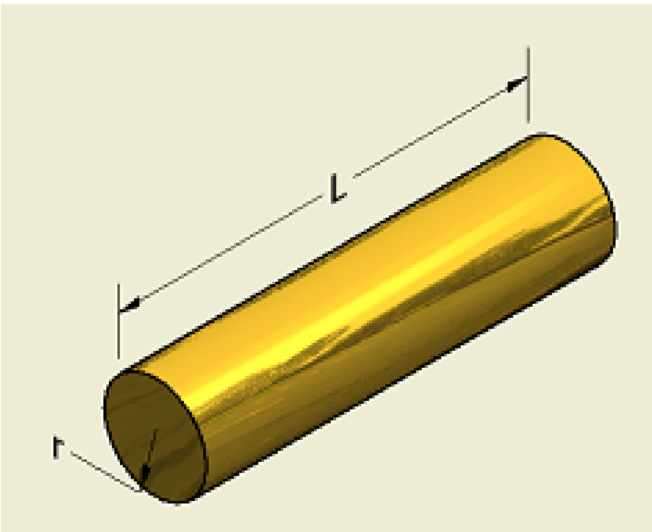


Figure 1.1 A Simple Wire Shawn Liner

Resistance is related to the type of material, its shape, and its temperature. Generally, a sample of material has a higher resistance, the longer it is, and a lower resistance the larger its area. Consider a wire, pictured below, the greater the length of the wire (L), the greater the resistance will be and the greater the area (A), the lower the resistance. The resistivity () is a property of the substance from which the wire is made.

The resistivity of an insulator, like rubber, is around 10^{14} m. On the other hand, a conductor, like copper, has a resistivity of 1.72×10^{-8}m. The low resistivity of copper leads to it being a very efficient conductor, unless its area is small, or its length to long. And wires can get long in many applications. For example a simple electric motor can have 30-40 m of wire in it. And, of course, we want to send electrical power miles from the power plant to our houses. Resistance uses up about 10% of the energy we put into it. That would be like putting 10 gallons of gasoline into your car, but losing one gallon before you could use it! So, how do we decrease resistance?

A couple of easy ideas come to mind. By using large diameter wires we can increase the area of the wire, and therefore decrease the resistance. However, this is a limit to how big of a wire we can use and large wires get expensive. Another option is to use materials, like copper, that are good conductors. Perhaps the best conductor is silver (resistivity=16nm). But, as you can imagine, silver gets expensive to use in wiring a whole city with electricity. As a result we tend to use copper (17nm) and aluminum (27nm). Finally, we can adjust the temperature.

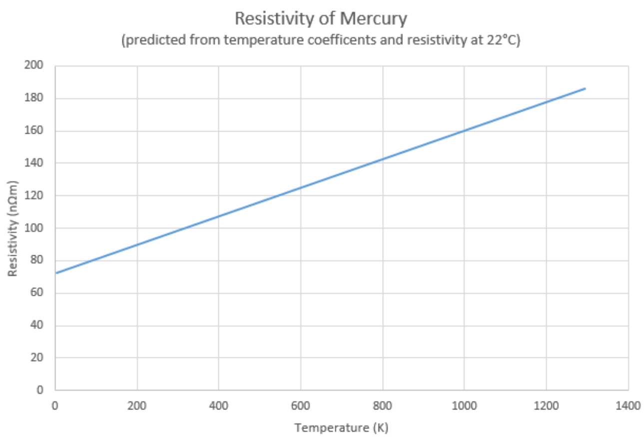


Figure 3 Resistivity of Mercury: Shawn Liner

Most conductors are temperature sensitive. That is, they conduct better when it's colder. For example the resistivity of mercury at 20°C(295K) is 98 nm and it changes by 0.9 nm every degree we cool it down. So we would predict the following graph for the resistivity of mercury.

However, in 1908 a group led by Kamerlingh Onnes was able to liquefy helium. Then in 1911 they used the liquid helium to cool mercury to below 4K (-452°F). A surprising thing happened. Around 4.2K, the resistivity stopped following our prediction, and dropped to zero. Thus we discovered the property of superconductivity.

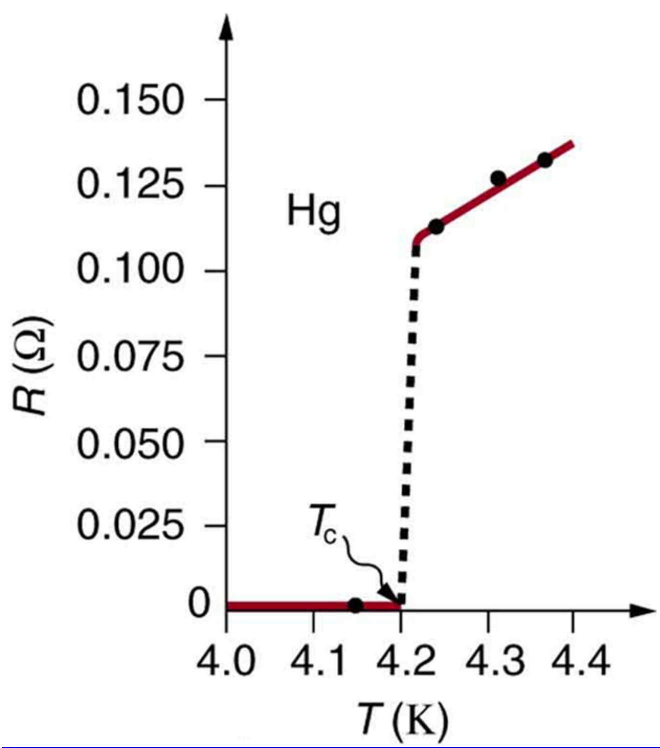


Figure 4 Graph of the resistance of mercury as a function of temperature. Used under creative commons license (OpenStax College)

So it would seem that we would immediately start making electrical wires out of frozen mercury and keep it cold. However, it is very difficult and expensive to keep the temperature low enough for mercury to remain a superconductor. (This temperature is known as the critical temperature, Tc). So, scientists dove into the task of finding materials that would exhibit superconductivity at a higher critical temperatures.

For 75 years (from 1911 until 1986), scientists made incremental steps in critical temperatures. (Figure 5 Historical Graph of Tc). Then in 1987, $YBa_2Cu_3O_7$ (YBCO), was discovered to have a critical temperature above that of boiling liquid nitrogen. This new family of Copper Oxide based materials are called High Temperature Superconductors (HTSC). Liquid nitrogen is relatively cheap and environmentally friendly. Now we had crossed a line that made superconductors much more useful. However, it should be noted that the highest critical temperature on our chart is ~140K. This is still 280°F below room temperature. So we're a long way from being able to use a superconductor without some cooling mechanism in place.

