Determination of Molar Mass by Freezing Point Depression

Learning Objectives

Understand the term "colligative properties", specifically how the freezing point of a solvent is affected by adding a solute.

To experimentally determine the freezing point depression of a pure solvent and a solution.

Use freezing point depression data to determine the molar mass of an unknown solute.

Introduction

At this point, you should be very familiar with the concept of a solution – a homogeneous mixture in which a solute is dissolved into a solvent. Solutions have characteristics that differ from that of the pure solvent, these are known as **colligative properties**. Colligative properties depend only on the total number of solute particles present in the solution. There are four colligative properties of solutions:

1. Vapor-Pressure Reduction
2. Freezing Point Depression
3. Boiling Point Elevation
4. Osmotic Pressure

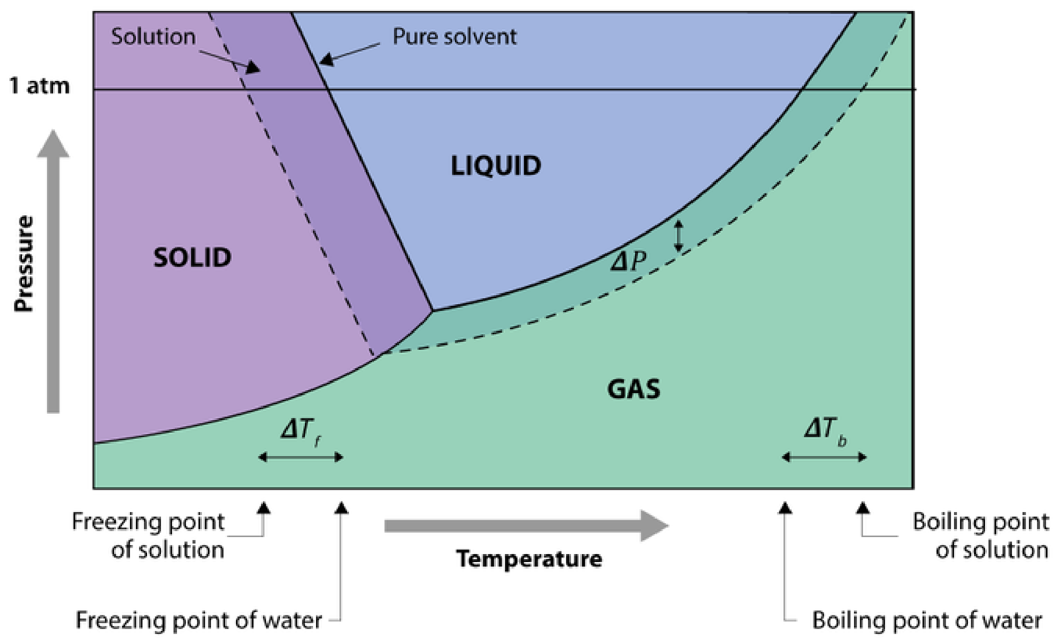

Figure FPD.1: Phase diagram of a pure solvent (—) and a solution (- - -)

In the phase diagram in Figure FPD.1, you can see that when a solute is added to a solvent, the vapor-pressure curve lowers (ΔP). This results in a raising of the boiling point temperature (ΔT_b), and a lowering of the freezing point temperature (ΔT_f). The lowering of the freezing point is known as **freezing point depression**, and can be expressed with the mathematical equation:

$$\Delta T_f = ik_f m \qquad \text{(Equation FPD.1)}$$

where $\Delta T_f = T_\text{final} - T_\text{initial}$, k_f is the freezing point depression constant for the solvent, m is molality of the solution, and i is known as the Van't Hoff factor. You can read more about the Van't Hoff factor in your General Chemistry textbook. For our purposes, it is sufficient to know that for molecular (nonelectrolyte) solutes, $i = 1$.

