CNS Institute for Physics Teachers

Title:	**Too Cool to Resist**
Original: **Revision:**	1 July 2003 25 June 2010
Authors:	Eric Smith and Allister McRae
Appropriate Level:	Regents and AP Physics
Abstract:	Students measure the voltage across a copper resistor and a superconductor starting at room temperature and at intervals cooling down to approximately 77K. The temperature is controlled by varying the amount of thermal contact with liquid nitrogen. By graphing their results, the students see the effect of temperature on the resistance of a "normal" conductor, and the radically different effect on a superconductor. The lab ends with a demonstration of the Meissner Effect, a superconducting classic!
Time Required:	One 40 minute period is required for the lab activities. Pre-lab worksheet and post-lab analysis require additional class time, or can be assigned as homework.
NY Standards Met:	4.11 All materials display a range of conductivity. At constant temperature, common metallic conductors obey Ohm's Law. 4.1m The factors affecting resistance in a conductor are length, cross-sectional area, temperature, and resistivity.
Special Notes:	**Too Cool to Resist** is a kit available in the CIPT Equipment Lending Library, www.cns.cornell.edu/cipt/.

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Behavioral Objectives:

Upon completion of this lab a student should be able to:

- explain the relationship between the resistance (resistivity) of an electrical conductor and its temperature.
- explain how some materials become superconducting below the critical temperature
- describe the Meissner effect, in which a superconductor expels all magnetic flux from its interior.

Class Time Required:

- One 40 minute period is required for the lab activities.
- Pre-lab worksheet and post-lab analysis require additional class time, or can be assigned as homework.

Teacher Preparation Time:

- 5 minutes to set up kits

Materials Needed:

- The Too Cool to Resist kits, come with an optional Dewar for liquid nitrogen (available from the CIPT Lending Library at www.cns.cornell.edu/cipt)
- One ringstand for each student group
- Liquid nitrogen, ~8 oz. per use (contact CIPT for assistance with locating a source of liquid nitrogen)

Safety:

This lab is safe to do, but care must be exercised when using liquid nitrogen.

- Safety glasses should be worn during this lab.
- Students will be using liquid nitrogen in this lab and care should be taken to avoid spills. Instruct students to stand while working with the liquid nitrogen (as in working with chemicals). Brief contact with skin is not dangerous (the liquid boils on initial contact with warm skin and forms an insulating gas layer). However liquid nitrogen can become dangerous if it soaks into clothing. If clothing comes into contact with liquid nitrogen, it should be removed immediately. This is serious.
- The teacher should clamp the apparatus to the ring stand ahead of time to ensure the clamps are secure and minimize the risk of spills.

Assumed Prior Knowledge of Students:

- Ohm's Law, $V = IR$
- Simple series circuits
- $R = \rho l/A$ for a conductor of length l, cross-section area A, resistivity ρ

Background Information for Teacher:

A Brief History

It all turns out to be due to a great scientist's sleepy assistant. Heike Kamerlingh Onnes, one of the pioneers in the study of thermodynamics at very cold temperatures, successfully liquefied helium in 1908. This opened up a whole new range of temperatures for studying the properties of materials at low temperatures. His lab was continuing its investigation of the increase in conductivity of various pure metals with decreasing temperature. By 1911, they were studying mercury, fully expecting the conductivity to level off at some low temperature, as had already been discovered with platinum and gold. They were frustrated though by the apparent malfunctioning of their apparatus. When bathed in liquid helium the resistance of the mercury sample was consistently reading zero, meaning of course that there had to be a short circuit somewhere! Finally, in the last of their many attempts to locate the problem, the assistant charged with keeping a constant temperature dozed off and the temperature started to rise. As the sample passed through its transition temperature (4.2 K) the resistance instantly reappeared showing that the apparatus was indeed working properly. This was the first observation of superconductivity and its critical temperature.