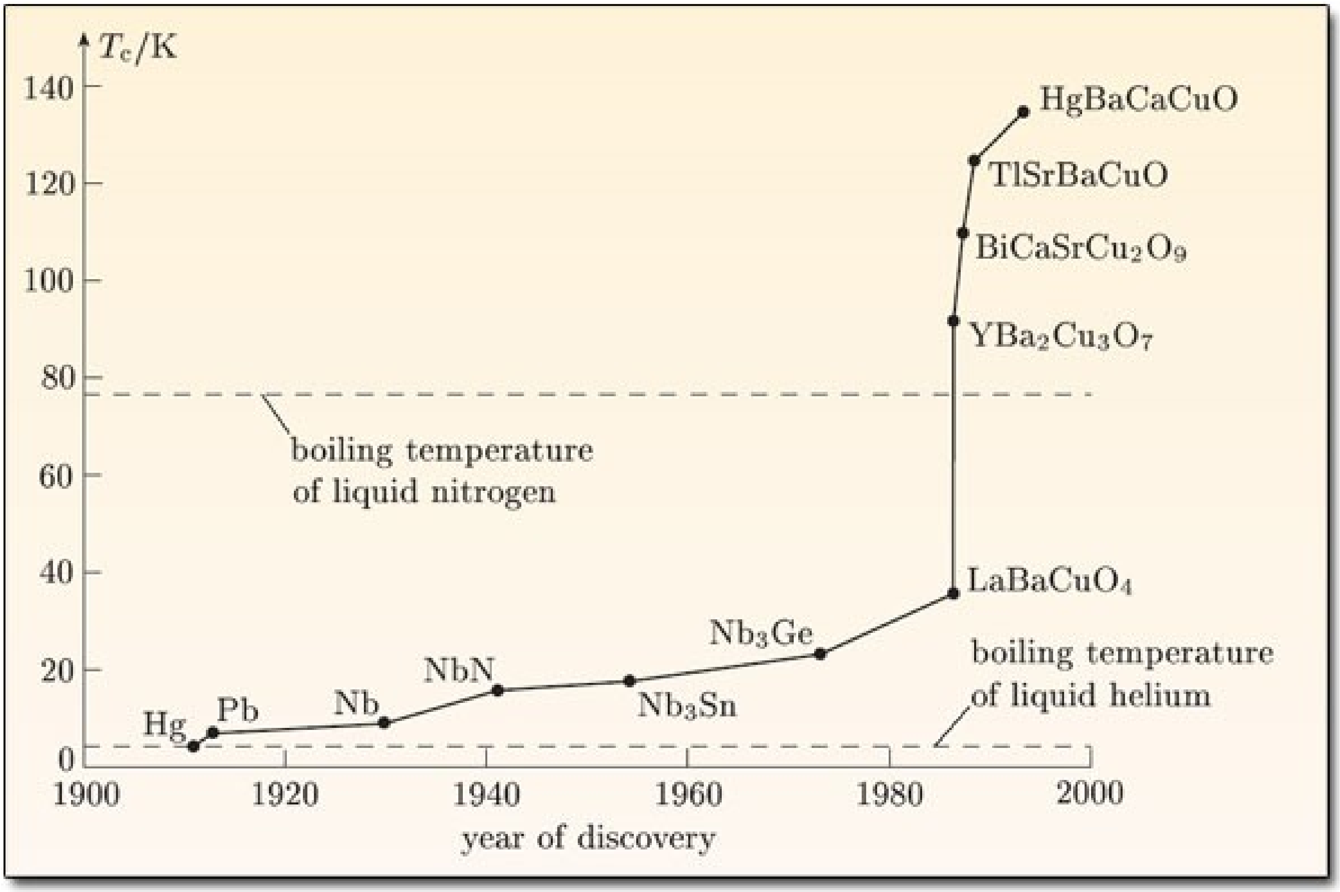


Figure 5 Historical Graph of Tc Used under Creative Commons
(University of Cambridge)

Magnetic Characteristics of Superconductors

What is Magnetism?

Magnetism can be a mystical and confusing thing for many people. So we're going to look at a few basics before we talk about the magnetic properties of superconductors. Most materials fall into one of three magnetic categories, **ferromagnetic** , **paramagnetic** , and **Diamagnetic** .

First, ferromagnets retain magnetization even in the absence of a permanent magnet. This the type that you have experienced when you have used a magnet to hold a note to a refrigerator door. These magnets are magnetic because something in their structure is causing unpaired electrons to spin in the same direction. These spinning electrons act as little tiny magnets and when they are aligned correctly cause the material itself to act as a magnet.

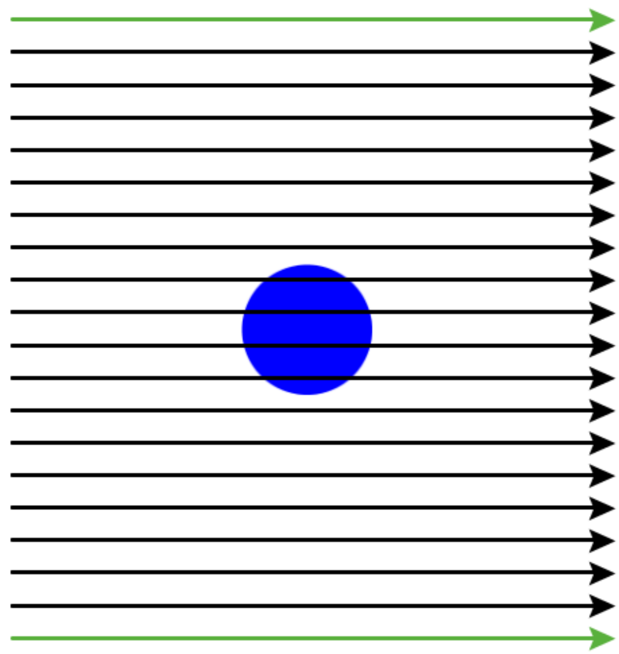


Figure 6 Magnetic Field lines through a paramagnetic material Shawn Liner

On the other hand paramagnetic materials do not have any alignment of their unpaired electrons. However, they do allow magnetic fields to enter their body, which will align their electrons to the field. This gives them temporary magnetic properties and they behave like magnets. Thus they are attracted to magnets. However, when the magnetic field is removed the paramagnetic material's electrons will return to random orientation and the magnetic properties will disappear. Usually paramagnetism is too weak to observe without precise instruments.

Diamagnetic materials “expel magnetic **flux** ” that is to say they do not allow the magnetic fields inside their body. For an analogy think of a boat. A boat “expels water”. As a result of pushing the water out of its interior it will float, assuming that its weight is low enough compared to the amount of water it pushes aside .

A common example of a good diamagnetic material is pyrolytic carbon. In the picture below, a small wafer of pyrolytic carbon is levitating above four neodymium magnets. It actually sits in a dip in the magnetic field created by the magnets. Diamagnetic materials are repelled by magnets. It is important to note that they are repelled by both the north and south ends of a magnet.