Recall that molality is a concentration expression,

$$m = \frac{\text{moles solute}}{\text{kg solvent}} \qquad \text{(Equation FPD.2)}$$

where the resulting concentration has units of "m" or "molal". The take-home message is that **a solution will always freeze at a lower temperature than the pure solvent.** This is why salts like NaCl or $MgCl_2$ are scattered on icy roads in the winter; they lower the freezing point of the water, thus melting the ice. The freezing point of both a pure liquid and a solution can be determined quite simply by experiment. One can collect temperature data at specific time intervals as the pure liquid or solution is cooled. This results in a "cooling curve", as shown in Figure FPD.2. Let's discuss the case of the pure liquid first. As heat is slowly removed from the pure liquid, the temperature will decrease until the liquid begins to convert to a solid. At this stage, the temperature will remain constant until all of the liquid has been converted to solid. Once only solid is present, the temperature will decrease again. This can be seen in Figure FPD.2 for the pure liquid curve – the temperature levels off for a time, then dips down again. Now let's think about what happens when a solute is added to the solvent. As the solution is slowly cooled, pure solid solvent will begin to form at some temperature, and this is considered the freezing point of the solution. It is important to determine the temperature at which solid *first* forms, because unlike the case of freezing the pure solvent, the temperature of the solution continues to decrease as additional solvent freezes out from the solution. This slow decrease in the freezing point of the solution occurs because the molality (concentration) of the solution increases as more and more solvent is converted to solid. In other words, the same amount of solute remains dissolved in less and less solvent. This phenomenon needs to be taken into account when determining the freezing point of a solution graphically.

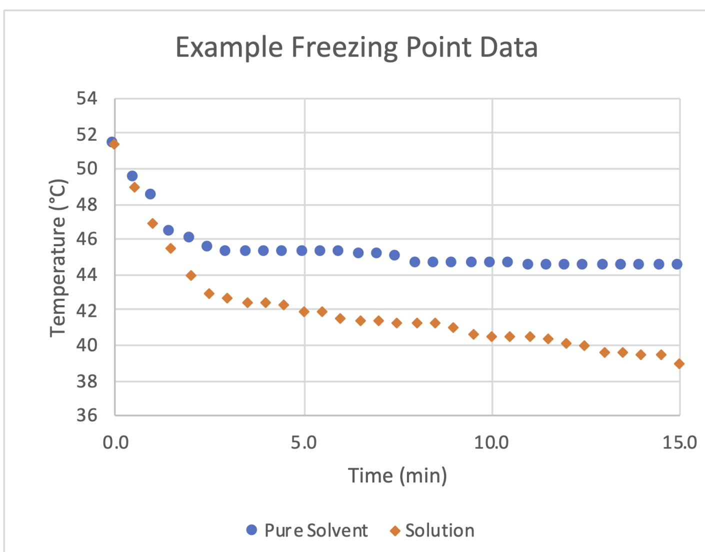

Figure FPD.2: Sample cooling curves for pure solvent (circles) and solution (diamonds)

The freezing point is taken as the intersection of the horizontal portion of the curve, where the temperature does not change with time, and the vertical portion where the temperature drops rapidly with time. For both the pure solvent and the solution, extrapolation may be necessary to determine the freezing point temperatures. In other words, draw the best straight lines through the vertical and horizontal portions of the curve, and take the intersection of these lines to be the freezing point. For example, in Figure FPD.3, extrapolation of the solution curve gives a freezing point temperature of about 43 °C.

