14. Concentration of a Solution: Beer's Law

Driving Questions

Common sense tells us that the darker a solution is, the more light that solution is absorbing. Is there a mathematical pattern between absorbance and concentration that would allow you to determine the concentration of an unknown solution directly?

Background

You have seen that energy and matter are closely related. Light is energy and can interact with chemical substances. By examining the wavelength of light (its color) that is absorbed by a chemical substance, we can determine the chemical's identity and quantity in a sample.

How a chemical appears to our eyes depends on how the light interacts with the substance. Light can either be transmitted (pass through), reflected (scattered), or absorbed by the substance. What we see is determined by the light that is not absorbed. This depends on the chemical nature of the substance, its concentration in solution, and the thickness of the sample the light passes through.

These variables can be related to one another in Beer's law, $A = \varepsilon \times b \times c$, where A is measured absorbance of the light, ε is the absorbance coefficient, b is the path length, and c is the concentration. This is a directly proportional relationship and supports the observation that darker solutions are more concentrated.

In this experiment, you will use a colorimeter to find the mathematical relationship between the absorbance of orange (610 nm) light and the concentration of a solution of copper(II) sulfate. From the equation of the best fit line for a series of known concentrations with known absorbances (a calibration curve), you will be able to determine the unknown concentration of a copper(II) sulfate solution.

Materials and Equipment

For each student or group:

- Data collection system
- Colorimeter
- Sensor extension cable
- Glass cuvette with cap (7)
- Beaker (2), 100-mL
- Test tube (6), 20-mm x 150-mm
- Test tube rack
- Volumetric pipet with a bulb or a pump (2), 10-mL
- Non-abrasive cleaning tissue
- 0.80 M Copper(II) sulfate ($CuSO_4$), 30 mL
- Unknown Copper(II) sulfate ($CuSO_4$), 10 mL
- Distilled (deionized) water, 30 mL

Safety

Add these important safety precautions to your normal laboratory procedures:

- Copper(II) sulfate is hazardous to the environment and should not be disposed of down the drain. Make sure you follow your teacher's instruction to properly dispose of the copper(II) sulfate solutions.

Sequencing Challenge

The steps below are part of the Procedure for this lab activity. They are not in the right order. Determine the proper order and write numbers in the circles that put the steps in the correct sequence.

Create a calibration curve by graphing absorbance versus concentration.	Create five copper(II) sulfate solutions of known concentration.	Measure the absorbance of the unknown and determine its concentration.	Measure the absorbance of each known copper(II) sulfate solution using a calibrated colorimeter.	Determine the linear equation for the calibration curve's line of best fit.

Procedure

After you complete a step (or answer a question), place a check mark in the box (☐) next to that step.

Note: When you see the symbol "�" with a superscripted number following a step, refer to the numbered Tech Tips listed in the Tech Tips appendix that corresponds to your PASCO data collection system. There you will find detailed technical instructions for performing that step. Your teacher will provide you with a copy of the instructions for these operations.

Part 1 – Calibration Curve

Set Up

1. ☐ Start a new experiment on the data collection system. �(1.2)

2. ☐ Connect the colorimeter to the data collection system using a sensor extension cable. �(2.1)

3. ☐ Calibrate the colorimeter.

   a. Fill a cuvette with distilled water and cap it.

   b. Holding the cuvette by the lid, wipe the outside of the cuvette with a non-abrasive cleaning tissue.

   c. Place the cuvette in the colorimeter and close the lid.

   d. Push the green calibrate button on the colorimeter.

   e. When the green light turns off, the calibration is complete and the cuvette can be removed from the colorimeter.

4. ☐ Why is it necessary to calibrate the colorimeter using distilled water?

____

____

5. ☐ Configure the data collection system to manually collect absorbance of orange (610 nm) light and concentration in a table. Define concentration as a manually entered data set with units of molarity (M). �(5.2.1)

6. ☐ Why is the absorbance of orange (610 nm) light being used instead of another color?

____

____

7. ☐ List the dependent and independent variables used in this experiment. Also, list the units for each.

____

____

8. ☐ Measure approximately 30 mL of 0.80 M copper(II) sulfate ($CuSO_4$) stock solution into a 100-mL beaker.

9. ☐ Measure approximately 30 mL of distilled water into a different 100-mL beaker.

10. ☐ Take six clean, dry test tubes and place them in a test tube rack. Label the test tubes "1", “2”, “3”, "4", "stock", and "unknown”.

11. ☐ Why do the test tubes need to be dry? What error would be caused by wet test tubes?

____

____

12. ☐ Prepare the five standard copper(II) sulfate ($CuSO_4$) solutions listed in Table 1 below.