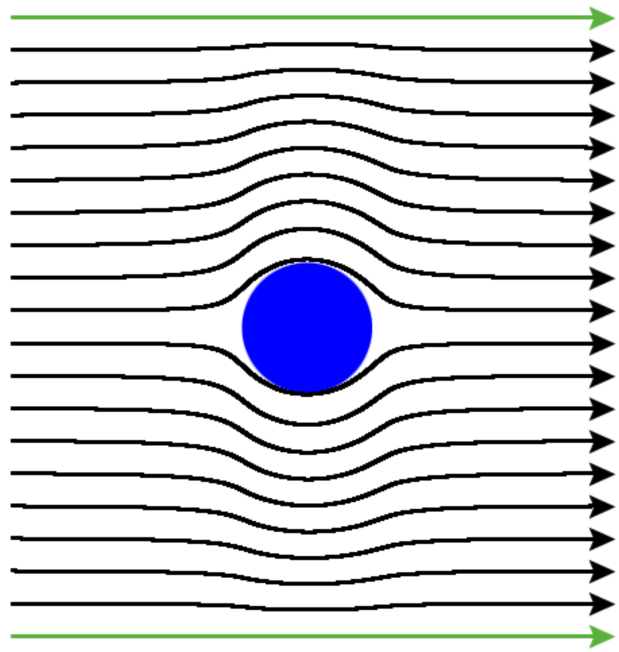


Figure 7 A diagram of diamagnetic material excluding magnetic field lines
Shawn Liner

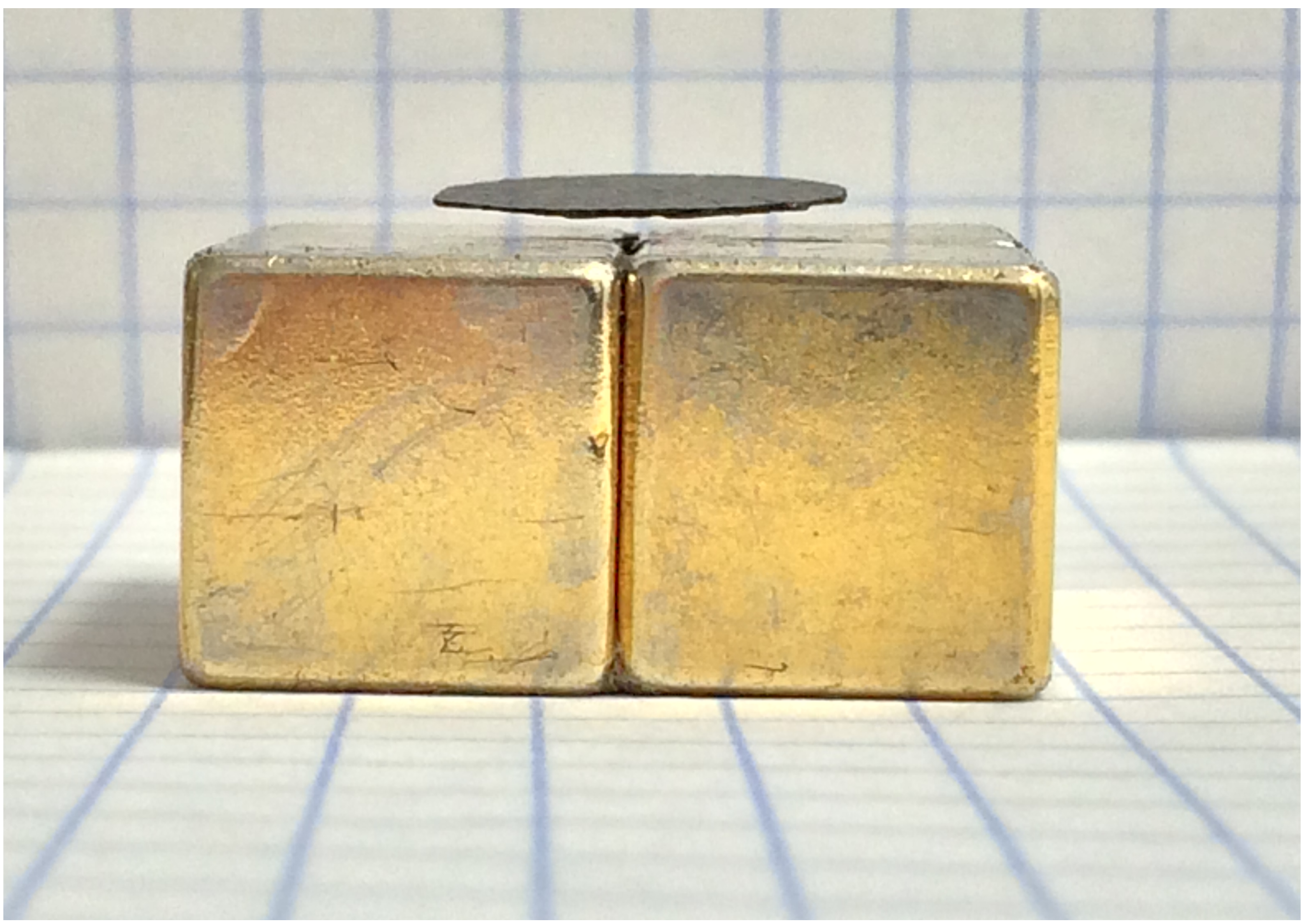


Figure 8 Pyrolytic Carbon as an example of diamagnetic levitation Shawn Liner

Most materials are diamagnetic. In fact you are diamagnetic. However, the force provided by their diamagnetism is very weak. It would take an extremely strong magnet to cause you to levitate. Scientists have created a magnet strong enough to levitate a frog! (See the video here https://www.youtube.com/watch?v=A1vyB-O5i6E). So why is the graphite able to levitate on these magnets? First they are pretty strong magnets, 13200 Gauss compared to about 50 Gauss for a refrigerator magnet. But perhaps more importantly, the graphite disk is a good diamagnet, and is very light.

Superconductors Expel Magnetic Flux

Figure 9 A magnet levitating above a superconductor Shawn Liner

ike the pyrolytic carbon, a superconductor is diamagnetic. In the picture above, you see a magnet levitating above a superconducting disk. In this case we were able to levitate the magnet, instead of a thin, lightweight piece of graphite. However, there are some big differences between the superconducting material and the graphite. First, superconductors are very good diamagnets, better than the graphite, expelling almost all of the magnetic flux. Secondly, superconductors are usually only weakly diamagnetic at room temperature and change to being near-perfect diamagnets below a certain temperature. So the material itself is not diamagnetic, something else is going on to make it that way. (An explanation is given in the theory section.)

Pinning

ype II superconductors have an interesting property where they can allow some magnetic flux inside their interior. (For a detailed explanation as to why, please read the Theory section)

Essentially, this happens when the magnetic field is within a certain range. Too strong and it will destroy the superconducting properties. Too weak and the magnetic field won’t penetrate into the superconductor. The magnetic field lines that do make it into the interior of the superconductor get "pinned" in place and are held to their location inside the superconductor.

The really interesting thing about pinning is that it actually holds the magnet and superconductor to a certain distance from each other. This property is used to help keep magnetic levitation trains on their tracks.