Since then, materials with ever increasing critical temperatures (T_c) have been found. The first wave of discoveries in metals culminated with an alloy of niobium and germanium (T_c of 23K). However, in the 1980s, a new class of ceramic superconductors with much higher critical temperatures was discovered, bringing superconductivity into a temperature range that could be achieved much more economically with liquid nitrogen (77 K). So far, the record critical temperature for one of these materials is 138 K (visit http://superconductors.org for an amusing banner displaying the current high temperature). The ceramic superconductor used in this lab is BiPbSrCaCuO (nicknamed "BISCO"), where the proportions of the non-lead components are 2:2:2:3. The accepted value for the T_c of this form of BISCO is 110K, but this can change slightly depending on sample processing (Tarascon *et al.*, Phys. Rev. B, **38,** 13 (1988)).

Due to the fact that these ceramic materials are more brittle and harder to work with, most current applications of superconductivity still rely on metals and the use of liquid helium. Even so, the cost of supplying liquid helium is far outweighed by the savings due to the zero resistive heat loss. For example, it can require up to 50 kilowatts of electricity to run an MRI machine using traditional electromagnets (producing a field of 0.2-0.3 T). Using superconducting wire coils bathed in liquid helium is much cheaper and the magnets can be made much more powerful (up to 2 T or more). Even more powerful superconducting electromagnets are used in particle colliders where the cost benefits are even greater.

Theoretical Background

John Bardeen, Leon Cooper, and John Schrieffer were awarded the Nobel Prize for their work in the 1950s that explained the mechanism of superconductivity. The so-called BCS Theory (an acronym formed from their last names) states that below the critical temperature, each up-spin electron pairs with a down-spin electrons to form what are called Cooper pairs. As one member of the pair moves through the superconductor, it distorts the lattice structure in such a way that it influences the second electron; in this way their motions are linked and the electron pair can be thought of as a single particle. The Cooper pair has a spin of zero, unlike the individual electrons that have spin one-half. That means the Cooper pairs can all share the same quantum state as opposed to electrons that cannot share states. The Cooper pairs, all in the same quantum state, act collectively as one unit and are said to be "in phase." Due to the large momentum of this collective state, small impurities in the material can no longer scatter electrons. Therefore, the resistivity of the superconductor drops to exactly zero.