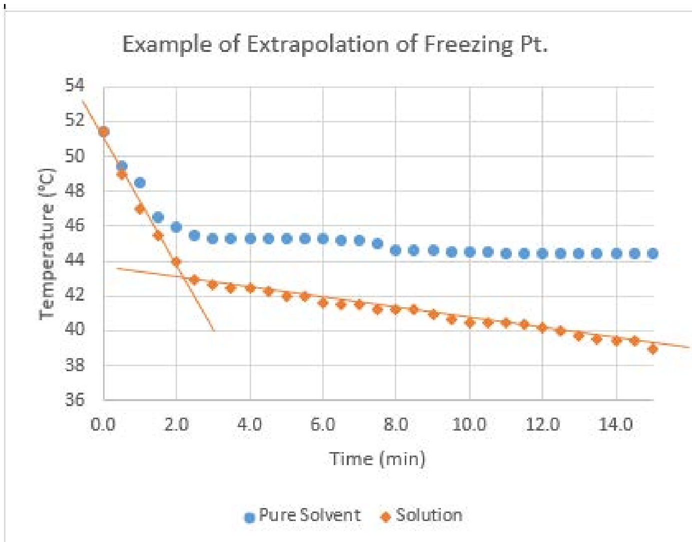

Figure FPD.3: Extrapolation of the Freezing Point of the Solution (diamonds)

The most accurate and robust way to determine the freezing points is by plotting the data using a graphing software, such as Microsoft Excel©. There are two resources available on LabFlow to help you with plotting your data correctly:

1. Video: ”Data Workup Help - Freezing Point Depression”
2. Document: ”Plotting Instructions - Freezing Point Depression”

In this experiment, you will measure the freezing point of pure lauric acid, $C_{11}H_{23}CO_2H$, and the freezing point of a solution of an unknown solid non-electrolyte dissolved in lauric acid. These can be used to find the freezing point depression, ΔT_f. The freezing point depression constant (k_f) of lauric acid is 4.40 °C/molal of solute. These data can then be used to calculate the molality (m) of the unknown solution, and ultimately calculate the molar mass of the unknown solid.

Experimental Procedure

Safety Precautions

Wear safety glasses and a lab coat/apron when performing this experiment.

Part A: Determination of the Freezing Point of Pure Lauric Acid

1. Assemble the apparatus shown in Figure FPD.4 (but leave the test tube and thermometer out until Step 7). Use a 400-mL beaker, filled with approximately 200 mL of water for the water bath. Set the hot plate to around 100-115 °C to heat the water. The final temperature of the water only needs to reach between 50-55 °C. *(It is a good idea to get this water bath set up first, as it takes time for the water to heat up.)*

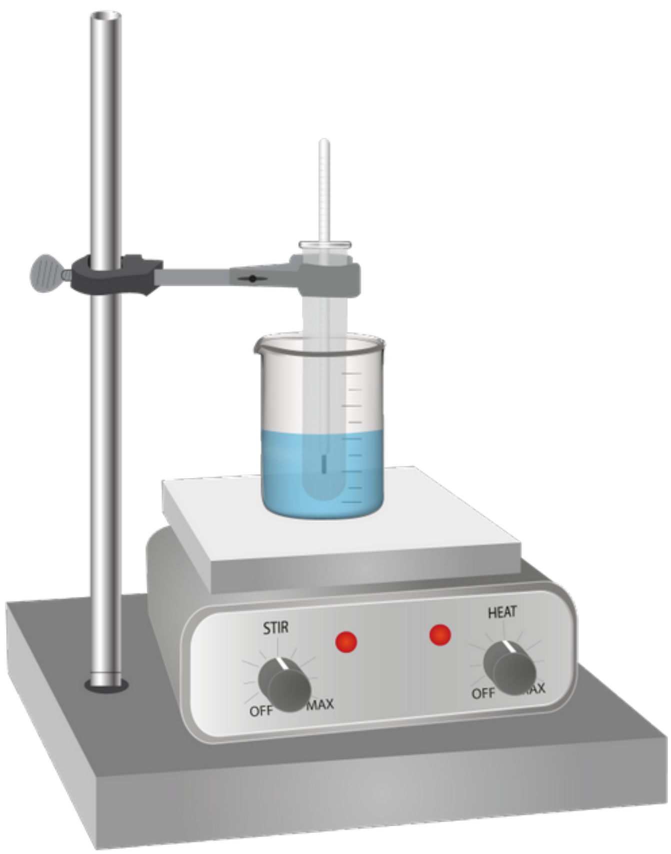

Figure FPD.4: Apparatus for determining freezing point

2. Obtain a clean and dry 25 x 200 mm test tube *(from the Stockroom window)*. Weigh the empty test tube on an a balance in the Balance Room. *(It may be a good idea to put a small beaker on the balance first, and tare it. Then place the test tube in the beaker so that it is held upright.)* Record the exact mass of the empty text

tube in Report Table FPD.1. (Record all of the digits shown on the balance!)