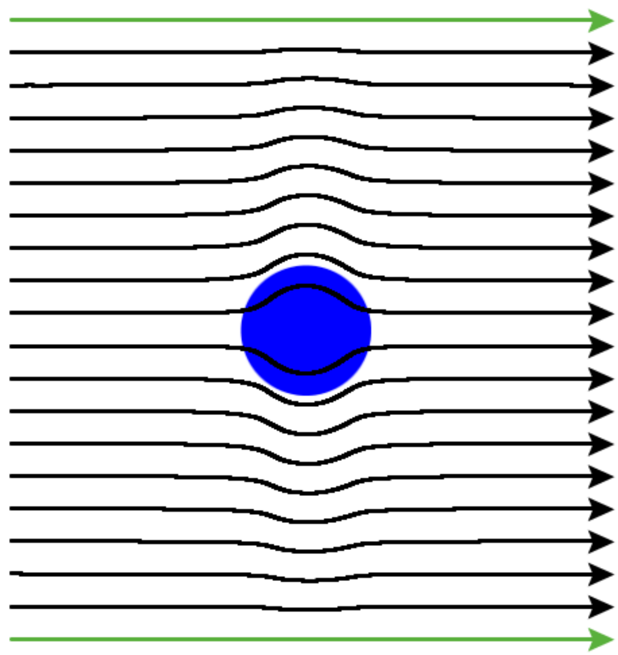


Figure 10 Type II superconductors allow magnetic flux near their surface. Shawn Liner

2 Limitations of Superconductors

Chapter Objectives

1. Understand the temperature restrictions in current superconductors
2. Understand the magnetic restrictions in current superconductors.
3. Understand the electrical restrictions in current superconductors.
4. Understand the physical limitations in current superconductors.

Figure 2.1 Modern superconductors are fragile ceramics. This piece shattered after being dropped from a table. Shawn Liner

Despite their amazing properties, superconductors do have their limitations. In this section we are going to look at some of the biggest limitations to current superconductors. These limitations are considerations that must be taken into account when applying superconductive technology, but they are also the challenge of up-coming scientists. The scientific community is in a continuing battle to overcome these limitations by discovering, or creating, new superconductors.

Section 2.1 Temperature Limitations

Do Superconductors Have to Be Kept So Cold?

Perhaps the most obvious limitation to current superconductors is their need to be cooled well below room temperatures. The temperature below which a material will act like a superconductor is known as the transition temperature. The highest "well known" transition **temperature** is 133 K (-220°F), which is still well below room temperature, normal refrigeration temperatures, even below the temperature of dry ice.

Recent developments have brought us "high temperature superconductors" like YBCO, which transitions above that of boiling liquid nitrogen. This was an important step in the progress of superconductors because liquid nitrogen is relatively inexpensive and environmentally safe.

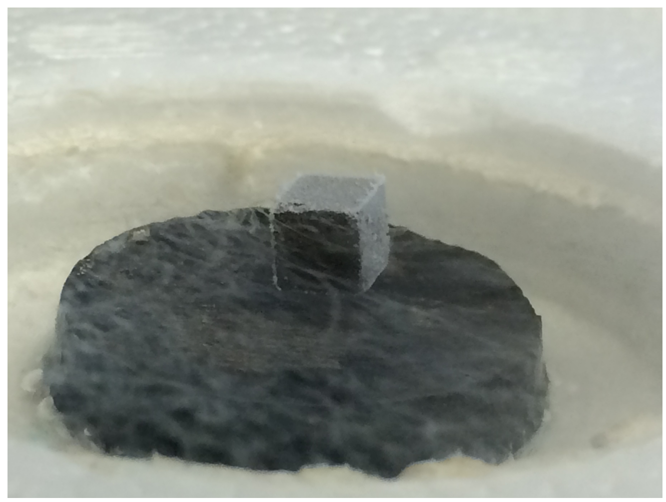


Figure 12 A magnet levitating above a superconducting disk resting in liquid nitrogen to keep it cold. Shawn Liner

The next step to allow superconductors to really take their place in technology would be a superconductor with a transition temperature at least above that of a household freezer. This would allow devices to operate with normal refrigeration. The dream of course would be a " room temperature superconductor" which would work in a normal room. This would allow the big dreams like superconducting computers.

Magnetic Limitations

Could a Superconductor Repel a Huge Magnet and Lift a Building?

Superconductors can expel magnetic field. However, there is a limit to how much magnetic field they can handle. Too much (too strong of a magnet) and they lose their superconducting properties. The maximum magnetic field a superconductor can handle is called the critical magnetic **field** (Bc). It is temperature sensitive. Meaning, that as the temperature goes lower and lower the critical magnetic field increases. So If we tried to use a super strong magnet to lift something really heavy, we would actually cause the superconductor to stop acting like a superconductor.

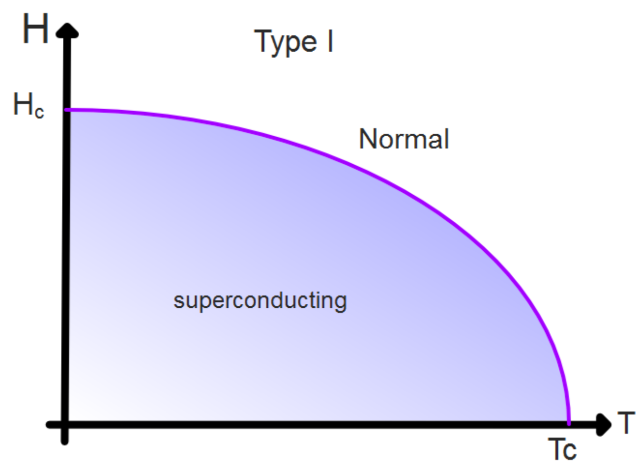


Figure 13 The critical magnetic field increases as temperature decreases. However, there is a maximum even at zero Kelvin. Shawn Liner

Electrical Limitations

If there is zero resistance, can a small superconducting wire carry all the electricity for a whole city?

Current refers to the flow of electricity through a conductor. For an analog think of water flowing through a pipe. Current would be analogous to how much water passes through the pipe in a certain amount of time. Initially most students will think that since there is zero resistance, a superconductor could pass an infinite current through it. However, we’re dealing with electrons, not water. Electrical currents cause magnetic fields (see theory section for more information) and as mentioned in the previous section magnetic fields destroy the superconducting state. Too much current produces too much magnetic field. This maximum current is the critical **current** . So we actually have three related properties that affect our ability to act as a superconductor, Temperature, Magnetic Flux, and Current.

