

Colligative Properties Problem Set, Solutions

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1. For a mixture prepared by combining 200.0 mL of nitrobenzene and 1.00 L of water.
a. Calculate the mole fraction of each compound in the mixture

Volume

$$V_{\text{nitrobenzene}} := 200.0 \cdot \text{mL}$$

$$V_{\text{water}} := 1.00 \cdot \text{L}$$

Density

$$\rho_{\text{nitrobenzene}} := 1.2037 \cdot \text{gm} \cdot \text{mL}^{-1}$$

$$\rho_{\text{water}} := 0.998203 \cdot \text{gm} \cdot \text{mL}^{-1}$$

Mass

$$\text{mass}_{\text{nitrobenzene}} := V_{\text{nitrobenzene}} \cdot \rho_{\text{nitrobenzene}}$$

$$\text{mass}_{\text{nitrobenzene}} = 240.74 \cdot \text{gm}$$

$$\text{mass}_{\text{water}} := V_{\text{water}} \cdot \rho_{\text{water}}$$

$$\text{mass}_{\text{water}} = 998.203 \cdot \text{gm}$$

Molecular Mass and Moles

$$\text{MW}_{\text{nitrobenzene}} := (6 \cdot 12.0107 + 5 \cdot 1.00794 + 14.00674 + 2 \cdot 15.9994) \text{ gm} \cdot \text{mole}^{-1}$$

$$\text{MW}_{\text{nitrobenzene}} = 123.109 \cdot \text{mol}^{-1} \cdot \text{gm}$$

$$\text{mole}_{\text{nitrobenzene}} := \frac{\text{mass}_{\text{nitrobenzene}}}{\text{MW}_{\text{nitrobenzene}}}$$

$$\text{mole}_{\text{nitrobenzene}} = 1.955 \cdot \text{mol}$$

$$MW_{\text{water}} := (2 \cdot 1.00794 + 15.9994) \cdot \text{gm} \cdot \text{mole}^{-1}$$

$$MW_{\text{water}} = 18.015 \text{ gm} \cdot \text{mole}^{-1}$$

$$\text{mole}_{\text{water}} := \frac{\text{mass}_{\text{water}}}{MW_{\text{water}}}$$

$$\text{mole}_{\text{water}} = 55.409 \cdot \text{mol}$$

Mole Fraction

$$X_{\text{nitrobenzene}} := \frac{\text{mole}_{\text{nitrobenzene}}}{\text{mole}_{\text{nitrobenzene}} + \text{mole}_{\text{water}}}$$

$$X_{\text{nitrobenzene}} = 0.034$$

$$X_{\text{water}} := \frac{\text{mole}_{\text{water}}}{\text{mole}_{\text{nitrobenzene}} + \text{mole}_{\text{water}}}$$

$$X_{\text{water}} = 0.966$$

b. Calculate the vapor pressure of each compound in the mixture

$$P_{\text{nitrobenzene_pure}} := 55.1 \cdot \text{Pa}$$

$$P_{\text{nitrobenzene_mixture}} := P_{\text{nitrobenzene_pure}} \cdot X_{\text{nitrobenzene}}$$

$$P_{\text{nitrobenzene_mixture}} = 1.878 \cdot \text{Pa}$$

$$P_{\text{water_pure}} := 3167 \cdot \text{Pa}$$

$$P_{\text{water_mixture}} := P_{\text{water_pure}} \cdot X_{\text{water}}$$

$$P_{\text{water_mixture}} = 3.059 \cdot 10^3 \cdot \text{Pa}$$

c. Calculate the total vapor pressure of the mixture

$$P_{\text{total}} := P_{\text{nitrobenzene_mixture}} + P_{\text{water_mixture}}$$

$$P_{\text{total}} = 3.061 \cdot 10^3 \cdot \text{Pa}$$

2. For a mixture prepared by mixing 5.00 g of caffeine ($C_8H_{10}N_4O_2$) with 250.0 mL of water. The final density of the mixture is 1.05 g mL^{-1} .

$$\text{mass}_{\text{caffeine}} := 5.00 \cdot \text{gm}$$

$$\text{MW}_{\text{caffeine}} := (8 \cdot 12.0107 + 10 \cdot 1.00794 + 4 \cdot 14.00674 + 2 \cdot 15.9994) \cdot \text{gm} \cdot \text{mole}^{-1}$$

$$\text{MW}_{\text{caffeine}} = 194.191 \text{ gm} \cdot \text{mole}^{-1}$$

$$\text{mole}_{\text{caffeine}} := \frac{\text{mass}_{\text{caffeine}}}{\text{MW}_{\text{caffeine}}}$$

