CNS Institute for Physics Teachers

Title:	**The Nature of Resistance**
Original: **Revision:**	7 August 2008 13 February 2009
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:	• 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. **The Nature of Resistance** is a kit available from the CIPT Equipment Lending Library, www.cns.cornell.edu/cipt/.

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

Answers to questions & background information for teachers:

1. Pre-lab: Soccer Ball Activity

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. *The electrons drift under the applied voltage and current is produced. Electrons do not travel far to light the light, it is slight collective movement of electrons in the entire circuit that results in the immediate response of the switch. You can think of this as water immediately coming out the end of a full hose when the spigot is turned on.*

2. Give your best estimate of how fast the electrons move through the wire when the light is turned on. *Electrons actually drift under typical operating conditions at a velocity between $10^{-4} – 10^{-3}$ cm/sec.*

3. The fire department says you should never run appliances off extension cords. Why? *Appliances, which generally consume lots of power, are built with heavy gauge wires. If you connect an appliance to an extension cord, the current density in an extension cord, which likely has a smaller diameter wire that the appliance, will be too high. The resulting Joule heating (resistive heating of the wire) in the extension cord due to the increased current density, could be a fire hazard.*

4. Why do power lines have a large diameter and why does the tungsten filament in a light bulb have a very small diameter? *A larger diameter wire is used for a higher current carrying power line since it has a lower current density and therefore loses less electrical energy to heat. A power cable should also be constructed of a low resistivity metal to minimize its resistance. Copper is one of the lowest resistivity metals: $\rho = 1.67\ \mu\Omega$-cm. The opposite is needed for a light bulb. In this case, the object is to resistively heat the wire so much that it glows. Thus, you need a very small diameter wire made from a thermally stable metal. Tungsten is used because its very high melting point (T_m = 3422 ºC) enables it to maintain dimensional stability when glowing (at 3000 ºC). The resistivity of tungsten is also more than three times that of Cu, which makes it easier to Joule heat than copper.*

Background Information for Teacher:
This activity is an analogy for electron drift and is intended to give students an introduction to the idea that a 'gradient' (i.e. voltage in a wire) can alter the path of random thermally-induced electron motion. Although it is not suggested that the teacher discuss this concept at the start of the lesson, it is an activity to be returned to in an effort to better clarify the electron activities presented later in the lesson.

5. Draw an arrow on both pictures from the initial to the final ball position. What is the difference between the two vectors? *The soccer ball ended up in two very different places.*

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. *Answers may vary during discussion but the teacher should lead the students to the fact that the land must be sloped and it causes the ball to wander in the downhill direction each time it was kicked. Another valid explanation is that there is a stiff wind blowing to the right. (NOTE: This will be used as an analogy for applying a voltage to a conductor…relating gravitational potential energy to potential difference. Under very high current densities, electrons can actually cause metal atoms on a computer chip to move in the direction of current flow. In this case, scientists refer to an "electron wind" to explain this phenomenon, which is called electromigration.)*

7. If the soccer ball represents an electron, what does the geographic feature you identified represent in an electrical system? *Applied voltage (potential difference).*

Note: Please make sure you discuss these concepts before moving onto activity 2.

2a. Thermal Motion

Background Information for Teacher:
Above absolute zero (0 ºK or -273ºC) all materials have internal (thermal) energy, which causes the atoms in the material to vibrate (the fancy word for these thermal vibrations is a phonon). Some of this energy is transferred from atoms to nearby electrons and can cause a free electron to change both its direction and velocity. Since room temperature is about 300 ºC warmer than absolute zero, you can imagine that atoms are vibrating with more than enough energy to transfer some to nearby electrons. In the thermal motion activity, students will model how energy transfer between atoms in a metal and free (conducting) electrons affects electron motion.

Due to the random nature of the dice rolling and the rules for moving to another atom, the student-to-student results should be very random. This randomness and lack of direction characterizes thermal motion.

8. Length of your net vector (in cm): *Answers will vary.*

9. Class average for the net vector length (in cm*): Answers will vary.*

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? *The results of the student's work should show random behavior with resultant vectors showing up in all sectors. The vector length will vary, but on average should not be too long. The sum of all the vectors from the class would ideally produce no resultant displacement*

of the electron. Given the small sample size, a small net motion based on all class data is expected.

13. In order to make something move it requires energy. Where did the electrons get the energy in this activity? *Heat in the metal.(Internal energy = Q)*

14. What happens to the atoms in the metal as the temperature increases? *The amplitude of their vibration away from their equilibrium lattice position increases as the temperature increases.*

15. What is the ideal condition that would allow no movement of atoms in a metal? *Absolute zero = no atomic motion.*

16. What effect does this ideal condition have on the conductivity of a metal? *Resistivity decreases with decreasing temperature since the atoms do not scatter electrons nearly as much as they do at high temperatures. Superconductivity in certain materials at low temperatures, which is special case involving correlated electron motion, is not addressed in this lab.*

2c. Thermal Motion + Voltage:

Background Information for Teacher:
The thermal coefficient of resistance, α, is used to calculate the thermal dependence of the resistance. The following equation is used in the linear regime:

$$R = R_o\left[1+\alpha\left(T_1 - T_o\right)\right] = R_o\left[1+\alpha\Delta T\right]$$