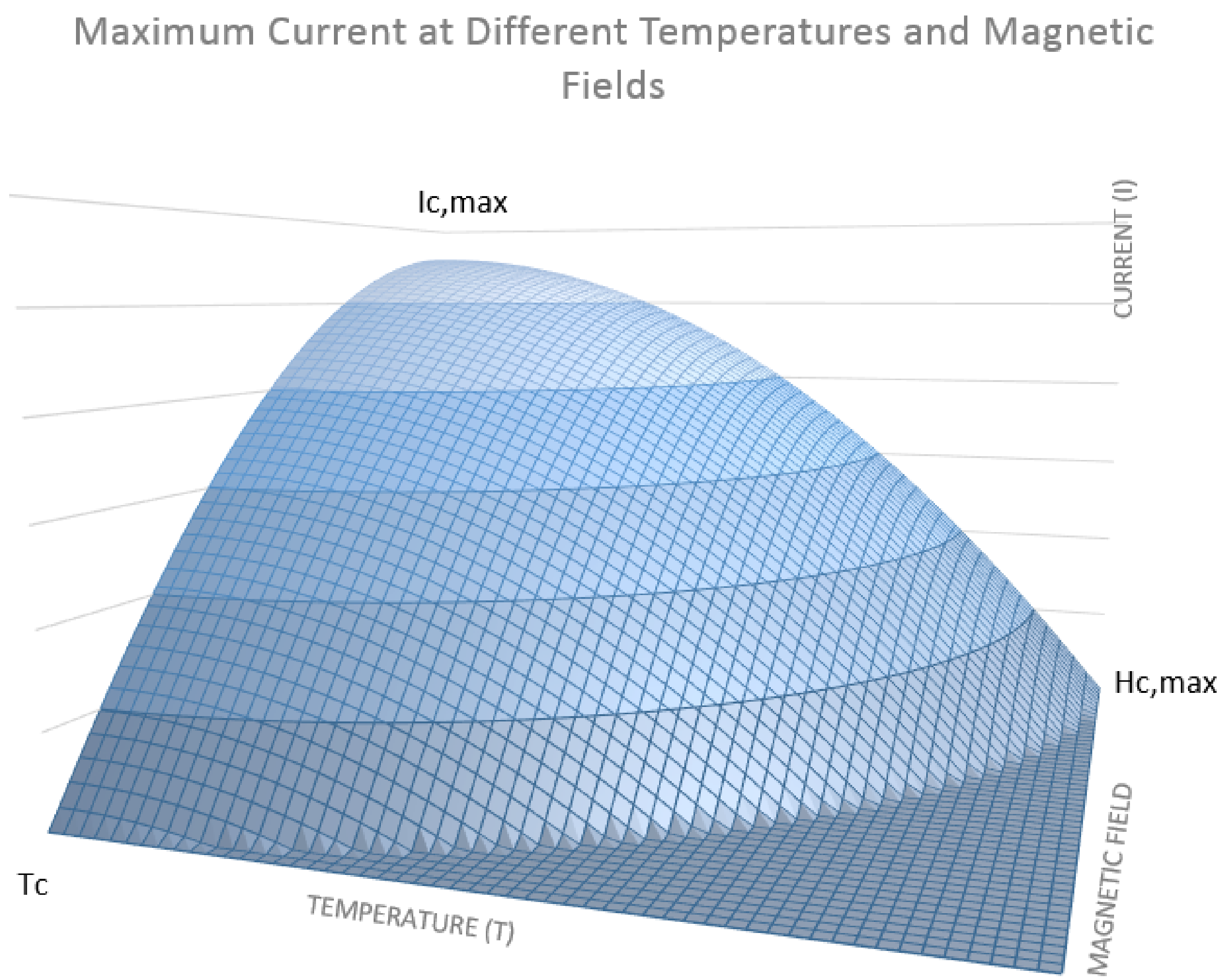


Figure 14 Three properties affect an objects ability to superconduct. Shawn Liner

The graph above shows that our perfect superconducting condition would be no current, no magnetic flux, and zero kelvin temperature. Upon careful inspection you may notice that the colder it is, the more current it will be able to carry. So, even if we do reach room-temperature-superconductors, we may still wish to keep them cooled, and no matter how cold we keep them, there is still a limit to how much current a wire can carry.

Physical Limitations

Can we make superconducting wires for my house?

The first superconductors discovered were metals, mercury and lead. However, modern “high temperature” superconductors are ceramics. They resemble clay pots in texture and can be just as fragile. The above image is of a superconducting disk of BSCCO that was dropped on the floor and shattered into many small pieces. The brittleness of modern superconductors limits their applications in many situations. One dream of future superconductors is that they would be more rugged, more malleable, and more ductile.

Figure 15 BSCCO superconducting disks are very fragile Shawn Liner

Another limitation of the ceramic modern superconductors is that they cannot be drawn into wires easily. One of the properties of metals is that they are **ductile** . This allows them to be drawn out into long wires, perfect for transmitting electricity and electrical signals. Despite our desire to use superconductors to transmit electricity, we are limited by their inability to easily be made into wires . So while some companies have created methods of layering bands of ceramics into a wire like structure. True superconducting wires don’t really exist.

3 Superconductor Technology

Other than little magic tricks, what can we actually do with superconductors?

While it is fun to watch magnets levitate above superconducting chips and create a little levitating train above a magnetic track, the question many people have is, “Can we do anything useful with super conductors. In this section, we’ll take a look at the many ways that superconductivity is already in use and ways that we hope to use it in the future.

Figure 3.1 MRI Machine in Gothenburg, Sweden can be used to look inside the human body. Jan Ainali (CC3.0)

Uses of Superconductivity

Magnetic Resonance Imaging (MRI)

It’s difficult to imagine modern medicine without the ability to do “non-invasive imaging ”. Most people are aware of the x-ray, but a very common method now involves exposing the body to a strong magnetic field and looking for faint signals given off by the body when the magnet is turned off. This method is called Magnetic Resonance Imaging (MRI) and has an advantage over x-rays of not exposing the body to x-ray radiation and of being able to see soft tissue.

Figure 3.2 MRI of Human Head CC Ranveig

Squids (Superconducting Quantum Interference Device)

Squids use superconducting circuits to measure very weak magnetic fields. These can be used in science to measure the magnetic properties of materials. This of course leads to better research about materials electrical and magnetic properties, very likely leading to better superconductors.

They also have fantastic applications for measuring magnetic fields produced by the brain. This magneto-encephalograms allow us to “see” brain activity and better map the areas of the brain. This is interesting scientifically, but perhaps lifesaving to someone with head injuries.

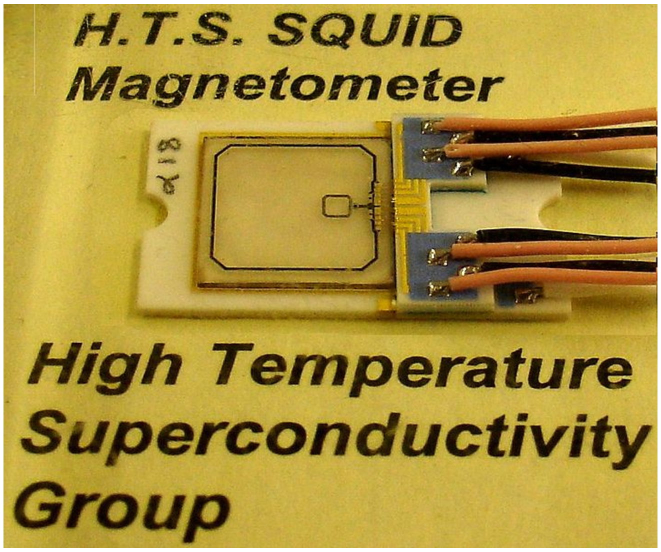


Figure 3.3 HTS SQUID Superconductivity allows SQUIDS to measure very small Magnetic Fields. Zureks (CC Wikimedia)

Squids could also be used to increase the efficiency of MRI machines. By using squids we could use weaker magnetic fields in our MRI machines, or increase the resolution of current MRI machines.

