

CNS Institute for Physics Teachers

Title:	The Nature of Resistance
Original: Revision:	7 August 2008 29 June 2010
Authors:	Jim Overhiser and Julie Nucci
Appropriate Level:	Regents and AP Physics
Abstract:	Students perform a series of guided activities that illustrate how microscopic and macroscopic features of metals relate to resistance and current flow. Activities include: thermal considerations of resistance, electron drift under an applied voltage, the effect of defects on resistivity, and the effect of length and cross-sectional area on resistance.
Time Required:	Three to four 40 minute lab periods
NY Standards Met:	<ul style="list-style-type: none">• Energy may be stored in electric or magnetic fields. This energy may be transferred through conductors or spaces and may be converted to other forms of energy. (4.1j)• All materials display a range of conductivity. At constant temperature, common metallic conductors obey Ohm's Law. (4.1l)• The factors affecting resistance in a conductor are length, cross-sectional area, temperature and resistivity. (4.1m)
Special Notes:	This activity assumes knowledge of atomic bonding, Ohm's Law and conceptual definitions of current, resistance, and voltage.

Behavioral Objectives:

Upon completion of this lab activity, students should be able to:

- Describe and explain the factors that influence the resistance of a conductor including: thermal effects, material defects, length of the conductor, and cross-sectional area of the conductor.
- Accurately explain how electrons move in a conductor.

Class Time Required:

- 120 minutes for main lab activities

Teacher Preparation Time:

- Minimal. Setting out materials and background reading.

Tips for the Teacher:

- Check all meters and batteries prior to lab
- Study material explaining the influence of defects on resistivity.

Assumed Prior Knowledge of Students:

- Ohm's Law
- Conceptual definitions of: voltage, current, charge, chemical bonding

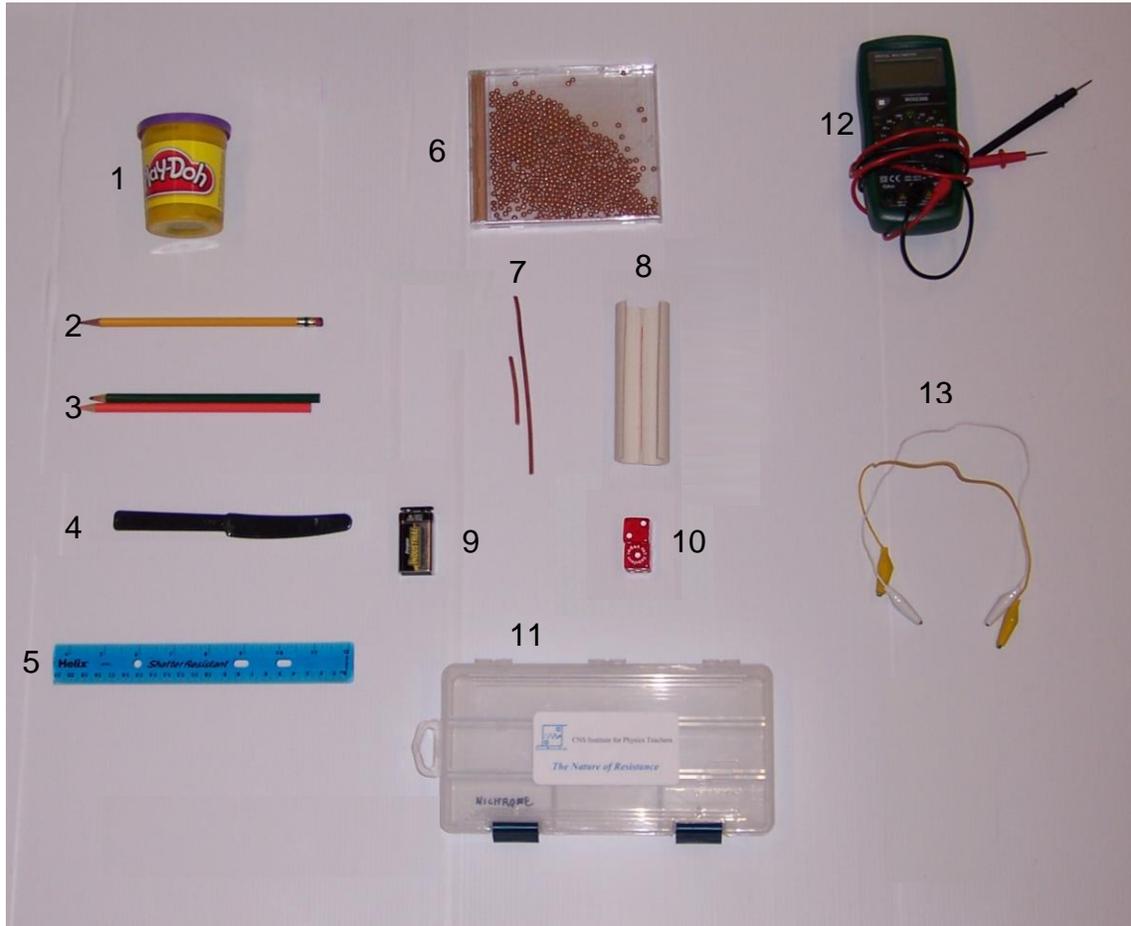
Activities overview:

1. Pre-lab. Students define terms and identify concepts important to understanding electrical conduction on an atomic level.
2. Electron interactions
 - a. Thermal motion: Using a pencil and paper activity, students explore the thermal behavior of electrons in a conductor on an atomic level.
 - b. Heat and resistance: Students perform an activity to illustrate the effect of temperature on resistance (via its effect on the resistivity).
 - c. Voltage and electron drift: Using a pencil and paper activity, students examine how electrons drift when a voltage is applied to a metal.
3. Defect Effects
 - a. Atomic BBs: Students use BBs to model the arrangement of atoms in a polycrystalline metal. The concept of crystallographic defects as a source of residual resistivity will be introduced. The main defects discussed are vacancies and grain boundaries.
 - b. Grain boundaries: Using a pen and paper activity, students examine the effect of grain boundaries on electron drift in a metal under an applied voltage.
4. Temperature dependence of resistivity in a metal (demonstration)

5. Play-Doh™ Resistor: Students use Play-Doh™ to measure the effect of conductor shape on resistance.

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

The Nature of Resistance



Material List

Item No.	Quantity	Item
1	1	Play-Doh™
2	1	pencil
3	2	colored pencils
4	1	plastic knife
5	1	ruler
6	1	CD case with BBs
7	2	pieces of metal rod
8	1	3/4" Play-Doh™ resistor form
9	1	9-volt battery
10	2	dice
11	1	kit box
12	1	multimeter
13	3	alligator clips
Not shown	1	Sheet of graph paper

The Nature of Resistance



Experimental Section

Introduction

This lab is a series of guided activities that explore the *microscopic* and *macroscopic* factors that influence the electrical resistance of conducting materials. You will examine how temperature and voltage affect electron motion in a metal, learn about defects in metals and how they impact resistivity, and investigate how geometry influences the resistance of Play-Doh™ (Play-Doh™ is an ionic conductor). All activities explore the important equation for resistance, R :

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

where:

ρ is the resistivity, which is a material property of the resistor (microscopic property)

l is the length of the resistor (macroscopic property)

A is the cross-sectional area of the resistor (macroscopic property)

1. Pre-lab: (Soccer Ball Activity)

Pre-lab discussion questions:

1. A simple circuit in your house contains wires that connect a switch to a light.
Describe what electrons in the wires do when you flip the switch and turn on a light.
2. Give your best estimate of how fast the electrons move through the wire when the light is turned on.
3. The fire department says you should never run big appliances off extension cords.
Why?

4. Why do power lines have a large diameter and why does the tungsten filament in a light bulb have a very small diameter?

Prelab Materials

- Soccer Activity sheet

Pre-lab Activity

Study the Soccer Activity sheet and answer the following the questions.

5. Draw an arrow on both pictures from the initial to the final ball position. What is the difference between the two vectors?
6. Assuming no barriers (i.e. trees and rocks), explain what geographic feature could have caused the soccer ball to take such a different path.
7. If the soccer ball represents an electron, what does the geographic feature you identified represent in an electrical system?

2. Electron Motion in a Metal

2a. Thermal Motion:

(How and electron moves in a metal at temperatures above absolute zero)

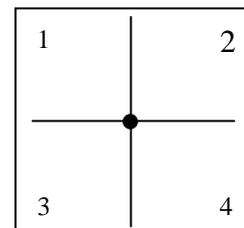
Materials:

- Two color pencils
- One die
- Small ruler
- “*Thermal motion*” activity sheets. (Instructions on sheet)

Answer the following questions after completing “*Thermal Motion*” activity:

8. Length of your net vector (in cm): _____
9. Class average for the net vector length (in cm): _____

10. On the chart to the right, indicate with a vector the general direction of your resulting direction from your starting point (use a colored pencil).



11. Distribution of net vector directions for the entire class: Using a different color pencil, draw the vectors produced in the other experiments in class.
12. Explain the class results and the effect demonstrated by rolling the dice?
13. In order to make something move it requires energy. Where did the electrons get the energy in this activity?
14. What happens to the atoms in the metal as the temperature increases?
15. What is the ideal condition that would allow no movement of atoms in a metal?
16. What effect does this ideal condition have on the conductivity of a metal?

2c. Thermal Motion + Voltage:

(How an electron *drifts* in a metal when you apply a voltage)

In the first dice activity you learned that electrons at room temperature are constantly moving, even if their net motion is very small. Now let's see what happens to the net motion of electrons in a metal at room temperature when a voltage is applied.