3. Weigh about 4.0 g of lauric acid onto a piece of weighing paper (no need to record the mass yet). Now transfer the lauric acid to the test tube and reweigh the tube. Record the exact mass of test tube + lauric acid in Report Table FPD.1. *Clean up any spilled lauric acid.*

4. Clamp the test tube containing the lauric acid on the ring stand so that the bottom of the test tube is approximately one inch above the bottom of the beaker.

5. **Carefully**, insert a thermometer into the test tube. Heat the water with a hot plate to about 50 °C. Allow all of the lauric acid to melt.

6. Raise the tube out of the beaker, clamping it **away** from the water bath. Take temperature readings every 0.50 minutes (30 seconds) for approximately 15 minutes. Record your temperature-time data in Report Table FPD.2. **It is important to *carefully* stir the sample with the thermometer at a constant rate as the lauric acid cools.** The temperature will decrease at first but will remain steady as the sample freezes. After the sample has solidified completely, the temperature will start to drop again. Continue to take temperature-time measurements until stirring becomes impossible.

   > The best data is obtained when students stir consistently at a constant rate and take careful temperature readings.

Part B: Determination of the Freezing Point of the Solution of an Unknown Solid in Lauric Acid

1. Choose one of bottles of Unknown provided on the Reagent Shelf, or by your Instructor. **Record the number of the unknown in Report Table FPD.3.**

2. Use a piece of weighing paper to weigh about 0.40 g of the unknown acid on a balance in the Balance Room. Tare the weighing paper on the balance, weigh out about 0.40 g of the unknown sample, and record the exact mass of the unknown in the Report Table FPD.3. *Carefully* transfer the unknown to the test tube of lauric acid.

3. Tap the test tube with your fingers so that all of the unknown solid is down in the lauric acid and not stuck to

the sides of the test tube. Insert the tube back into the water bath and allow the solution to melt completely.

4. Raise the tube out of the beaker, clamping it away from the water bath. Take temperature readings every 0.50 minutes (30 seconds) for approximately 15 minutes. It is important to stir the sample with the thermometer at a constant rate as the solution cools until stirring becomes impossible. (Stir at the same rate of stirring as for pure lauric acid.) Record your temperature-time data in Report Table FPD.4.

5. When you have completed the experiment, warm the test tube gently in your water bath until the lauric acid melts, remove the thermometer and wipe it clean. Pour the molten lauric acid solution into the waste container on the reagent bench marked **USED LAURIC ACID**. ***Do not pour the lauric acid solution into the sink.*** You may need to repeat this process a few times to remove all of the lauric acid.

6. Clean the test tube thoroughly with detergent and HOT water to remove the last residue of lauric acid. Put away all other equipment and clean your benchtop. Have your instructor initial your data before leaving the lab.

Plotting the Temperature vs. Time Data

You will need to plot temperature (°C) versus time for Part A to determine the freezing point of the pure lauric acid, and for Part B to determine the freezing point of the unknown solution.

You may create the plots in one of two ways:

- Use the graph paper provided on the Calculations page.
- ***Highly Preferred Method:*** Use a graphing program, such as Microsoft Excel©. Refer to the resources on LabFlow for assistance.

Part A Data

Report Table FPD.1: Mass Data for Lauric Acid

Mass of test tube (g)	________
Mass of test tube and lauric acid (g)	________
Mass of lauric acid (g)	________

Report Table FPD.2: Temperature-Time Data for Cooling Pure Lauric Acid.