Cellular Telephone Base Stations.

Superconductors create excellent microwave filters that are nearly lossless. This allows them to be used in cellular telephone base stations to improve service quality, increase coverage, and allow cell towers to be built further apart. Thousands of these models are in place now.


Figure 3.4 Cellular Phone Tower *COURTESY OF ILDAR SAGDEJEV, VIA WIKIMEDIA COMMONS*

Electrical Power

Figure 3.5 Power Lines Run Across the Country Side in UK. Courtesy of Sue Jones via Wikimedia Commons

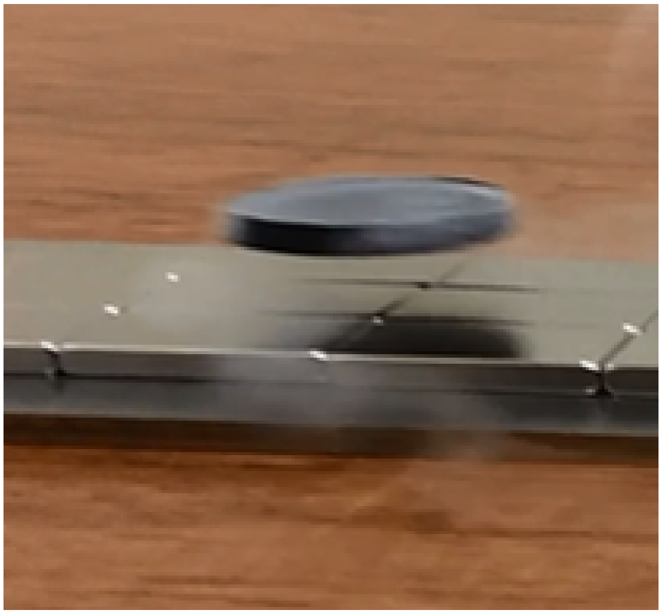
Traditionally, superconducting wire has been used when cost was not as much of an issue or proof of concept was the goal. Normal copper transmission lines can lose as much as 10% of their electrical power to heat due to resistance. Too much power can literally melt the wires. In 2001 Detroit installed underground high temperature super conducting power lines (Fairly). While this was a breakthrough, newer installations have superseded it. In 2008 (Nexan) a 574MVA transmission line was installed in Long Island. That's enough to power 300,000 homes. Superconducting power cables have an additional feature in that they provide some automatic protection against short circuits. (Heger). Essentially, if there is a short circuit, then the current will go above the critical current of the superconductor which will then lose its superconducting abilities. This will automatically decrease the electrical flow as the superconducting wire reverts to a normal conductor.

Another interesting application of superconductors is in electrical power generation. Electric generators made with superconducting wire have an efficiency above 99%, which far exceeds that of conventional copper based generators. This makes them very lucrative for power utilities and increases the viability of wind and hydroelectric power. (Superconductors.org)

Maglev

In August of 2003 passengers first boarded the Shanghei Maglev Train (Shanghei Maglev). The train is capable of traveling nearly 300mph as passengers travel between the city and its airport. It is possible to create maglev without superconductivity, but the application of superconductors provides some exciting promises. The train itself hovers above the track providing a smooth and nearly frictionless travel. There is an organization (Maglev2000) that is pushing for a network of maglev trains in North America. They argue that maglev could provide intercity travel for half the price of air travel.

Figure 3.6 Shangai Transrapid Maglev Train Courtesy Yosemite via wikimedia commons



VIDEO DEMO (YouTube): Maglev Demo Click the image above for a video demo of maglev model train. Shawn Liner

Links to some interesting maglev information.

- Shanghai maglev Train http://www.smtdc.com/en/index.html
- A French group invents a hoverboard. http://www.supraconductivite.fr/en/index.php#samuser-magsurf

- Maglev 2000, Organization pushing for trans-continental maglev trains in North America http://www.maglev2000.com/
- Antipodes Middle School Robotics Team build project on maglev http://www.theonerobot.com/maglevresearch

Computing

The future of faster computers is very much up-the-in-the-air as several technologies compete for the ability to produce the next big step in computing. However, one distinct possibility is the use of superconducting quantum computing (SQC). SQC raises and interesting advancement in that SQC actually has 3 possible states for each bit as opposed to two in traditional computing. (Joint Quantum Institute). These computers could possibly use SQUIDS for their version of a bit (called a qubit).

Superconducting E-bomb

Although some secrecy surrounds the event, there is evidence that a superconducting e-bomb was used by the United States in 2003 to shut down their enemies communications (KLAS Las Vegas). This device essentially emits a large amount of electrical power in a brief second. The most interesting application of this technology would be to stop automatically tracking missiles in their path. The e-bomb would effectively scramble the computer of the attacking missile.

Highly Sensitive Low Frequency Antennae

The lower the frequency of a radio signal the longer its wavelength. This means to reliably receive low frequency waves, you need a really long antenna. However, long antennae have larger resistance and therefore had difficulty picking up low signals. Superconducting antennae could solve this and allow us to pick up radio transmission from farther away. This would not only increase long range communication, but increase the sensitivity of our radio telescopes which listen to cosmic events and help us to explore our universe.

Figure 3.7 Four Antennae of the ALMA

Jose Salgado via Wikimedia Commons

What can we expect from superconductors in the future?

“Physicists in Finland have calculated that the EU could reduce carbon dioxide emissions by up to 53 million tons if high-temperature superconductors were used in power plants.”

Superconductors.org

Even without further advances in superconducting materials, it’s easy to see that superconductors have significant growth potential. They are already in use in many fields of technology and continue to grow in those areas. However, should new superconductors with higher transition temperatures be discovered, then the downside of their use would disappear and the growth would expand exponentially.

Another consideration of the growth of superconductors is their environmental impact. Superconductors reduce energy loss and therefore reduce the fuel requirements to energize our society, “Physicists in Finland have calculated that the EU could reduce carbon dioxide emissions by up to 53 million tons if high-temperature superconductors were used in power plants.” (Superconductors.org) This is a huge statement in a world more and more concerned with reducing our effect on the environment.

4 Theory of Superconductivity

But, how do materials act like superconductors?

The word “theory” is often confused by students. They tend to think it means “ guess” or thought. However, generally in science the word “theory” is best thought of as “explanation” or “model”. In this section we attempt to explain why some substances act as superconductors. We present mental models that we use to understand how the process works. This is meant to be an introduction to the theory, not to give you a PhD in superconductivity.

Scientific Theory

a well established explanation, or model, of some aspect of the natural world or scientific laws

Superconductivity

What causes electricity to flow without resistance?

While the theory explaining superconductivity is still in development, the most common theory is BCS Theory (named for the efforts of John Bardeen, Leon Cooper, and Robert Schrieffer). It can get pretty technical. Here we attempt to get a basic understanding.