17. Length of your net vector (in cm): *Answers will vary.*

18. Class average for the net vector length (in cm): *Answers will vary, but it should be longer than for the previous activity.*

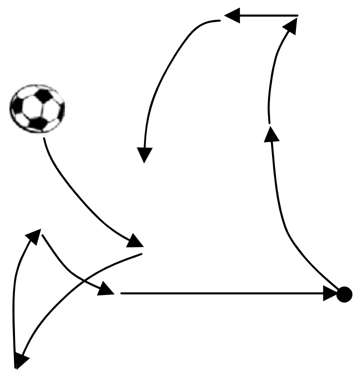
19. On the chart to the right, indicate with a vector the general direction of your resulting direction from your starting point (use a colored pencil). *Answers will vary.*

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. *Answers will vary, but the compared to the previous activity the vector should be longer and point more to the right.*

21. Explain the class results and comment on why these results are different from those for the thermal motion activity. *In general, the direction should be in the direction of sectors 2 and 4 primarily showing that an applied voltage gives a drift in a general direction opposite to the electric field or applied voltage (which goes from positive to negative).*

22. The arrow in this activity indicated an applied voltage to the conducting material. What rule change between this activity and the Thermal Motion modeled the presence of voltage? *If two numbers are equidistant from where you are, choose the number in the forward direction (in the direction opposite of the voltage arrow.)*

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 the temperature and the drift velocity? *As temperature increases the drift velocity decreases since the thermal scattering of the electrons, which is not directional, will increase.*

25. Explain the effect of temperature on resistance in terms of concepts explored in the dice games. *As the temperature increases so does the atomic motion (thermal energy). This results in more energy transfer between the atoms and the electrons via random collisions, which decreases the ability of electrons to drift through the material in response to the voltage applied by the battery.*

27. Based upon this dice activity, describe how current carrying electrons *really* move in a metal. *Although the electrons scatter in all directions, moving at speeds approaching the speed of light between collisions, they collectively drift much more slowly in the direction of the electric field.*

28. 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?

$$t = \frac{x}{v} = \frac{10\,cm}{10^{-3}\,cm/\mathrm{sec}} = 10^{4}\ \mathrm{sec} = 2.78\,h$$

29. If the soccer ball represents an electron and the hill represents the voltage, how would reducing the voltage affect the electron's drift velocity? *The drift velocity is linearly proportional to the electric field. Therefore, reducing the voltage reduces the drift velocity.*

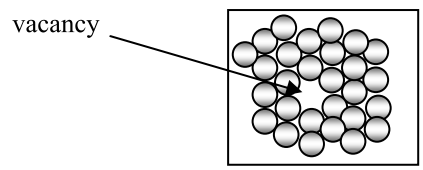
3a. Atomic BBs

30. What did you do to come as close to making a perfect crystal as possible? *Answers will vary, but slowly shaking and/or holding the CD case at a slight angle and slowing allowing the BBs to fall to the bottom will lead to a more ordered crystal.*

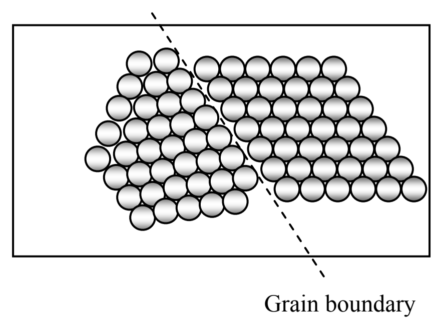
31. What processes did you simulate in your manipulation of the BBs? *Thermal processes - shaking gave the BBs the kinetic energy they needed to be able to move to different atomic positions and thereby help to eliminate defects.*

32. 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. *You simulate slow cooling by gradually slowing down the shaking process. Rapidly shaking and then suddenly stopping, simulates quenching (plunging a hot metal into cold water), which freezes in many defects.*

33. In the box, based upon your observations of the BBs in your CD case, draw a vacancy. Represent the atoms as circles.



34. In the box, 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. *Grain boundaries will not necessarily be straight.*



3b. Thermal Motion + Voltage + Grain boundaries:

(Effect of defects on an electron drifting at temperatures above absolute zero)

Background Information for Teacher:
** It is very important to convey this information to your students**

Metals are generally good conductors, which means they have a low *resistivity*. Remember that resistivity is ρ (ρ is a Greek letter and is spelled rho) in the resistance equation: $R = \rho L/A$. The resistivity is a property that is dictated by the specific material composition, how it is structured (defects in the material), and the temperature (you already saw how this works). At room temperature, thermal effects generally overwhelm any resistivity increase due to defects in the material. However, if you cool a material down really low, you will see that defects in the material contribute to the resistivity. This happens since these sudden changes in the periodic order of atoms in the crystal cause the electrons to scatter more. There are many types of defects in crystals, but we will talk about one called a grain boundary, which is where two crystals of different orientation meet. The grain boundaries scatter electrons more efficiently than grain interior. If you make nano-sized then the grain boundary resistivity will impact the overall resistivity at higher temperatures. If you sum up the effect of all the defects in a material on the resistivity you get what is called the residual resistivity, or $\rho_{residual}$.