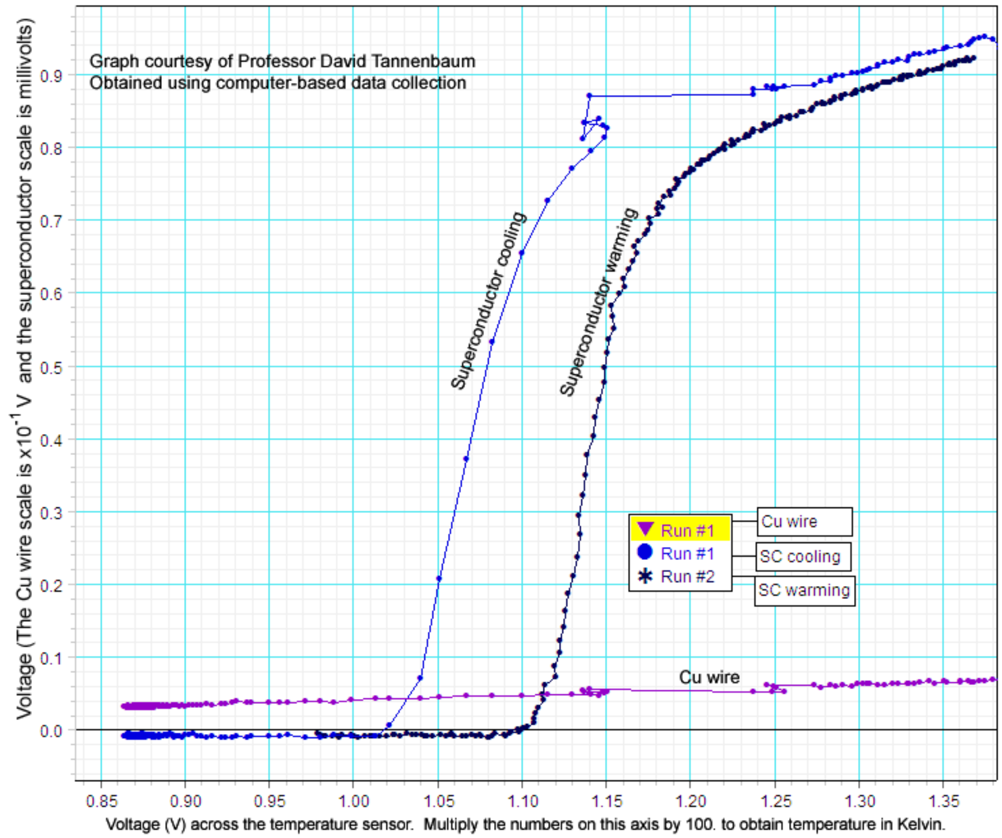
One of the startling consequences of superconductivity is the exclusion of magnetic fields. This is true only up to a limited field strength, known appropriately as the critical magnetic field, H_c. Beyond this field strength the material loses its superconducting properties. But at magnetic fields less than H_c, a superconductor will not allow field lines to penetrate below the surface of the material. Eddy currents are set up in the surface layer of the superconductor that exactly cancel the external magnetic field. This is why the small magnet provided for the Meissner Effect demonstration levitates above the superconductor. Note that this effect is not the result of Lenz's law as is sometimes supposed. The magnetic flux through the superconductor does not have to change to induce the currents. Instead any magnetic field, whether changing or not, will be excluded from the interior of the superconductor.

The Effect of Temperature on Resistance

The graph below is courtesy of Prof. David Tanenbaum and was obtained with a computer-based data collection system. The Cu wire is the linear data with V(T) between 0.2 and 0.8 V (the output of the circuit box was amplified by a factor of 10, so voltages are really 20 to 80 mV). The superconductor is the data with V(T) between 0 and 1 Volt (recall the amplifier has a gain of 1000, so really the data is 0 to 1 mV).

The graph focuses on the temperature range where the BISCO goes superconducting (note that the voltage on the horizontal axis is T/100, T is in Kelvin). Voltages across both samples drop approximately linearly from room temperature (not shown on graph).

There are distinctly separate curves when the superconductor is warming up (even run #s) and when cooling down (odd run #s). The slower the temperature changes, the closer the heating and cooling curves get to each other. The explanation for the separate curves is as follows: at higher temperatures, the cold finger boils the liquid nitrogen around it, creating a vapor barrier with low thermal conductivity. This results in relatively slow cooling until the temperature of the cold finger gets low enough that it can no longer sustain the vapor barrier (~125 K). At this point, the liquid nitrogen directly contacts the cold finger, causing rapid cooling as evidenced by the increased boiling of the nitrogen and the rapid drop in temperature. Since the BISCO does not have as good thermal contact with the metal plate as the temperature sensor, the superconducting transition incorrectly appears to happen at a lower temperature. In summary, more accurate data can be obtained with slower temperature change and/or with increasing temperature.



Answers to Questions: *send request for answers to cipt_contact@cornell.edu*

Tips for the Teacher:

- Be sure to talk with students about safety with liquid nitrogen before the start of the lab (see "Safety" section above). Remind students as often as necessary not to sit down while working with the liquid nitrogen.
- When connecting the multimeters to the circuit box, have them check that the GND side of the double banana plug goes to the black terminal of the circuit box and the COM (common) port of the multimeter.
- The students should work in groups of three. You can have them figure out their own roles or assign them as follows:
  - Students #1 prepares for taking data by filling temperature values into the data table ahead of time. During cooling, this student monitors the temperature, adjusts the cooling rate, and calls out the temperature so the other students know when to record the voltage values.
  - Student #2 records the voltage across the Cu each time Student #1 calls for it.
  - Student #3 records the voltage across the superconductor each time Student #1 calls for it.