Table 1: Copper(II) sulfate solution concentrations

Test Tube	0.80 M $CuSO_4$ (mL)	H_2O (mL)	Concentration (M)
1	2.0	8.0	0.16
2	4.0	6.0	0.32
3	6.0	4.0	0.48
4	8.0	2.0	0.64
Stock	~10	0	0.80

a. Use a 10-mL volumetric pipet to deliver 2.0, 4.0, 6.0, and 8.0 mL of the 0.80 M copper(II) sulfate solution into test tubes 1 through 4, respectively.

b. Use a different 10-mL volumetric pipet to deliver 8.0, 6.0, 4.0, and 2.0 mL of distilled water into test tubes 1 through 4, such that each test tube has a total of 10.0 mL of solution.

c. Thoroughly mix each solution by swirling each test tube.

d. Pour the remaining 0.80 M copper(II) sulfate solution from the beaker into the "stock" test tube to use as the fifth data point in your calibration curve.

13. ☐ Fill one cuvette with the 0.16 M $CuSO_4$ solution and cap it. Label the top of the cuvette lid.

14. ☐ Continue to fill one cuvette at a time until each solution is in a cuvette, the cap is on, and it is clearly labeled (0.32 M, 0.48 M, 0.64 M, and 0.80 M).

Collect Data

15. ☐ While viewing the table display, start a new manually sampled data set. �(6.3.1)

16. ☐ Use a non-abrasive cleaning tissue to wipe the outside of the cuvette containing 0.16 M $CuSO_4$, and then place the cuvette inside the colorimeter. Close the lid of the colorimeter.

17. ☐ Why is it necessary to wipe the outside of the cuvette before you place it in the colorimeter?

18. ☐ Why is it necessary to close the lid of the colorimeter before recording the data values?

19. ☐ Record the absorbance and enter the concentration into the table on the data collection system. �(6.3.2)

20. ☐ Remove the cuvette from the colorimeter.

21. ☐ Repeat this process for each of the other standard solutions. For each solution, make sure to wipe the outside of each cuvette before placing it in the colorimeter, record the absorbance, and enter the concentration of the solution into the data table on the data collection system. �(6.3.2)

22. ☐ When you have collected all of your data, stop the data set. �(6.3.3)

23. ☐ Copy the absorbance and concentration data collected from your data collection system to Table 2 in the Data Analysis section.

Analyze Data

24. ☐ Create a calibration curve using the absorbance and concentration data you just collected.

    a. Create a graph of Orange (610 nm) Absorbance versus Concentration (M). �(7.1.1)

    Note: To graph a scatter plot of the data points you may choose to hide the connecting lines between data points. �(7.1.8) Adjust the scale of the graph as needed. �(7.1.2)

    b. Apply a linear fit to the data. �(9.5)

25. ☐ What is the equation for the line of best fit?

26. ☐ Solve the equation for concentration.

Part 2 – Determining an Unknown Concentration

Set Up

27. ☐ Enter the equation you determined for concentration above, into your data collection system's calculator. �(10.3)

Note: When you enter your calculation into your data collection system make sure that the measurement is absorbance and that it is entered exactly like this—[Orange (610 nm) Absorbance].

28. ☐ Monitor Orange (610 nm) Absorbance and Calculated Concentration data in a digits display. �(6.1)

29. ☐ Obtain 10 mL of a copper(II) sulfate solution with an unknown concentration from your teacher. Put this solution in your test tube labeled "unknown".

30. ☐ Fill a dry, clean cuvette with your unknown solution, cap it, and label it "unknown".

Collect Data

31. ☐ Wipe the outside of the cuvette with a non-abrasive cleaning tissue and place the cuvette in the colorimeter.

32. ☐ Close the lid of the colorimeter and record the absorbance and concentration of the unknown solution below:

"Unknown" absorbance: ________________________

"Unknown" concentration (M): ________________________

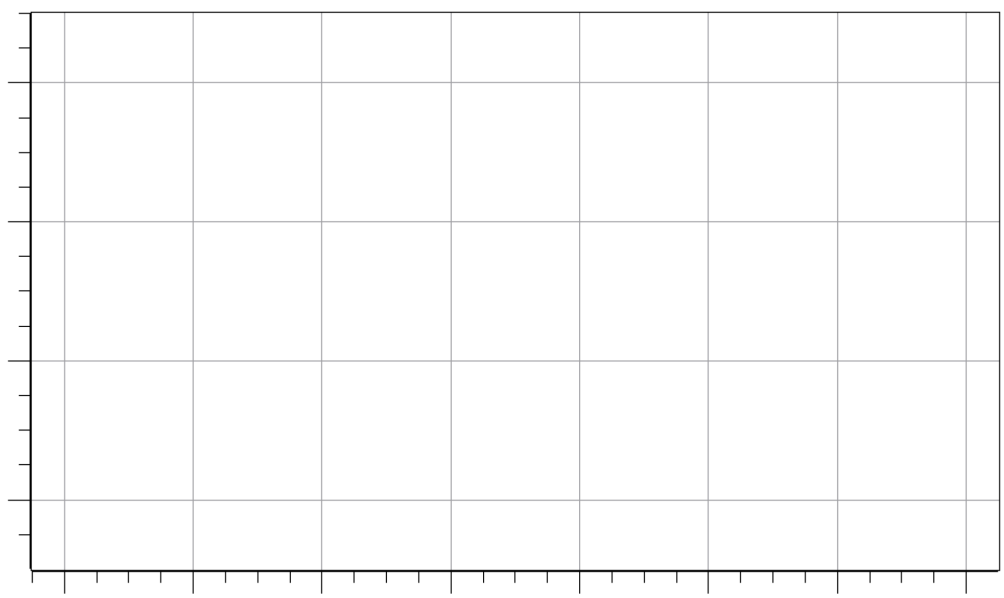
33. ☐ Save your experiment and clean up according to the teacher's instructions, including any special instructions for disposing of the copper(II) sulfate solutions. �(11.1)