35. State the effect of grain boundaries on electron drift in a metal. *The grain boundary presents an obstacle to electron flow and thereby slows the forward drift of the electrons.*

36. Study the two pictures below of grain structure in a metal. If both images were taken at the **same magnification**, which one would have resistivity at low temperatures, where the thermal contribution to resistivity is small? Explain your answer. *Material B would have a greater residual resistivity (resistance due to the nature of the material) as a result of the increased density of grain boundaries that would scatter the electrons.*

4. Play-Doh Resistor:

3/4" diameter PVC form		
Battery voltage: 3.06V	Cross-sectional area:	
Resistor length (cm)	Current (mA)	Resistance (Ω)
2	9.2	333
3	5.3	577
4	3.9	785
5	3.1	987
6	2.8	1093
7	2.5	1224
8	2.2	1391
9	2.0	1530
10	1.8	1700

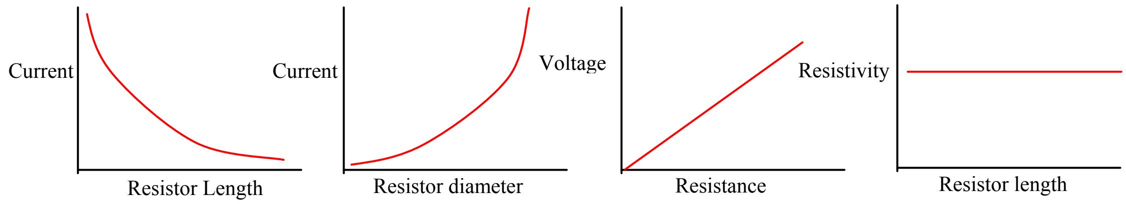
Note: To get good data on resistance as a function of length, the procedures need to be followed exactly. The play-Doh dries out as you use it, which changes its resistivity. It is therefore important to start measuring the smallest resistor length and then move on to measuring progressively longer resistors.

Effect of Cross-sectional Area on Resistance (Resistor length = ~10 cm)				
Battery voltage:				
Amt of Play-Doh	Resistor diameter (cm)	Resistor Area (cm^2)	Current (mA)	Resistance (Ω)
1 can	*3.75*	*11.05*	*15*	*200*
½ can	*2.5*	*4.91*	*5.2*	*577*
¼ can	*1.8*	*2.55*	*3.5*	*857*

Note: Another way to do the cross-sectional area experiment is to let the students design and conduct the experiment by themselves.

Note that although values will vary depending on the resistivity of the play-Doh, the trend should be good. The resistivity is very sensitive to both the salt and water content of the play-Doh.

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



38. What is the resistivity of Ply-Doh? Use your plot of resistance vs. length to get your answer. Show your work. *Slope = ρ/A. If you multiply your slope, as read off your graph, by the cross-sectional area, you will get the resistivity. Values will likely range between 100-1500 Ω-cm, depending on the salt and water content of your play-Doh.*

39. Would you expect the resistivity of Play-Doh to increase or decrease with moisture content? Explain your answer. *Increase. As the Play-Doh dries, the ions that allow for conduction become less mobile, which increases the resistivity.*

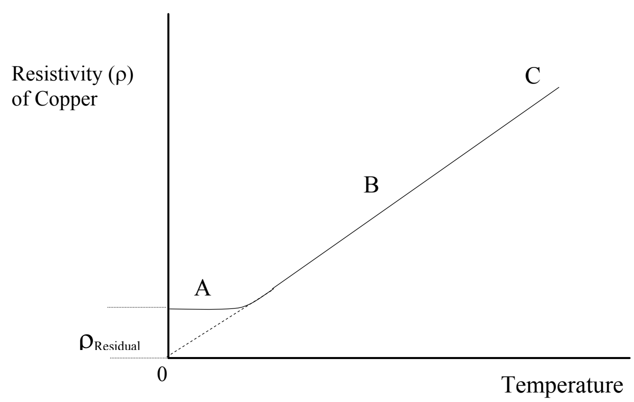
Post-lab Analysis

40. You know that energy can't be created or destroyed; it ca only be transformed. What energy transformation occurs in a resistor? *Electrical energy is converted to heat.*

41. 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. *The thin wire has a higher current density and therefore more interaction between electrons, which results in more thermal scattering. This increased thermal scattering in the small diameter wire results in it being hotter than the larger diameter wire, which has a lower current density.*

42. 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? *Higher Temperature; more electron scattering.*
- What could be the source of the residual resistivity