- Start cooling the samples with 0.5 to 1.0 cm of the Cu "cold finger" submerged in the liquid nitrogen. It will take several seconds for the samples to begin cooling. The rate of cooling is increased by dipping the cold finger further into the liquid nitrogen and decreased by pulling it out a bit. Warn students that there will be a time delay in observing the effect of a change, and not to 'overshoot' their desired setting.
- The sample will cool much more rapidly as the transition temperature is approached, making it *very* difficult to collect all the desired data points. If some data points are missed, continue cooling the probe and collecting data until the temperature of the system 'bottoms out'. Then remove the probe from the liquid nitrogen and collect the missing data as the probe warms up.
- For the Meissner effect demo, it works well to spin the magnet while it is levitating. This makes it easier to see that it is actually levitating.
- Check that both power switches are turned off when done. Leaving the power switches on drains the batteries.

References:

For an excellent introduction superconductors, visit http://superconductors.org.

Equipment List

Item Number	Quantity	Item
1	1	Control box
2	3	Multimeters
3	1	Styrofoam cup – 6 oz.
4	1	Dipstick (glass tube)
5	3	Banana plug wires
6	1	Ribbon cable
7	1	3-pronged clamp
8	1	Thermos (no lid)
9	1	Demo kit – tweezers
10	1	Demo kit – superconductor
11	1	Demo kit – magnet
12	1	Demo kit – base of Styrofoam cup
13	1	Ring stand

TOO COOL TO RESIST

Pre-lab:

As you may remember, electrical resistance in materials is defined by Ohm's Law. As voltage increases, so does the current, and their ratio, the resistance remains constant:

$$R = \frac{V}{I}$$

Resistance is caused when electrons scatter off a defect in the material they are traveling through. Scattering causes the electrons to deviate from their original path. At room temperature, the main cause of scatting is thermal vibrations of the ion cores in the material. These thermal vibrations distort the perfect crystalline arrangement of the ion cores, and such imperfections can cause the electrons to scatter. Impurities and other defects in a material can also cause electrons to scatter, adding to the resistance.

The resistance R of a material with length L, cross-sectional area A, and resistivity ρ is given by the formula:

$$R = \rho\frac{L}{A}$$

L and A are related to the size of the material whereas ρ is dependent on the properties of the material.

1. Which factor in the equation $R = \rho\frac{L}{A}$ do you think is most affected by temperature? Explain why.

2. Will cooling decrease or increase the resistance? Explain why.

3. "Conductivity" is a term that describes how well a material conducts electrical current. What do you think "superconductivity" refers to?

4. You have a 10 Ω and a 5 Ω resistor in series, and you measure a voltage of 1 V across the 10 Ω resistor.
   a. What is the current through the 10 Ω resistor?

   b. What is the current through the 5 Ω resistor?

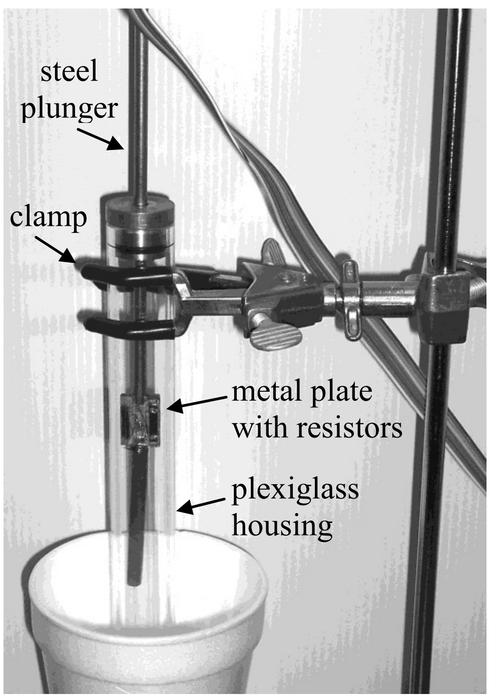
Lab:

In this lab you will investigate how resistance changes with temperature for two resistors, a copper wire and a BiPbSrCaCuO ceramic superconductor, nicknamed "BISCO." Both resistors are attached to a probe with a temperature sensor. You will immerse the probe in liquid nitrogen to cool the resistors from room temperature down to 77 K (–196° C), an extremely cold temperature. While cooling the resistors you will indirectly measure their resistance.

CAUTION: Use extreme care when handling liquid nitrogen! It can cause severe burns. Always stand when working with liquid nitrogen. If you spill liquid nitrogen on your clothing, remove it immediately.

The Apparatus

- Carefully push the steel plunger on the probe until you expose the metal plate with the two resistors. The **superconductor** and the **copper wire resistor** are mounted on one side of the metal plate. The **temperature sensor** is embedded in the plate. The resistors and the temperature sensor are in good thermal contact with the plate, so when you immerse the tip of the probe (the "cold finger") in liquid nitrogen they will also cool.



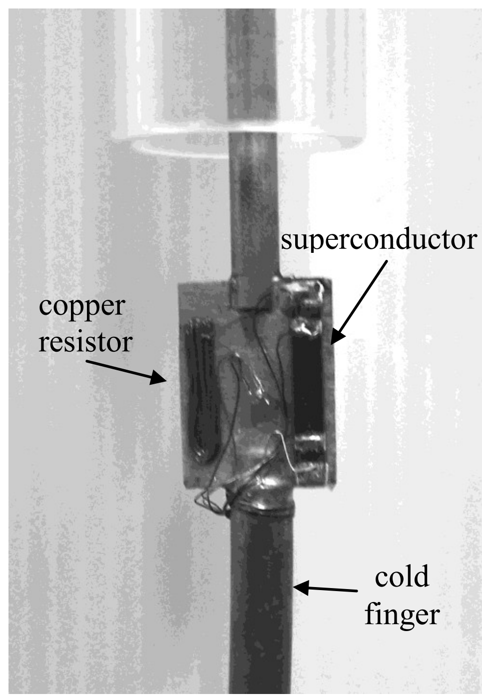


Figure 1. The probe (left) with a close-up of the Cu resistor and superconductor (right).

- Pull the steel plunger up so that the metal plate is at the top of the plexiglass housing.
- Clamp the probe system to a ring stand, as shown in figure 1, with the end of the plexiglass housing a centimeter or two above the bottom of the high-tech liquid nitrogen container (the Styrofoam cup).

- Plug one end of the ribbon cable into the top of the probe and the other end into the box with the circuit diagram. The ribbon cable carries all the electrical connections from the probe to the circuit box.
- Study the circuit diagram in Figure 2. A 1.5 V battery inside the circuit box supplies power in the circuit. There are three resistors in series with the battery. The copper resistor ("Cu") and the superconductor ("SC") are located on the probe, and the 10Ω resister is inside the box. The wires from the probe enter this box and terminate at the black and red sockets where voltage across the copper resistor and the superconductor can easily be measured. The voltage drop across the superconductor is very small. Therefore, it is amplified by a factor of 1000 inside the box to bring it into a range the voltmeter is able to measure.