Materials:

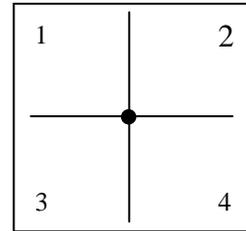
- Two color pencils
- One dice
- Small ruler
- “*Thermal Motion + Voltage*” activity sheet. (Instructions on sheet)

Answer the following questions after completing the “*Thermal Motion and Voltage*” activity:

17. Length of your net vector (in cm): _____

18. Class average for the net vector length (in cm): _____

19. On the chart to the right, indicate with a vector the general direction of your resulting direction from your starting point (use a colored pencil)



20. Distribution of net vector directions for the entire class: Using a different color pencil, draw the vectors produced in the other experiments in class.

21. Explain the class results and comment on why these results are different from those for the thermal motion activity.

22. The arrow in this activity indicated a voltage applied to the conducting material. What rule change between this activity and the *Thermal Motion* modeled the presence of voltage?

23. The soccer ball in the opening activity was influenced by gravity pulling the ball down the hill. What if you were kicking on a smaller hill than the one in the *Soccer Ball Activity*? Draw the path the ball would take on a smaller (less steep) hill.

24. What is the relationship between temperature and drift velocity?

25. Explain the effect of temperature on resistance in terms of concepts explored in the dice games.

A common misconception is that electrons travel in straight lines down a wire in a closed circuit like water flows through a pipe. Another *common misconception* is that electrons travel through a conductor at the speed of light. The truth is: an electron moves with a speed approximately 10^6 cm/s **between collisions** (1/100 of the speed of light). But this motion isn't producing current, since on average the electrons aren't going anywhere, as you saw in the first dice activity!

26. Based upon this dice activity, describe how current carrying electrons *really* move in a metal.
27. Under typical operating voltages, electrons *drift* at a velocity approximately 10^{-3} cm/s (1 billion times slower than the electron speed between collisions!). How long will it take an electron to traverse a 10 cm long wire if its drift velocity is 10^{-3} cm/s? Show your calculation and express your answer in hours. Is this what you expected?
28. If the soccer ball represents an electron and the hill represents the voltage, how would reducing the voltage affect the electron's drift velocity?

3a. Atomic BBs: how do defects affect the resistivity, ρ

This activity is used by permission of MAST (Materials Science and Technology Teacher's Workshop) Department of Materials Science and Engineering University of Illinois Urbana-Champaign

Materials:

- Copper BBs in a clear CD case

Directions:

The BBs in this activity represent atoms in a metal. Atoms occupy specific, ordered positions in crystalline metals. In a perfect crystal (as represented by this 2D BB model) each atom (BB) is surrounded by 6 atoms (BBs). (See Figure 1 on the next page.)

- Holding the case of BBs flat and just slightly at an angle to the horizontal try to make a perfect crystal with the BBs in the CD case.

Crystalline metals have many types of defects. We will explore two of them with the BBs. A vacancy (Figure 2) is a missing atom. A grain boundary is the disordered region between two crystalline regions of different orientation (Figure 3).

- Examine your attempt at the perfect crystal to see if you have these defects. If not, see if you can create vacancies (Figure 2) and grain boundaries (Figure 3)

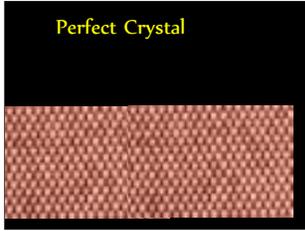


Figure 1

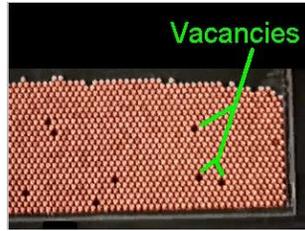


Figure 2

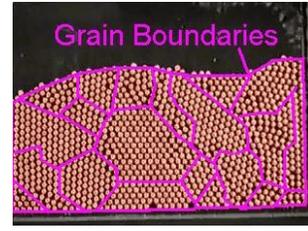


Figure 3

29. What did you do to come as close to making a perfect crystal as possible?
30. What processes did you simulate in your manipulation of the BBs?
31. Comment the importance of temperature and the nature of temperature changes in the quest for a perfect single metal crystal based on your experience in this activity.
32. In the box to the right, based upon your observations of the BBs in your CD case, draw a vacancy. Represent the atoms as circles.
-
33. In the box below, draw two grains and the grain boundary between them from your BB model. Use circles to represent atoms and carefully show the arrangement of atoms at the grain boundary and within the grains.
-

3b. Thermal Motion + Voltage + Grain boundaries:

This activity explores the effect of defects on electron drift. This is seen at really low temperatures (where the thermal effect is small) or for very small grain sized materials (nanomaterials).