measured at very low temperatures? *Defects in the metal.*

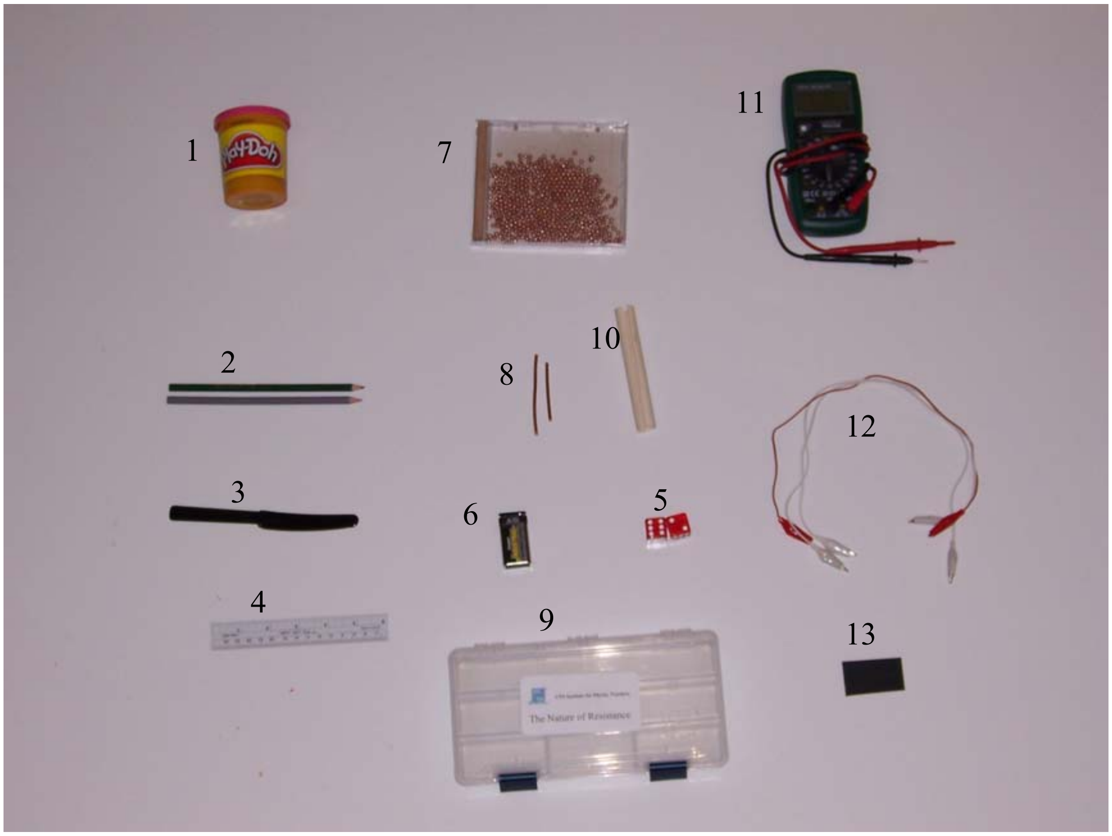
43. Let's say you are watching a bad science video on YouTube that models electricity as ping pong balls flowing through a tube. How would you explain the person watching with you, what is wrong with this model?__*If the balls represent electrons flowing in a wire, they actually move forward in the wire very slowly (.0001 m/s), They do move from atom to atom in the wire at speeds closer to the speed of light (1 000 000 m/s). Actually the balls are representing the energy moving through the wire as a result of voltage being applied.*

44. AWG = American Wire Gauge. Normal household circuits are constructed using mostly AWG 12 and AWG 14 wire. If 12-gauge wire as 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? *AWG 12 is fatter wire. Fatter wire has less resistance and therefore heats up less - preventing things like fire! It also saves energy.*

45. The filament in an incandescent light bulb is made of a long, thin tungsten wire. Explain why the filament heats up and is able to produce light energy when a voltage is applied. *Because it has a tiny cross-sectional area (A) its resistance is very high. At a higher voltage electrons trying to migrate (drift) through the wire meet more resistance and lose some of their energy as heat. This in turn heats the filament and makes it glow.*

46. Electrical power stations are typically far from the point where the electrical energy is put to use. If you have to transmit electrical energy long distances, what would be the ideal properties of the wire? *Ideally you would want a large cross-sectional area wire made from a low resistivity material. Resistance = loss of energy. For a given power, you would want to maximize voltage and minimize current to keep resistances losses low.*

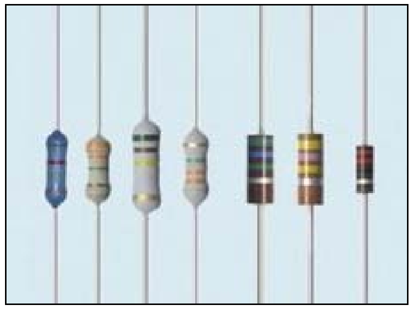
The Nature of Resistance



Material List

Kit Contents:	Other materials:
2. 2 colored pencils	1. Play-Doh™
3. plastic knife	11. multimeter
4. ruler	
5. 2 dice	
6. 9-volt battery	
7. CD case with BBs	
8. 2 pieces of copper wire	
9. kit box	
10. Play-Doh resistor form	
12. 3 alligator clips	
13. Emory 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. Students 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 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

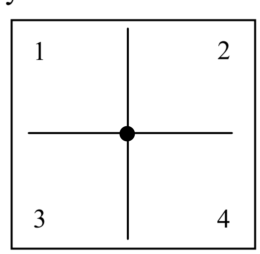
2a. Thermal Motion:

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

Materials:

- Two color pencils
- One dice
- 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.