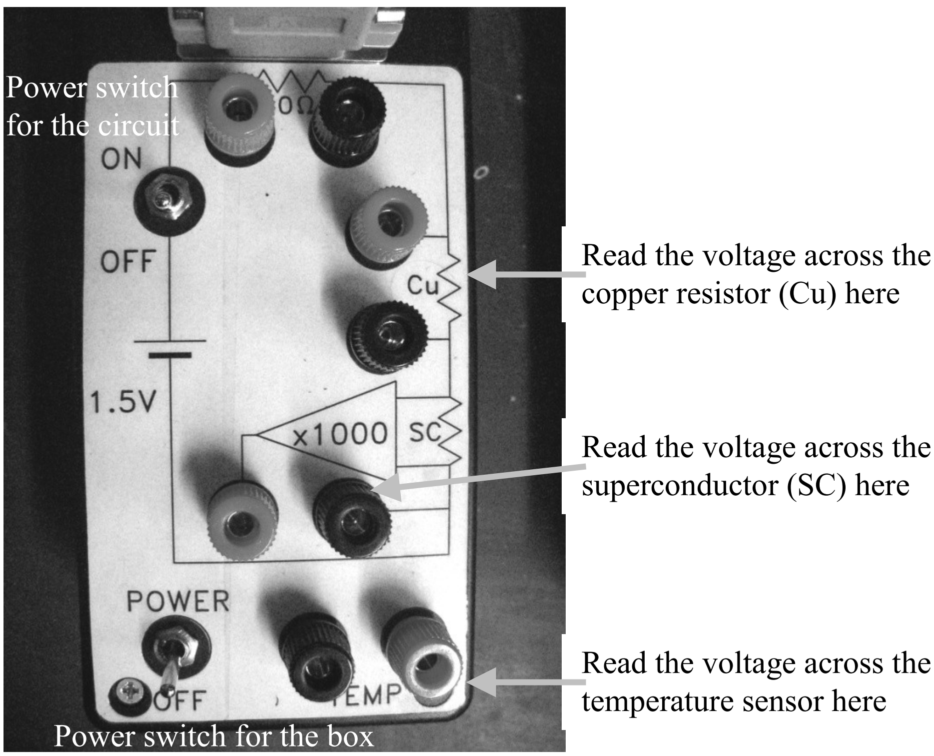


Figure 2. The circuit box.

- The wires from the temperature sensor in the probe terminate at the TEMP sockets. Wire them to one of the voltmeters and set the meter to a range suitable for reading 0 to 3 volts. Turn on the power switch at the bottom of the circuit box. In reading the probe's temperature with the voltmeter, ignore the decimal place (for example, 2.98 V would be 298 K).
- When connecting multimeters to the circuit box, check that the GND side of the double banana plugs goes to the black terminal of the circuit box and the COM port of the multimeter.
- Wire the copper resistor (Cu) and the superconductor (SC) to the other two voltmeters. Set the Cu voltmeter to the 2 V range and the SC voltmeter to the 20 V range.

The Effect of Temperature on Resistance

First, determine the current in the series circuit consisting of the battery, the 10Ω resistor, the copper resistor, and the superconductor.

- Turn on the power to the circuit and measure the voltage across the 10Ω resistor with either available voltmeter. Use Ohm's Law to calculate the current through the circuit and record it in the space just above the data table below.

Now you are ready to measure the effect of temperature on the resistors. You can't measure their resistance directly because the resistance of the wires leading from the probe to the circuit box would be a major source of error. The resistance of the copper resistor and the superconductor are quite small here! You will measure voltages instead, because current is constant, and since voltage is directly proportional to resistance it will serve our needs and avoid that error.

- Have your instructor fill the Styrofoam cup three-quarters full of liquid nitrogen. It will boil vigorously until the cup and plastic cool.
- Record the voltages across the two resistors (Cu and SC) at regular temperature intervals until the temperature reaches a minimum at around 80K. Decide on your temperature intervals ahead of time and enter them in the data table.
- Use the steel plunger to lower the probe until the cold finger is submerged 0.5 cm into the liquid nitrogen. The temperature should start to decrease after a few seconds. Adjust the depth of the cold finger to control the rate of cooling. Record the voltage across the Cu and the voltage across the SC at each temperature in the data table.