The Simple Version of BCS

The simplest version of this is a particle explanation. As an electron moves through the crystal, it deforms the lattice because the nuclear centers are positive and the electron is negative. This pulls the lattice toward the first electron creating a positive center right behind the first electron. This moving positive charge center pulls the second electron along. (See illustration below). A macroscopic analogy is when race cars draft behind another race car. Pairs of electrons travelling in this method create a "draft" effect that pulls other electrons along.

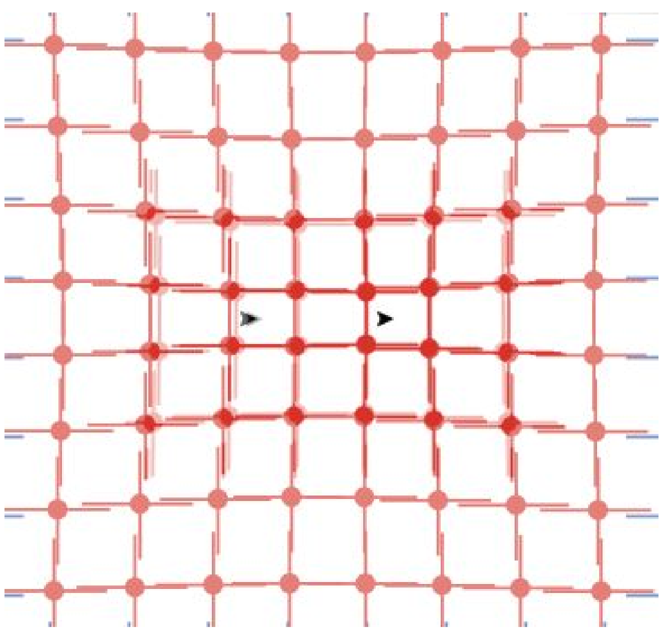


Figure 4.1 Illustration of Cooper Pairs. The electrons distort the lattice as they travel through Shawn Liner

When a crystal is warm, random deformations travel due to heat. These random deformations destroy the drafting effect and cooper **pairs** cannot form. Thus superconductivity only appears at colder temperature.

A More Detailed Version

In order to better understand the BCS Theory and Cooper pairs, we have to delve into the standard model. Although, for a basic understanding, not too much.

In Chemistry class we learn that electrons occupy orbitals in sublevels and levels of an atom. There may be eight electrons on the second shell of an atom, but two of them are in an “s” sublevel and six of them are in a “p” sublevel. Inside the “p” sublevel, there are three orbitals that each hold two electrons. The two electrons are spinning in opposite directions. The electrons must spin in opposite directions because of a property called the “Pauli Exclusion Principle”.

Now, it turns out that electrons are “ **fermions** ” with a ½ spin, and that’s why they must obey the Pauli Principle. In a super conductor electrons pair up (despite their repulsion) due the interaction with the lattice distortion, called a “**phonon** ”. This Cooper pair of electrons acts as a “ **boson** ” with an integer spin number and therefore do not have to obey the Pauli principle. The electrons can now act as a single wave function which travels smoothly through the superconductor. The electrons are said to have “condensed” into a single energy state. Many Cooper pairs can occupy one collective state.

Phonon

An imaginary particle located at the compression point in a solid. Phonons can be created by heat, sound, or other forms of compression in the solid.

Heat

Heat manifests itself as randomly travelling phonons in the crystal. These random phonons can destroy the Cooper Pair phonon and destroy the superconductivity of the material.

Remember it is the lattice distortion (or phonon) that causes the electrons to be attracted enough to overcome their repulsion for each other and form the Cooper pair. If the temperature of the superconductor raises, then random phonons will be created by random vibrations in the material. That is, heat manifests itself as randomly travelling

distortions within the crystal. These
random distortions will destroy the Cooper pairs and the electrons will cease to travel as a single wave function. They will again travel as separate electrons and will be pulled off of the single direction, increasing their path and the resistance of the material to their flow.

Levitation

So how does the superconductor just float there?

Figure 4.2 A magnet levitation above BSCCO superconductor Shawn Liner

In the introduction material it was mentioned that superconductors are weakly diamagnetic above a certain temperature, but then become near perfect diamagnets. The reason for this is related to the superconductor's ability to conduct electricity. Magnets and electrons are very closely related. In fact you can make a magnet, by causing electrons to travel in a circle around a nail. Perhaps, you have made one of these simple electromagnets by wrapping wire around a nail. So moving electrons create magnets. Likewise moving magnets will cause electrons to move.

When a conductor is moved inside of a magnetic field, the magnetic field causes a current in the conductor. Magnets pull electrons. This current causes a magnetic field to be created from the conductor. That magnetic field will always be in opposition to the magnetic field acting on the conductor. So, in a matter of speaking, the conductor is a "magnetic mirror". As seen in the illustration below, a magnet dropped into a copper pipe will fall slowly. The magnet will be slowed because its movement will cause a current in the pipe (red arrow). This current will cause a magnetic field that opposes the fall of the magnet. However, the magnet won't stop because as the magnet slows so does the induced magnetic field of the pipe.

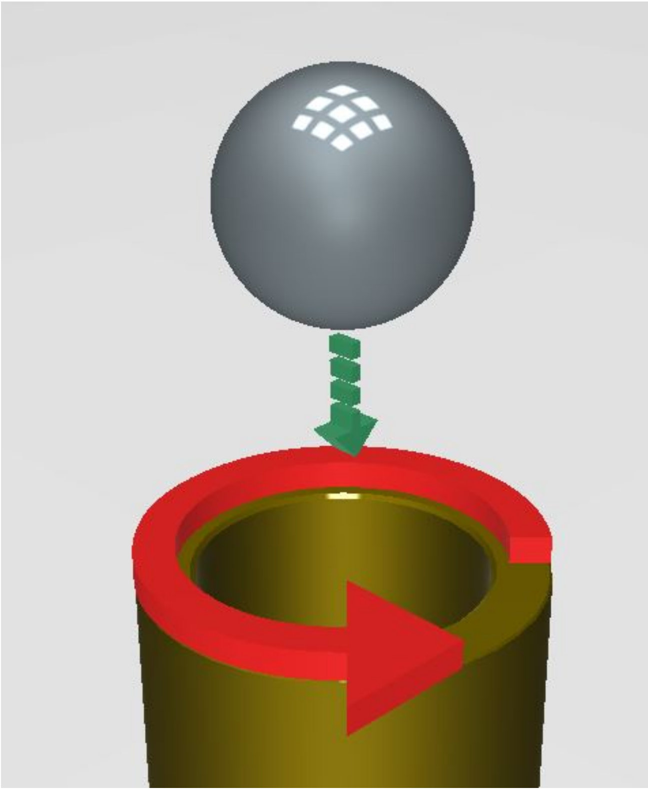
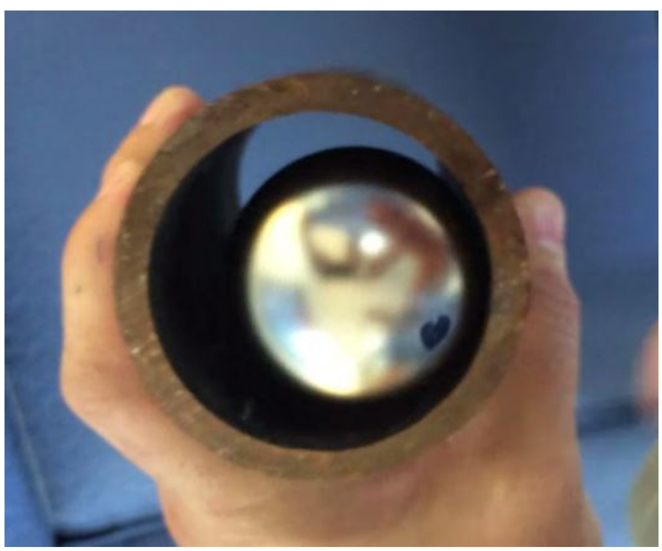