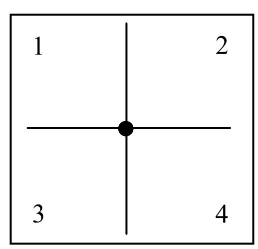
Materials:

- 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 betwen 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)

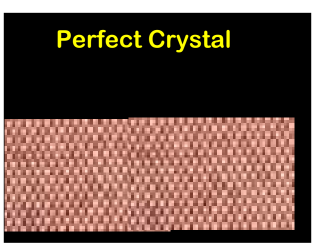


Figure 1

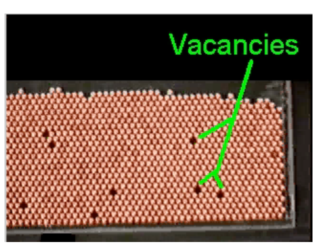


Figure 2

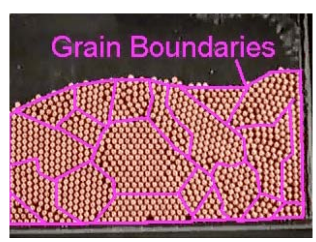


Figure 3

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.

<u>3b. Thermal Motion + Voltage + Grain boundaries:</u>

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).

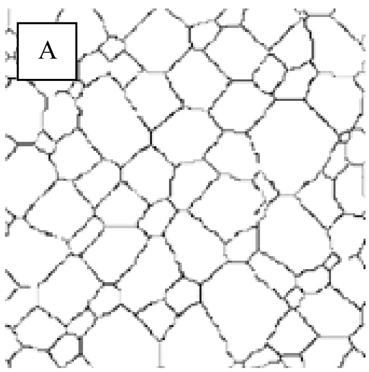
<u>Materials:</u>

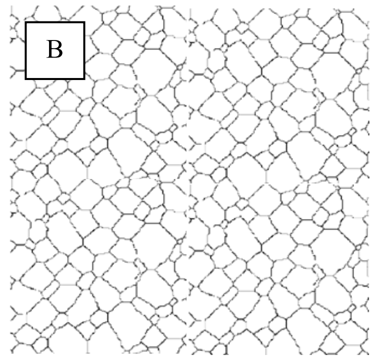
- Two color pencils
- One dice
- Small ruler
- *"Thermal Motion + Voltage + Grain Boundaries"* activity sheet

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 low temperatures, where the thermal contribution to resistivity is small? Explain your answer.





4. 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.

Remember that:

$$\boldsymbol{R} = \frac{\boldsymbol{\rho l}}{\boldsymbol{A}}$$ where ***l*** is the resistor length and ***A*** is the resistor cross-sectional area

Materials:

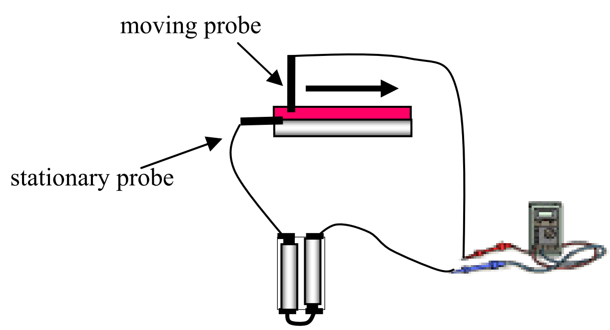
- Play-Doh™
- 3/4" Play-Doh resistor form
- 2 pieces of copper wire
- multimeter
- 2 AA batteries
- AA battery holder
- 3 connecting wires w/ alligator clips
- small ruler
- graph paper or access to a graphing program (ie Microsoft EXCEL)
- small plastic knife
- sandpaper

4a. Explore how the resistor length affects the resistance

Read through the directions carefully before you begin this activity.

- Measure the length and diameter of the resistor. Record your data in the table on the next page.
- 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.
- Remove half of the Play-Doh form.

- Hold your resistor stably in place on the table by pressing it into a blob of Play-Doh.
- Insert one copper wire 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 of the copper wire 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 **first measurement** is illustrated in the following figure. Push the moving probe about 3 mm into the top of the Play-Doh.
- Take this measurement 3 cm from the end of the resistor. The measured resistor length is the distance between the probes. In this case, it is 2 cm.



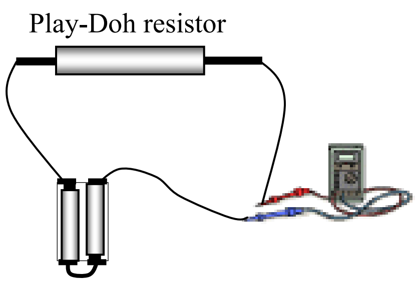
- Hold the probe steady while you take the measurement to maintain good contact with the Play-Doh. The current will drop very quickly upon insertion of the probe. Record the current value *5 seconds* after you insert the probe.
- Quickly remove any play-doh from the probe tip using the sandpaper.
- Take more current measurements using the same method at one centimeter intervals along the resistor and record your data in the table.
- Calculate the resistance using Ohm's Law and fill it in the table.
- Plot the resistance vs. length.