Data Analysis

Table 2: Measured orange light absorbance readings

Concentration of $CuSO_4$ Solution (M)	**Orange (610 nm) Absorbance**
0.16	
0.32	
0.48	
0.64	
0.80	

1. ☐ Plot or print a copy of your calibration curve (Orange (610 nm) Absorbance versus Concentration (M)) including the linear line of best fit. Label the overall graph, x-axis and y-axis, and include units on the axes. �(11.2)



2. ☐ Where does your unknown copper(II) sulfate solution fit on the calibration curve above? Place an “X” on the graph to mark this location and label it “unknown”.

Analysis Questions

1. **State Beer's law. Does your data support this statement?**

2. **Would an error occur if some of the cuvettes were dirty? Explain.**

3. **Explain the difference between absorbance and transmittance of light.**

4. **Why is $CuSO_4$ a bluish color? Are colors of light other than blue transmitted?**

Synthesis Questions

Use available resources to help you answer the following questions.

1. **A solution of sodium sulfate is clear and colorless, and yet a solution of copper(II) sulfate is blue. Which ions are causing the blue color? Could you use Beer's law to find the concentration of a sodium sulfate solution?**

2. **What is the minimum number of points needed to create a calibration curve? How many points were used in this experiment? Why?**

---

3. **Other sensors, such as for pH and conductivity, still need to be calibrated, but are able to determine unknown concentrations without creating a calibration curve. Explain how this works.**

Multiple Choice Questions

Select the best answer or completion to each of the questions or incomplete statements below.

1. **Which of the following variables affects the absorbance of light in a solution?**

   A. The distance the light has to travel through the solution (path length)
   B. The amount of solute in each volume (concentration)
   C. The wavelength of the light that is interacting with the solution
   D. All of the above

2. **A sample 0.10 M copper(II) chloride is placed into a cuvette with a 1.00 cm path length. The solution has a measured absorbance of 2.0. What would you expect the absorbance of a 0.05 M copper(II) chloride solution to be?**

   A. 1.0
   B. 2.0
   C. 4.0
   D. Not enough information

3. **What should be in the 'blank' cuvette when the colorimeter is calibrated?**

   A. Nothing
   B. The solution with the greatest concentration of solute
   C. The solvent
   D. A 1.0 M sample of the solution

4. **What color of light is transmitted through a copper(II) sulfate solution?**

   A. Red
   B. Orange
   C. Green
   D. Blue

5. **How many colors make up white light?**

   A. 1
   B. 3
   C. 4
   D. More than five

Key Term Challenge

Fill in the blanks from the list of words in the Key Term Challenge Word Bank.

1. Visible light is only a small portion of the ________________________ spectrum. When different wavelengths of light combine, they form new colors; when all of the wavelengths in the visible spectrum combine, they produce ________________________. The combined wavelengths can be separated into their individual colors by using a ________________________. Light can be reflected, absorbed, or transmitted when it encounters an object. Black objects ________________________ all visible wavelengths of light, while white objects ________________________ all visible wavelengths of light. Colored objects and solutions absorb only a portion of the wavelengths they encounter. We see the light that is not absorbed by the object or solution. A ________________________ measures the absorbance and transmittance of light through solutions. When light is ________________________, it passes through the solution; when light interacts with the solute it is ________________________

2. Beer's law is the ________________________ proportional relationship between the absorbance of light and the concentration of solute in the solution; increasing the concentration will ________________________ the observed absorbance. The relationship depends on the nature of the chemical substance; the concentration of the solution, and the ________________________ of the light. Plotting the absorbance values for solutions with ________________________ concentrations produces a calibration curve. This curve allows for the determination of an ________________________ concentration of the solution.

Key Term Challenge Word Bank

Paragraph 1	Paragraph 2
absorb	decrease
absorbed	directly
colorimeter	increase
electromagnetic	indirectly
energy	intensity
light	known
light sensor	path length
prism	strength
radio	unknown
reflect	wave length
transmit	
transmitted	
white light	