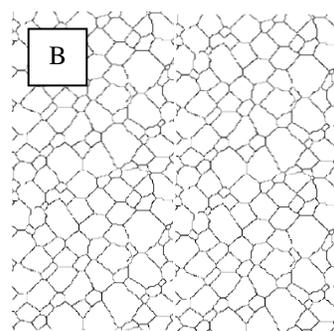
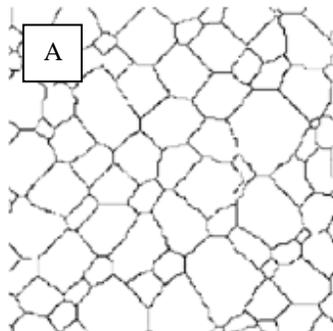
Materials:

- Two color pencils
- One dice
- Small ruler
- “*Thermal Motion + Voltage + Grain Boundaries*” activity sheet

Answer the following questions after completing the “*Thermal Motion + Voltage+ Grain Boundaries*” activity:

34. What is the effect of grain boundaries on electron drift in a metal?

35. Study the two pictures of grain structure in a metal below. If both images were taken at the **same magnification**, which one would have higher resistivity at very low temperatures, where the thermal contribution to resistivity is small? Why?



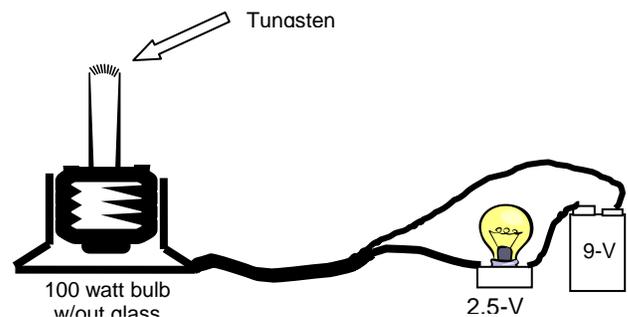
4. The effect of temperature on the resistivity of metals (demonstration)

Materials:

- Thermal resistance set-up (see illustration to the right)

Directions:

- Connect the series circuit shown.
- Darken the room.
- Gently blow on the bare filament of the 100 watt bulb. (Do not touch your mouth to the filament!)
- Use your observations to respond to the following questions.



Equipment design: Martin Alderman

5. What effect does the blowing air have on the filament?
6. Based on your observations, what do you think happened to the resistance in the circuit when you blew on the filament? How did the circuit current change? Justify your answer.
7. Explain the effect of temperature on resistance in terms of concepts explored in the dice games you played at the start of this lab.
8. In reference books, ρ values are often given with the statement “values at 20°C”. In light of what you have learned in this activity, explain why this is important.

5. Play-Doh™ Resistor: (how l and A affect R)

Now you have learned something about what happens inside a metal and explored factors that affect its resistivity, ρ . You will now examine how the geometry of a resistor affects its resistance using Play-Doh™. Play-Doh™ doesn't conduct electricity via mobile electrons, as in a metal. Instead, Play-Doh™ is an ionic conductor; it conducts through the motion of ions. A large component of Play-Doh™ is salt, which you know from chemistry, is an ionic compound. It is the salt and water in the Play-Doh™ that provide a source of mobile ions that can generate current.

Note: Exposure to air and current dries out the Play-Doh™, which will adversely affect your measurements. Minimize the time your Play-Doh™ is out of the container to keep it moist. When taking electrical measurements, take as little time as possible between measurements and immediately disconnect the circuit when you finished taking data.

Materials:

- Play-Doh™
- 3/4" Play-Doh™ resistor form
- 2 pieces of metal rod
- multimeter
- 9V battery
- 3 connecting wires w/ alligator clips

- small ruler
- graph paper or access to a graphing program (ie Microsoft EXCEL)
- small plastic knife
- sandpaper

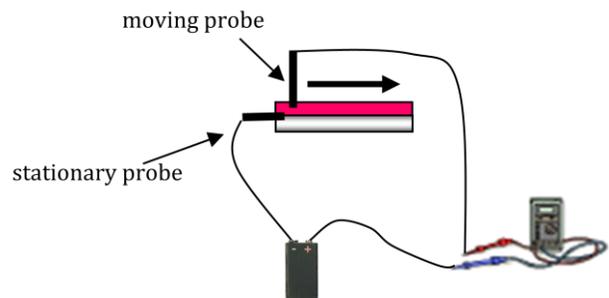
4a. Explore how the resistor length affects the resistance

Read through the directions carefully before you begin this activity.

- Measure the diameter of the resistor. Record your data in the table on the next page.
- Calculate the cross-sectional area and add this value to the data table.
- Using the multimeter as a voltmeter, measure the battery voltage. Record value.
- Now set up the multimeter as a current meter.
- Using the PVC form, fill it with enough Play-Doh™ to overflow the form when it is closed. Press the form closed and trim the excess Play-Doh™ off the edges. Pack the Play-doh to ensure you don't have any voids in the resistor.
- Hold your resistor in place on the table by pressing it into a blob of Play-Doh™.
- Remove half of the Play-Doh™ form. Note the 1 cm hash marks on the PVC pipe.
- Sand the ends of the metal rods to ensure good electrical contact (you are removing oxide or old Play-doh™).