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

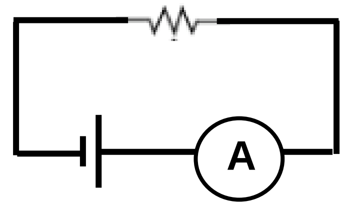
<u>4b: Explore how the cross-sectional area affects the resistance</u>

- Using the multimeter as a voltmeter, measure the battery voltage. Record this value in the table below.
- Now set up the multimeter as a current meter.
- Your play-doh should be so moist that it is almost sticky. If it is not moist enough, add water and knead it thoroughly.
- 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.
- Lastly, push the copper probes 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.
- Now 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 and10 cm long.
- Measure the diameter and record the data in the table.
- If the probe has dried play-doh residue on it, then use the sandpaper to clean it.

- 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.



or equivalently using circuit diagrams

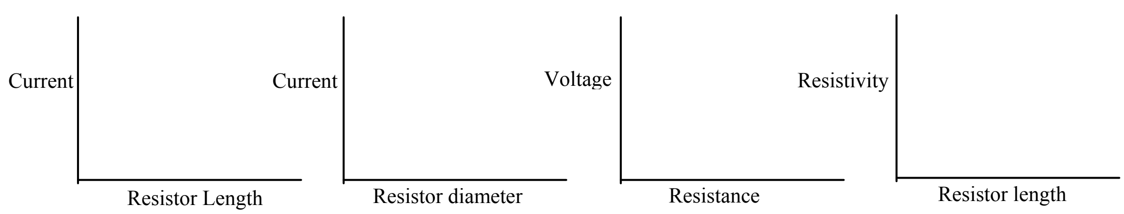


Effect of Cross-sectional Area on Resistance (Resistor length = ~10 cm)			
Battery voltage:			
Resistor diameter (cm)	Resistor Area (cm^2)	Current (mA)	Resistance (Ω)

Answer related questions using your knowledge of Ohm's Law and the following equation:

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

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



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

39. Would you expect the resistivity of play-doh to increase or decrease with moisture content? Explain your answer.

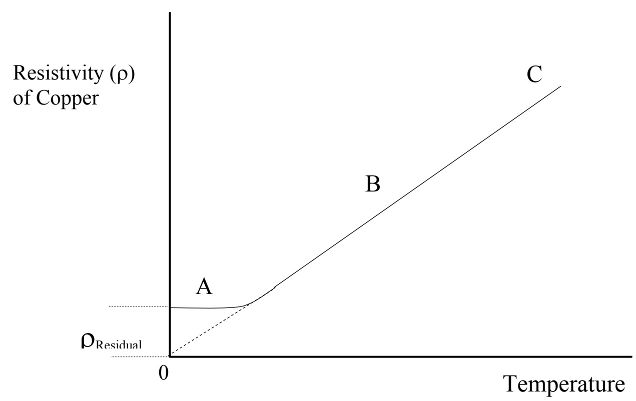
Post-lab Analysis

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

41. 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.

42. 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?

43. 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?

44. AWG = American Wire Gauge. Normal household circuits are constructed using mostly AWG 12 and AWG 14 wire. If 12-gauge wire as 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?

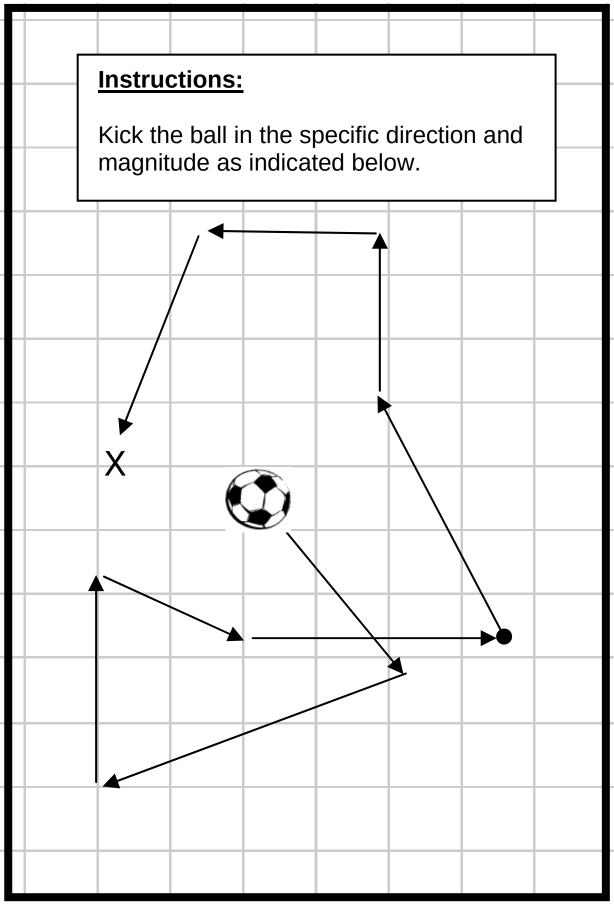
45. The filament in an incandescent light bulb is made of a long, thin tungsten wire. Explain why the filament heats up and is able to produce light energy when a voltage is applied.