Time (min)	Temperature °C	Time (min)	Temperature °C	Time (min)	Temperature °C
0.00	________	6.00	________	12.00	________
0.50	________	6.50	________	12.50	________
1.00	________	7.00	________	13.00	________
1.50	________	7.50	________	13.50	________
2.00	________	8.00	________	14.00	________
2.50	________	8.50	________	14.50	________
3.00	________	9.00	________	15.00	________
3.50	________	9.50	________	15.50	________
4.00	________	10.00	________	16.00	________
4.50	________	10.50	________	16.50	________
5.00	________	11.00	________	17.00	________
5.50	________	11.50	________	17.50	________

Part B Data

Report Table FPD.3: Mass Data for Unknown Solid

Unknown number	______
Mass of unknown solid (g)	______

Report Table FPD.4: Temperature-Time Data for Cooling Lauric Acid-Unknown Solution.

Time (min)	Temperature °C	Time (min)	Temperature °C	Time (min)	Temperature °C
0.00	______	6.00	______	12.00	______
0.50	______	6.50	______	12.50	______
1.00	______	7.00	______	13.00	______
1.50	______	7.50	______	13.50	______
2.00	______	8.00	______	14.00	______
2.50	______	8.50	______	14.50	______
3.00	______	9.00	______	15.00	______
3.50	______	9.50	______	15.50	______
4.00	______	10.00	______	16.00	______
4.50	______	10.50	______	16.50	______
5.00	______	11.00	______	17.00	______
5.50	______	11.50	______	17.50	______

Calculations

If you choose to plot your data manually, you can use the graph paper below. Draw both plots on the same graph, making sure to label each. Determine the freezing point for each sample using your graphs and record the freezing points in Report Table FPD.5. Remember, graphing software is the *highly preferred* method of creating these plots!

Report Table FPD.5: Graph paper

Report Table FPD.6: Molar Mass of Unknown.

Freezing point of pure lactic acid (°C)	
Freezing point of solution (°C)	
Freezing point depression, ΔT_f (°C)	
Molality of unknown, m	
Moles of unknown (mol)	
Molar mass of unknown (g/mol)	

Sample Calculations

Use the space below to write your work for the calculations, you will be required to upload a picture of this work to your report in LabFlow.

Freezing point depression, ΔT_f

Molality of unknown, m

Moles of unknown

Molar mass of unknown

Questions to Consider

The questions below may appear on your Lab Report in LabFlow – they are provided here to get you thinking before completing your lab report.

1. Solutions
    a. What is the solid that forms when a *solution* starts to freeze?

    b. Will your answer for part a of this question be correct for *all* solutions that use solvents that are liquids at room temperature? Explain.

2. Freezing points
    a. Compare the temperature change as a pure liquid is converted to a solid at its freezing point with the temperature change as a solution is converted to a solid at its freezing?

    b. Explain how your answer to part a. of the question is related to the equation given at the end of the Introduction to this Experiment.

3. If you weigh the lauric acid to the nearest 0.1 g and you weigh the unknown solid to the nearest 0.0001 g, can you calculate a molar mass (molecular weight) of your unknown solid to three significant figures? Show your reasoning.

4. If 2.15 g of an unknown solid nonelectrolyte is dissolved in 18.6 g of naphthalene, the resulting solution is found experimentally to freeze 4.3 °C lower than pure naphthalene. If the freezing point depression constant for naphthalene is 6.85 °C/m, calculate each of the following.
    a. The molality of the solution by using *only* the freezing point depression and the freezing point depression constant.

    b. The number of moles of unknown dissolved in the 18.6 g of naphthalene using the mass of naphthalene and the molality of the unknown.

    c. The molar mass of the unknown.

    d. The molecular formula of the unknown if it is comprised of 40.0% carbon, 6.7% hydrogen and 53.3% oxygen