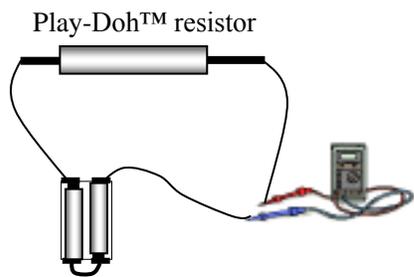
3/4" diameter PVC form		
Battery voltage:	Diameter (cm): Cross-sectional area (cm ²):	
Resistor length (cm)	Current (mA)	Resistance (Ω)
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		



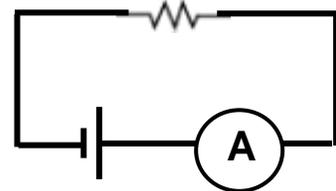
- Insert one rod about 1.0 cm into the end of the Play-Doh™ resistor. This is the stationary probe. Make sure it is inserted in the middle and perpendicular to the cross-sectional area of the resistor. **Support the other end by placing something under it so the probe maintains good contact with the Play-Doh™.**
- You will now take a series of current measurements along the length of the resistor *starting at the end with the stationary probe.*
- The circuit with the **first measurement** location is illustrated in the previous figure. Push the moving probe halfway into the Play-Doh™.
- Take this measurement 2 cm from the end of the resistor. The measured resistor length is the distance between the probes. In this case, it is 1 cm (since the stationary probe is inserted 1 cm into the Play-doh™).
- Hold the probe steady while you take the measurement to maintain good contact with the Play-Doh™ and wait for the measurement to just stabilize.
- Take more current measurements at 1 cm intervals along the resistor and record your data in the table.
- Calculate the resistance using Ohm's Law and add the resistance values to the tables.
- Plot the resistance vs. length.

4b: Explore how the cross-sectional area affects the resistance

- Measure the battery voltage again and record the value in the following table.
- Now set up the multimeter as a current meter.
- Using the entire can of Play-Doh™, roll out a Play-Doh™ cylinder that is 10 cm long. Take care to keep the cross-sectional area as uniform as possible.
- Measure the diameter of the Play-Doh™ resistor and record it in the table.
- Connect the circuit as shown in the figure below, with the exception of the Play-Doh™ resistor.



or equivalently
using
circuit diagrams



- Push the metal rods about 1 cm into the center of each end of your Play-Doh™ resistor, read the current, and ***disconnect the circuit immediately.***
- Record the current value in the table on the next page.
- Cut your cylinder in half and put the extra Play-Doh™ back in the container to keep it moist.

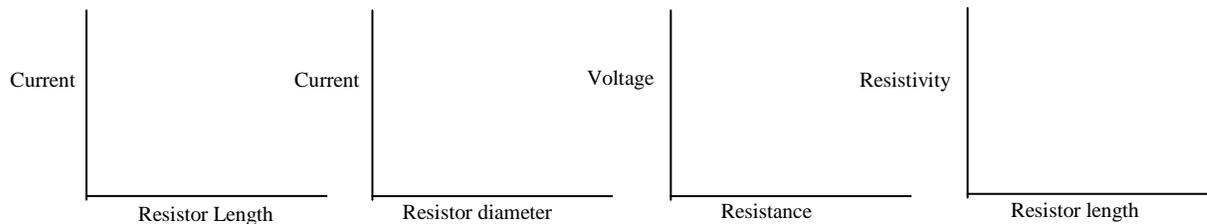
- Roll out the remaining Play-Doh™ so that it is again uniform in cross-section and 10 cm long.
- Measure the diameter and record the data in the table.
- Measure the current, disconnect the circuit immediately, and record the data.
- Repeat this process one more time, so you now are using about ¼ of the original amount of Play-Doh™.
- Using Ohm’s law, calculate the values for the resistance and fill in the table below.

Effect of Cross-sectional Area on Resistance (Resistor length = ~10 cm)			
Battery voltage:			
Resistor diameter (cm)	Resistor Area (cm ²)	Current (mA)	Resistance (Ω)

Answer related questions using your knowledge of Ohm’s Law and the following

equation: $R = \frac{\rho L}{A}$ where ρ is the resistivity ($\Omega\text{-cm}$), L is the resistor length (cm)
 A is the resistor cross-sectional area (cm²)

9. Draw a line showing the general relationship between the following properties:



10. What is the resistivity of your Play-Doh™? Use your plot of resistance vs. length to get your answer. Show your work.

11. Would you expect the resistivity of Play-Doh™ to increase or decrease with moisture content? Explain your answer.

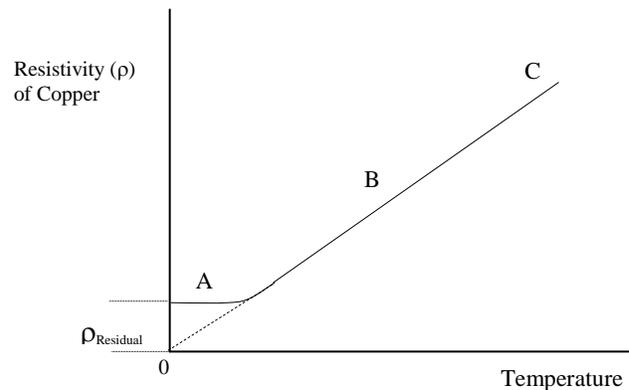
Post-lab Analysis

12. You know that energy can't be created or destroyed; it can only be transformed. What energy transformation occurs in a resistor?