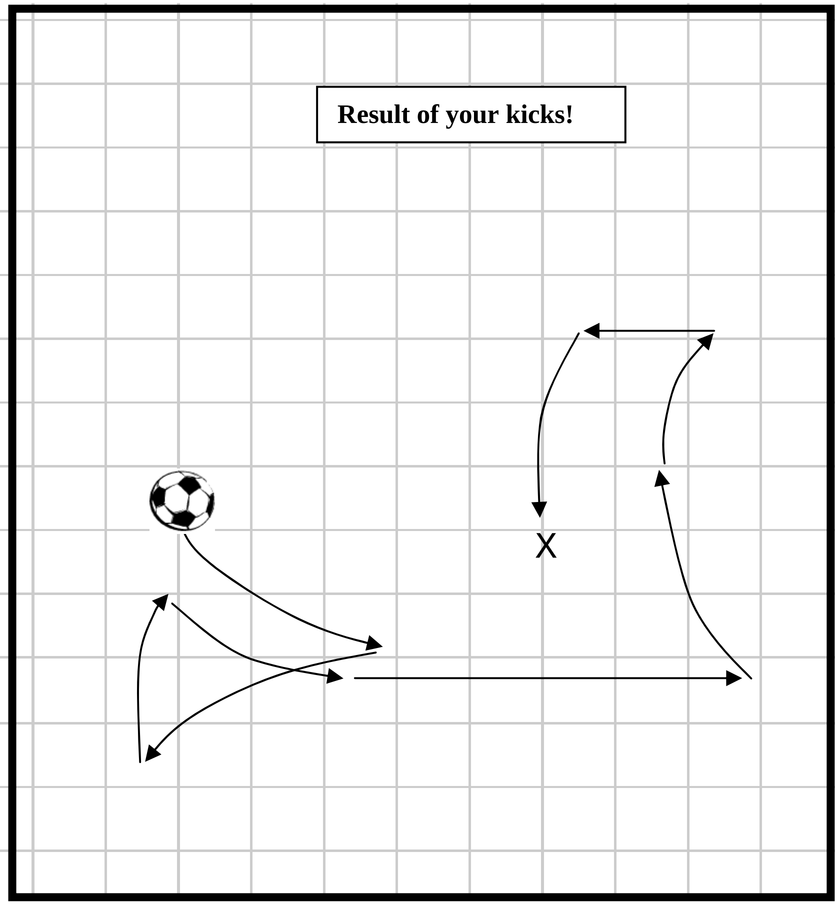
46. Electrical power stations are typically far from the point where the electrical energy is put to use. If you have to transmit electrical energy long distances, what would be the ideal properties of the wire?

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.

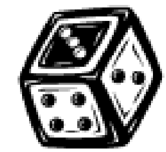




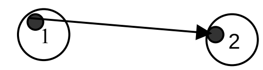
2a. Thermal Motion:
(How an electron moves in a metal at temperatures above absolute zero)

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.

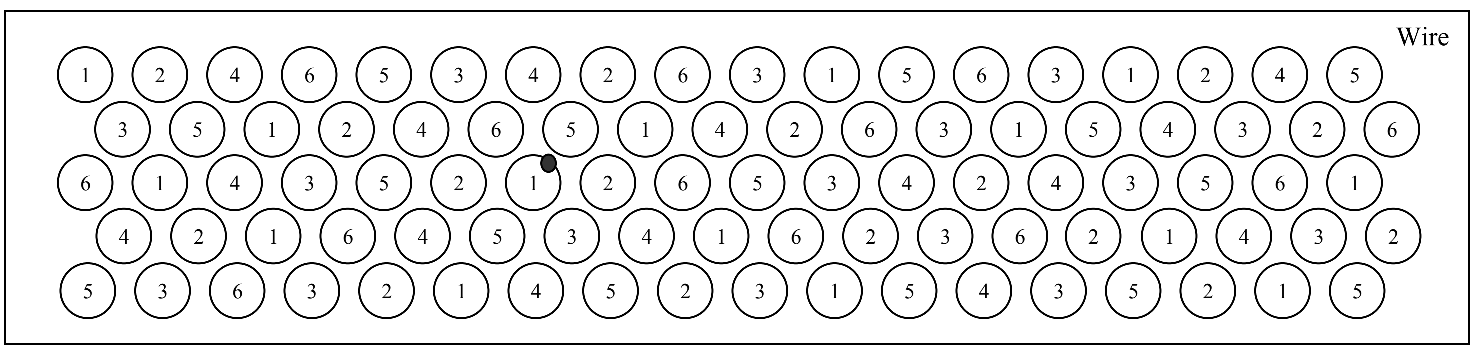
Rules of this activity:



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:
   a. You must choose the numbered circle *closest to the current electron* position.
   b. If you roll the number of the atom you are currently on, you must remain on that number.
   c. You *may go back to the atom you just left*.
   d. If you have equidistant numbers *go back* toward the original electron position.
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.

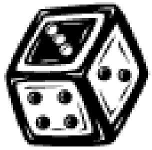


5. Continue this process for 15 rolls of the die.
6. Draw a fat arrow from the original electron position to the final electron position. This arrow is a vector that represents the net motion of the electron.
7. Measure the length of the vector (in cm) and note its direction. Record your result on the student sheet.
8. Compare your drawing to your neighbor.
9. Answer questions on the student sheet.