Figure 4.3 Illustration of a magnet falling into a copper pipe. The red circular arrow represents the flow of electrons Shawn Liner



Video Demo (Youtube)
Click to watch.
A magnet's fall is slowed by induced currents Shawn Liner

In addition, if you drop a strong magnet onto a copper plate, the magnet will move toward the copper plate, producing a current in the copper plate. This current produces a magnetic field. The copper plate becomes a magnet that opposes the magnet falling toward it. The magnet will slow down and slowly hit the copper plate.

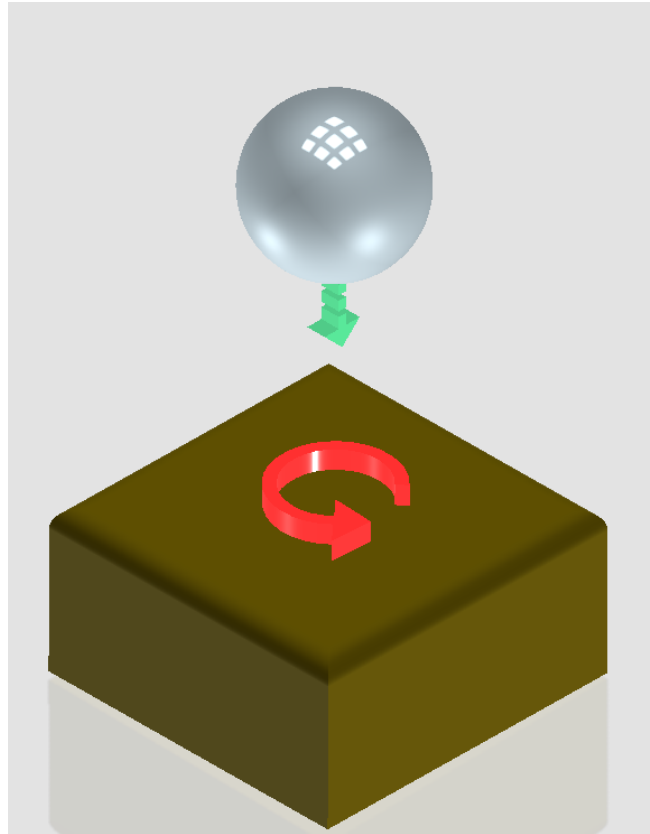


Figure 4.4 An Illustration of a magnet falling onto a copper plate. Shawn Liner

So, if the copper plate becomes a “magnet mirror”, why doesn’t the magnet just levitate above the copper plate? Two things prevent this from happening. First, current is created by the movement of the magnet. So, if the magnet stop moving then it would no longer cause a current. Second, the copper is not a perfect conductor. So, even though the falling magnet created a current in the plate, the current will die down due to resistance. However, if the copper plate was a superconductor, then the current would not die down, and the magnet would levitate. This is what happens with our superconductor. Gravity's attempt to pull the magnet down to the superconductor creates a current in the superconductor, which creates a magnetic field, and repels the falling magnet. Even after the falling magnet stops falling the current remains to create the magnetic field and repel the magnet.

Pinning

How does the superconductor stay so stable on top of the magnet?

As mentioned in the limitations sections, superconductors have a maximum magnetic field that they can expel. This is known as the critical magnetic field. In the graph below you can see that the farther below the critical temperature, the greater the amount of magnetic field the superconductor can expel.

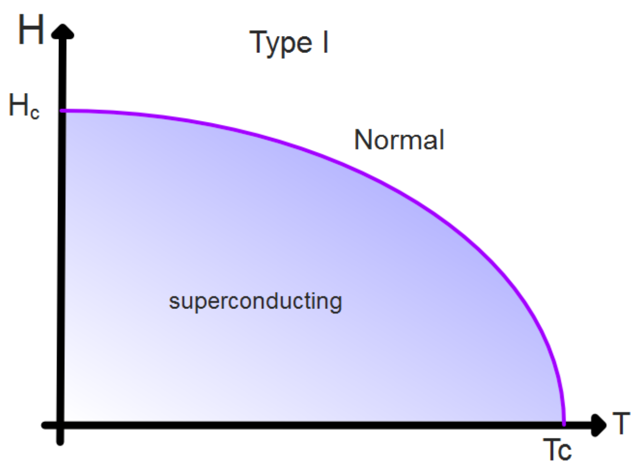


Figure 4.5 Critical magnetic field changes with temperature in a type I superconductor . Shawn Liner

However, a Type II superconductor has a slightly different behavior (see graph below). For a type II superconductor there are actually two critical magnetic fields (Hc). Above Hc,2 (That is, if the magnet is two strong) the

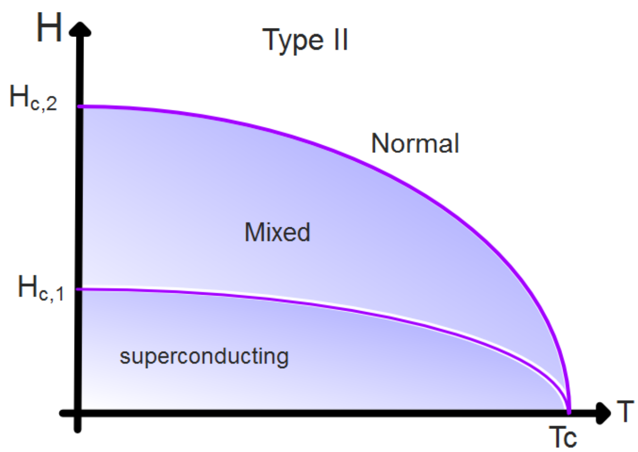


Figure 4.6 In Type II superconductors there are two critical magnetic fields. Shawn Liner

superconductor will not be able to expel any of the magnetic field and it will not behave as a superconductor. Below Hc,1 the superconductor expels all magnetic field and acts like a Type I superconductor.

The difference occurs between the two levels of magnetic fields. At this level we get a “mixed state ” and the superconductor will allow some magnetic fields in. These magnetic field lines get pinned inside the superconductor and as a result are held in place.

Video Demo (Youtube)
Click to Watch Video
A pinned magnet is spun while levitating on a superconductor Shawn Liner