13. The current density, j , is the current/unit area ($j = i/A$). Using the concepts you've learned in this lab, explain why for a given current, a thin wire would get hotter than the fat wire.

14. The graph below represents actual information on the resistivity of copper. Using what you learned in this lab, study the graph and answer the following questions:

- Why is the resistivity higher at point C than at point B?
- Why does region A not extrapolate to zero?



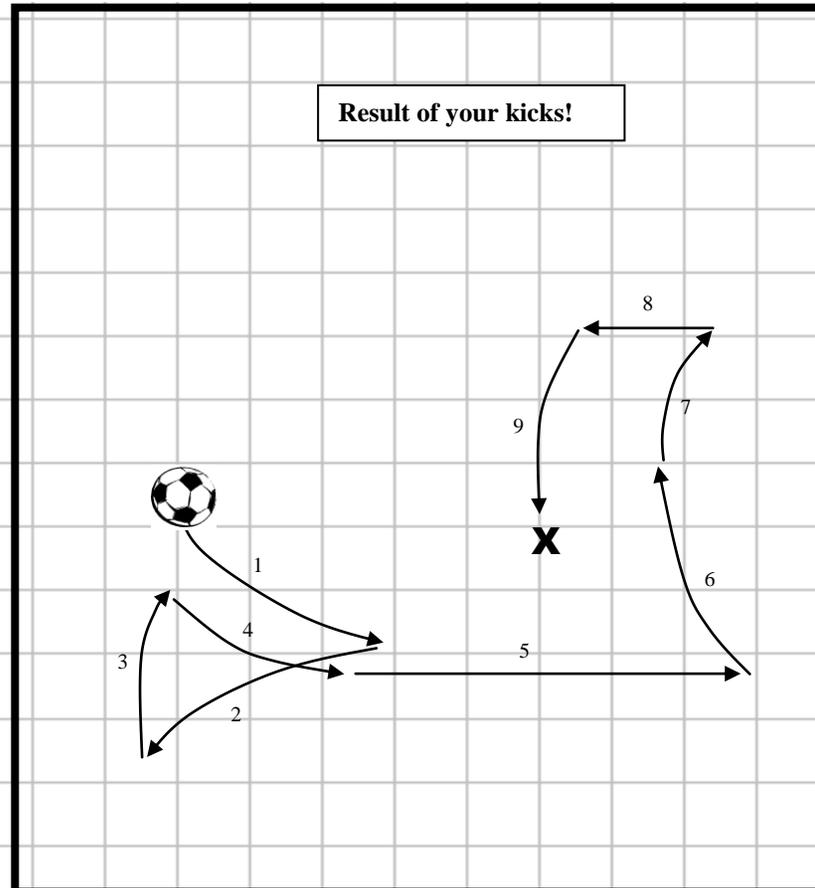
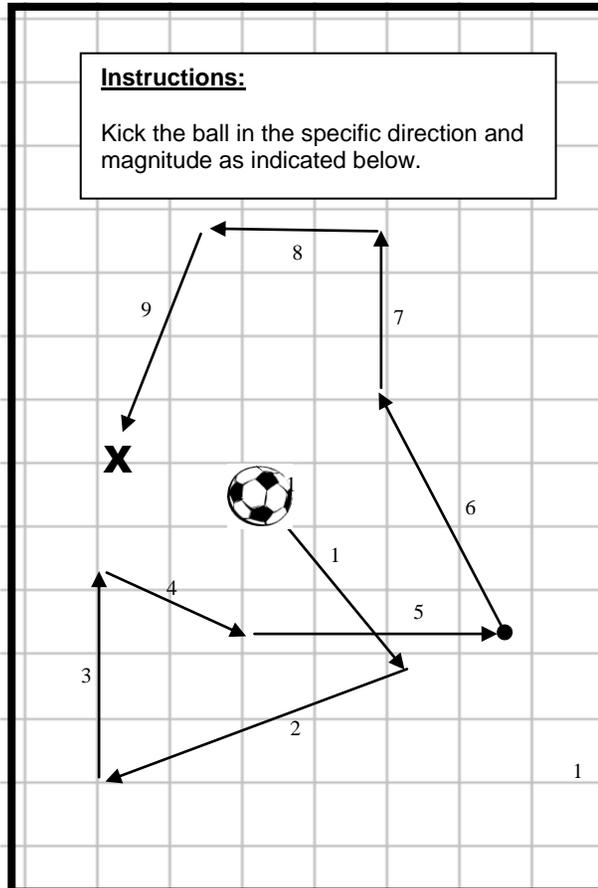
15. Let's say you and a friend are watching a bad science video on YouTube that models electricity as ping-pong balls flowing through a tube. How would you explain to your friend what is wrong with this model?