<u>2c. Thermal Motion + Voltage:</u>
(How an electron *drifts* in a metal under an applied voltage at temps above absolute zero)

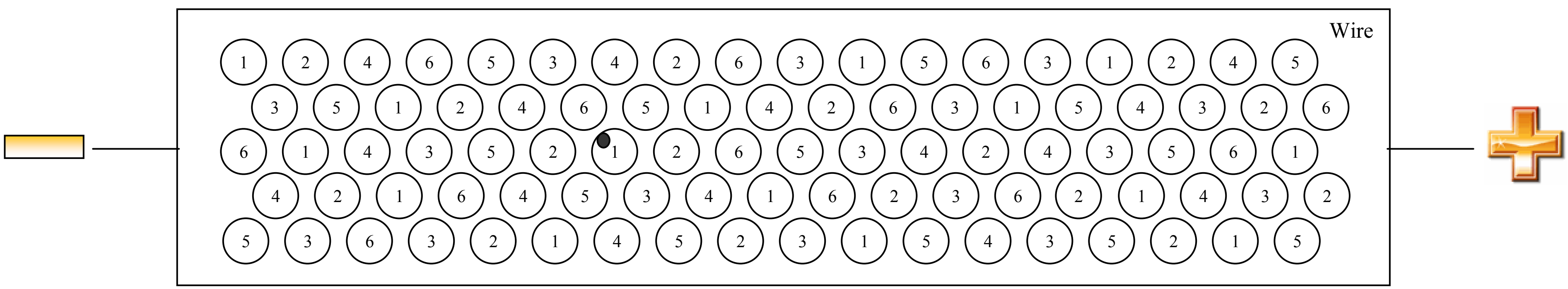
<u>Rules of this activity:</u>



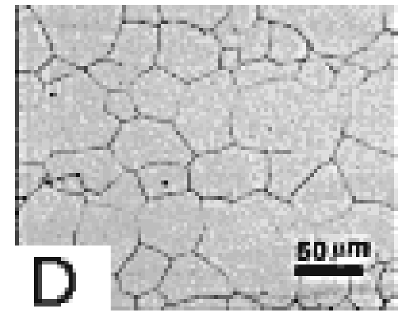
1. Begin again at the black electron dot drawn near the center of the wire.
2. Roll the die. The number rolled indicates the next atom the electron will move toward.
3. Here are the rules for moving to the next location (read carefully – rules change slightly when adding a voltage!):
    a. You must choose the numbered circle *closest to the current electron* position, even if it means going backwards.
    b. If you roll the number of the atom you are currently on, move your electron to the closest *same number*.
    c. If two numbers are equidistant from where you are, *choose the number in the forward direction* (in the direction of the plus sign)
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. Compare your drawing for electron drift to your neighbor's drawing.
10. Answer questions on the student sheet.

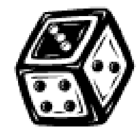
Wire connected in a circuit with an applied voltage indicated by + and - signs



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



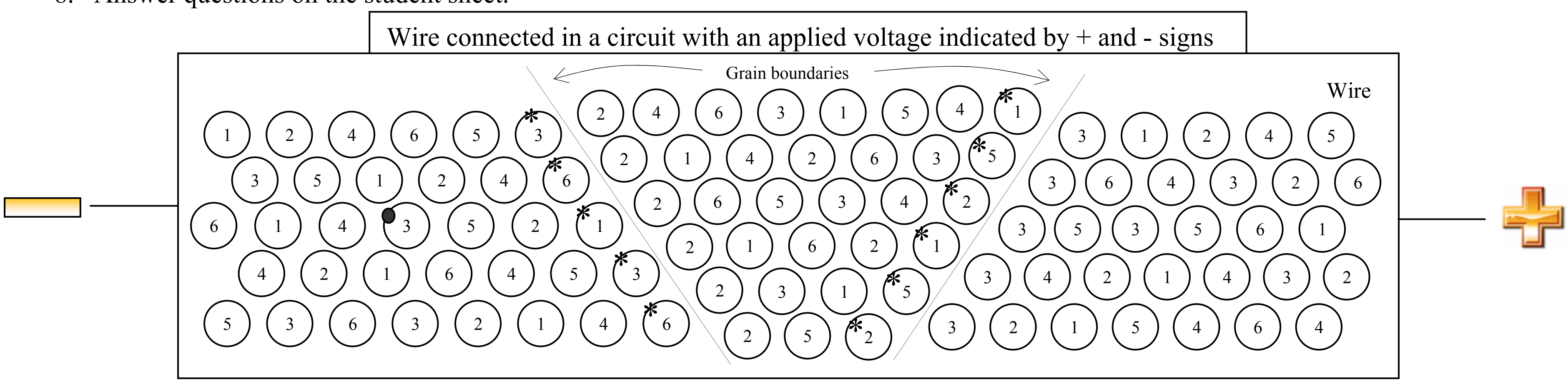
Grain boundaries, the regions where differently oriented crystals in a metal meet, are the dark lines in the figure to the right. They separate the light regions in between them, called grains. Grain boundaries are defects since the arrangement of atoms is more disordered there than within the well ordered 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!):
   a. Use the rules for the voltage activity.
   b. In addition, you can only *move across a grain boundary if you are on one of the adjacent atoms* (indicated with a *).
   c. 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.
   d. 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. Compare your drawing to your neighbor.
8. Answer questions on the student sheet.



Shortcut Directions for Dice Activities

Roll	
Roll 1	
2	
3	
4	
5	
6	
Final Net