Table 1. Voltage across the Cu resistor and superconductor. Current = ___________

	Temp (K)	Cu (mV)	SC (mV)		Temp (K)	Cu (mV)	SC (mV)		Temp (K)	Cu (mV)	SC (V)
1				17				33			
2				18				34			
3				19				35			
4				20				36			
5				21				37			
6				22				38			
7				23				39			
8				24				40			
9				25				41			
10				26				42			
11				27				43			
12				28				44			
13				29				45			
14				30				46			
15				31				47			
16				32				48			

- Now plot your results on the graph paper provided below. You will need to figure out appropriate scales for each of the three axes.

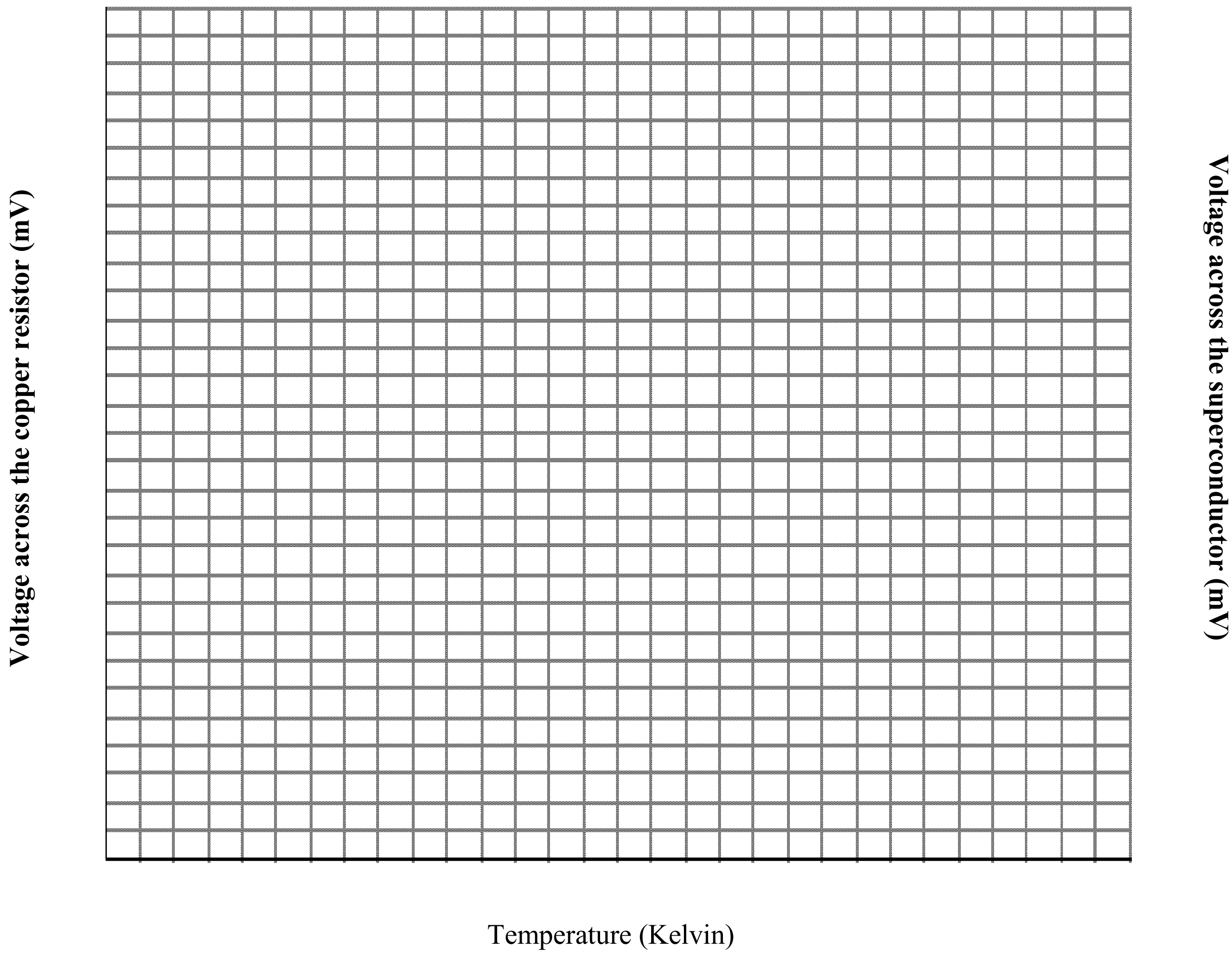


Figure 3. The effect of temperature on the voltage across a copper resistor and a superconductor with constant current supplied to the circuit.

The temperature where the voltage across the SC, and therefore the resistance, reaches zero is called the 'critical temperature' (T_c) of the superconductor, and is specific to each particular superconducting substance. In this case, T_c = __________

- Use any remaining time to improve your graph and more accurately find T_c
  One possible method is to let the probe gradually warm up by pulling it out of the liquid nitrogen. As the temperature increases, read and record the voltages, and then fill in the additional data points on your graph.

Demonstration of the Meissner Effect

Superconductivity is a quantum mechanical phenomenon. Most quantum phenomena deal with processes at the scale of atoms and individual electrons so they cannot be easily observed. In contrast, superconductivity is one of the few macroscopic quantum phenomena with effects that can be seen with the naked eye!

Below the critical temperature, the free electrons in the superconductor pair up, allowing them to occupy a single quantum state. As a result of being together in one quantum state, they are "in phase" with each other rather than acting as independent particles. In a sense, the sample is behaving like one giant atom. The collective momentum of all the electrons acting together is so large that small impurities can no longer cause scattering and resist electron flow. Without resistance, currents in a superconducting circuit can last for millions of years without any additional supplied power. Strictly speaking, the current will only last as long as the lab is willing to keep the superconductor below its critical temperature.