16. AWG = American Wire Gauge. Normal household circuits are constructed using mostly AWG 12 and AWG 14 wire. If 12-gauge wire has a diameter of 2.053-mm and 14-gauge wire has a diameter of 1.628-mm, why would you prefer to use 12-gauge wire to wire your house?

1. Prelab: Soccer Ball Activity

Imagine you are in an open field and are given a soccer ball and the set of instructions below. Although you are a skilled soccer player and you do your best to kick the ball according to the instructions, the result of your kicks is very different. What could have caused your ball to take the paths shown in the figure below? Hints: 1) you do not put spin on the ball when you kick and 2) you are not on a soccer field.

Answer related question on student sheet.



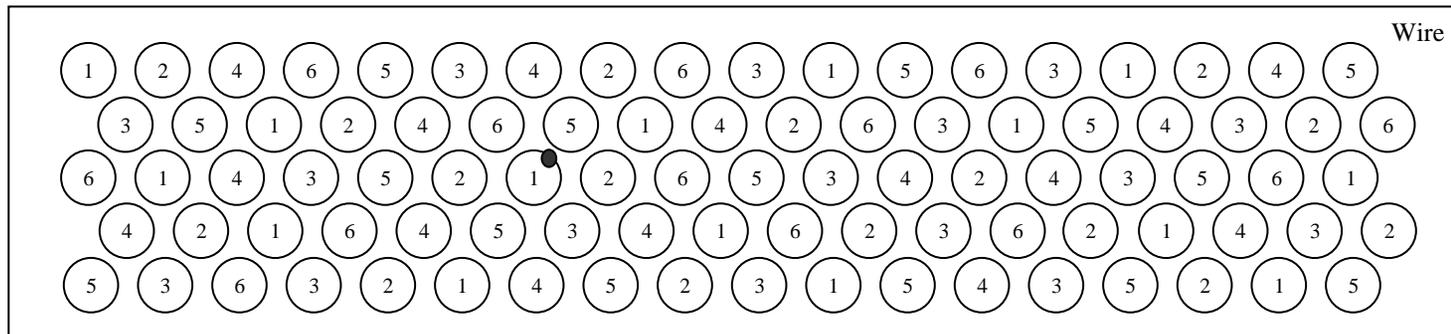
2a. Thermal Motion:

(How an electron moves in a metal at temperatures above absolute zero)

The rectangle below represents a piece of a metal wire. The black dot near the center of the wire represents an electron, whose thermal motion you will follow. The circles numbered 1 - 6 represent the atom in the wire.

Directions:

1. Begin at the black electron dot drawn near the center of the wire.
2. Roll the die. The number rolled indicates the next atom the electron will move toward.
3. Here are the rules for moving to the next location:
 - (1) You must choose the numbered circle *closest to the current electron* position.
 - (2) If you roll the number of the atom you are currently on, then move your electron to the *closest same number*.
 - (3) If you have equidistant numbers, then ***always go back towards the starting point.***
4. Draw a dot in the numbered circle to indicate the new position of the electron and an arrow pointing from the present electron position to the new location based on the number rolled.
5. Continue this process for 15 rolls of the die.
6. Draw a fat arrow from the original electron position to the final electron position. This arrow is a vector that represents the net motion of the electron.
7. Measure the length of the vector (in cm) and note its direction. Record your result on the student sheet.
8. Answer questions on the student sheet.



2c. Thermal Motion + Voltage:

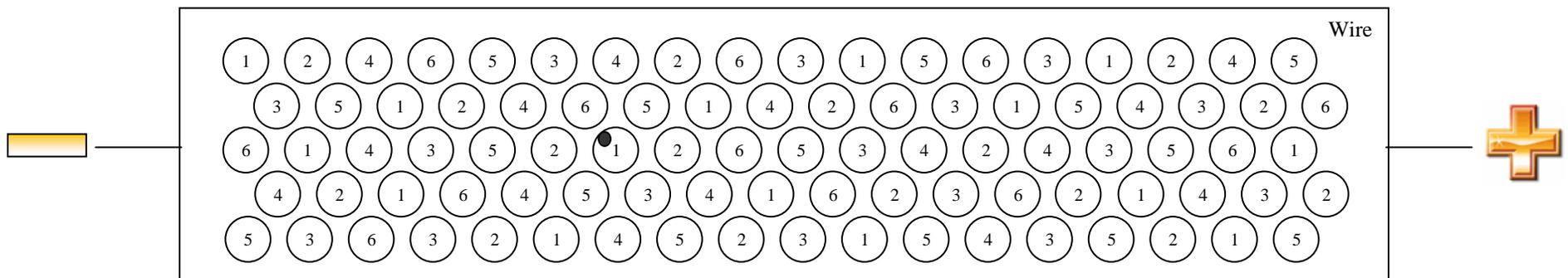
(How an electron *drifts* in a metal under an applied voltage at temps above absolute zero)