Interestingly, superconductors do not allow magnetic fields to penetrate them. The superconductor generates currents at its surface that exactly cancel the magnetic field inside. This is called the Meissner Effect, after its discoverer. A consequence of this is easily observable by cooling a superconducting disc and placing a magnet on top of it. The magnet levitates as long as the disc is superconducting.

The Meissner Effect is similar to Lenz's Law in that currents induced in the superconductor by the magnet oppose its magnetic field. However, it is subtly different. In normal, non-superconducting circuits, currents are induced by <u>changing</u> magnetic fields. The Meissner Effect is true for <u>any</u> magnetic field, whether it is changing or not.

How might one experimentally prove that the Meissner effect does not require changing magnetic flux to occur? That the currents in the superconductor are induced by <u>any</u> magnetic field, even a non-changing one?

Post-lab Analysis:

1. From your graph, what is the relationship between voltage and temperature for the copper resistor?

2. What does this tell about the relationship between temperature and resistance for the copper resistor?

3. From your graph, does it appear the resistance of the copper wire would ever reach zero? If so, at what temperature?

Theoretically, a totally pure sample of copper would have nearly zero resistance at 0 K. However this is very difficult to achieve in practice due to scattering from residual impurities and defects in the material. Many of the metals that we think of as good conductors never become superconducting. Instead, their resistivity levels off below about 10 K and never reaches zero.

4. Describe the relationship between temperature and resistance in the BISCO sample.

5. What is your estimate of the critical temperature of BISCO? Remember, this is the temperature at which the BISCO begins superconducting.

6. Does the copper or the BISCO have a higher resistivity at room temperature?
   Hint: Figure out the resistance.
   Hint: The voltage across the superconductor has been amplified by a factor of 1000.
   Hint: The dimensions are: BISCO: 3.0 mm x 2.0 mm x 14.0 mm
   Copper wire: diameter = 0.1 mm and length = 45.0 cm