Rules of this activity:

1. Begin again at the black electron dot drawn near the center of the wire.
2. Roll the die. The number rolled indicates the next atom the electron will move toward.
3. Here are the rules for moving to the next location (read carefully – rule 3 changes when adding a voltage!):
 - (1) You must choose the numbered circle *closest to the current electron* position.
 - (2) If you roll the number of the atom you are currently on, then move your electron to the *closest same number*.
 - (3) If two numbers are equidistant from where you are, then ***always move towards the (+) electrode.***
4. Draw a dot in the numbered circle to indicate the new position of the electron and an arrow from the present electron position to the new location based on the number rolled.
5. Continue this process until you have reached the right end of the wire or have rolled the dice 15 times.
6. Draw a fat arrow from the initial position to the final position of the electron. This arrow is the vector that represents the net motion of the electron.
7. Measure the length of the vector (in cm) and note its direction (right or left) and record your result on the student sheet.
8. Compare the length of this fat arrow to the fat arrow from the previous activity.
9. Answer questions on the student sheet.

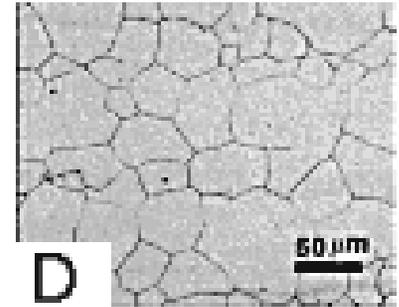


Wire connected in a circuit with an applied voltage indicated by + and - signs



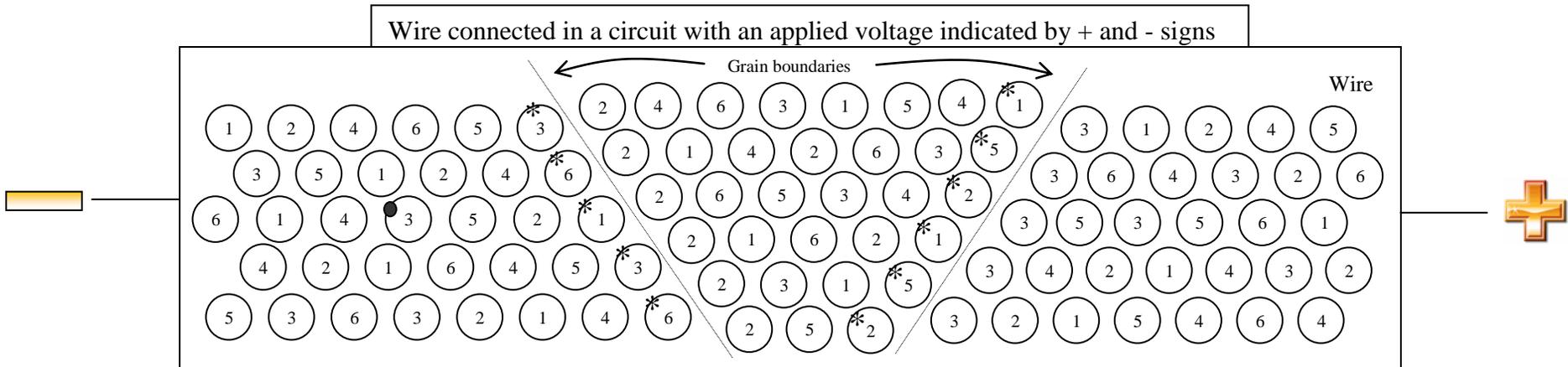
3b. Thermal Motion + Voltage + Grain boundaries: (Effect of defects on an electron drifting at temperatures above absolute zero)

Grain boundaries, the regions where differently oriented crystals in a metal meet, are the dark lines in the figure to the right. They separate the light regions in between them, called grains. Grain boundaries are defects since the arrangement of atoms is more disordered there than within the well ordered grains.



Rules of this activity:

1. Begin at the black electron dot.
2. Roll the die. The number rolled indicates the next atom the electron will move toward.
3. Here are the rules for moving to the next location (read carefully – there are additional rules for defects!):
 - (1) Use the rules for the voltage activity.
 - (2) In addition, you can only *move across a grain boundary if you are on one of the adjacent atoms* (indicated with a *).
 - (3) When you are at an atom along the grain boundary, *you must roll the number of the atoms just on the other side of the boundary to cross it*. If you do not roll this number, the electron must scatter back to the closest number you rolled.
 - (4) Once you have moved passed a grain boundary, *you can not cross back*.
4. Draw a dot in the numbered circle to indicate the new position of the electron and an arrow from the present electron position to the new location based on the number rolled.
5. Continue this process until you have reached the end of the wire or rolled the dice 15 times.
6. Draw a fat arrow from the original to the final electron position. This vector represents the net motion of the electron.
7. Answer questions on the student sheet.



Shortcut Directions for Dice Activities

Roll 1	
2	
3	
4	
5	
6	
Final Net	