$$\text{mole}_{\text{caffeine}} = 0.026 \cdot \text{mol}$$

$$V_{\text{water}} := 250.0 \cdot \text{mL}$$

$$\rho_{\text{water}} = 0.998 \text{ gm} \cdot \text{mL}^{-1}$$

$$\text{mass}_{\text{water}} := V_{\text{water}} \cdot \rho_{\text{water}}$$

$$\text{mass}_{\text{water}} = 0.25 \cdot \text{kg}$$

$$\rho_{\text{solution}} := 1.05 \text{ gm} \cdot \text{mL}^{-1}$$

$$V_{\text{solution}} := \frac{\text{mass}_{\text{water}} + \text{mass}_{\text{caffeine}}}{\rho_{\text{solution}}}$$

$$V_{\text{solution}} = 0.242 \text{ L}$$

$$M_{\text{solution}} := \frac{\text{mole}_{\text{caffeine}}}{V_{\text{solution}}}$$

$$M_{\text{solution}} = 0.106 \text{ mole} \cdot \text{L}^{-1}$$

$$m_{\text{solution}} := \frac{\text{mole}_{\text{caffeine}}}{\text{mass}_{\text{water}}}$$

$$m_{\text{solution}} = 0.103 \text{ mol} \cdot \text{kg}^{-1}$$

a. Calculate the boiling point of this mixture

$$K_b := 0.512 \cdot \text{K} \cdot \text{kg} \cdot \text{mole}^{-1}$$

$$\Delta T_b := m_{\text{solution}} \cdot K_b$$

$$\Delta T_b = 0.053 \cdot \text{K}$$

$$T_{b_pure} := 373.15 \cdot \text{K}$$

$$T_{b_mixture} := T_{b_pure} + \Delta T_b$$

$$T_{b_mixture} = 373.203 \cdot \text{K}$$

b. Calculate the vapor pressure of this mixture

$$\text{mole}_{\text{water}} := \frac{\text{mass}_{\text{water}}}{\text{MW}_{\text{water}}}$$

$$\text{mole}_{\text{water}} = 13.852 \cdot \text{mol}$$

$$X_{\text{water}} := \frac{\text{mole}_{\text{water}}}{\text{mole}_{\text{water}} + \text{mole}_{\text{caffeine}}}$$

$$X_{\text{water}} = 0.998$$

$$P_{\text{mixture}} := X_{\text{water}} \cdot P_{\text{water_pure}}$$

$$P_{\text{mixture}} = 3.161 \cdot 10^3 \cdot \text{Pa}$$

c. Calculate the freezing point of this mixture

$$K_f := 1.86 \cdot \text{K} \cdot \text{kg} \cdot \text{mole}^{-1}$$

$$\Delta T_f := m_{\text{solution}} \cdot K_f$$

$$\Delta T_f = 0.192 \cdot \text{K}$$

$$T_{f_pure} := 273.15 \cdot \text{K}$$

$$T_{f_mixture} := T_{f_pure} - \Delta T_f$$

$$T_{f_mixture} = 272.958 \cdot \text{K}$$

d. Calculate the osmotic pressure of this mixture at 25 C.

$$R := 8.314510 \cdot \text{joule} \cdot \text{K}^{-1} \cdot \text{mole}^{-1}$$

$$T := (273.15 + 25) \cdot \text{K}$$

$$\Pi := M_{\text{solution}} \cdot R \cdot T$$

$$\Pi = 2.633 \cdot 10^5 \text{ Pa}$$

3. For a mixture prepared by mixing 10.0 g of sodium sulfate in 250 mL of water. The final density of the mixture is 1.10 g mL⁻¹.

$$\text{mass}_{\text{sodium_sulfate}} := 10.0 \cdot \text{gm}$$

$$\text{MW}_{\text{sodium_sulfate}} := (2 \cdot 22.989770 + 32.066 + 4 \cdot 15.9994) \cdot \text{gm} \cdot \text{mole}^{-1}$$

$$\text{mole}_{\text{sodium_sulfate}} := \frac{\text{mass}_{\text{sodium_sulfate}}}{\text{MW}_{\text{sodium_sulfate}}}$$

$$\text{mole}_{\text{sodium_sulfate}} = 0.07 \cdot \text{mol}$$

$$\text{mass}_{\text{water}} = 0.25 \cdot \text{kg}$$

$$\rho_{\text{solution}} := 1.10 \cdot \text{gm} \cdot \text{mL}^{-1}$$

$$V_{\text{solution}} := \frac{\text{mass}_{\text{water}} + \text{mass}_{\text{sodium_sulfate}}}{\rho_{\text{solution}}}$$

$$V_{\text{solution}} = 0.236 \cdot \text{L}$$

$$M_{\text{solution}} := \frac{3 \cdot \text{mole}_{\text{sodium_sulfate}}}{V_{\text{solution}}} \quad M_{\text{solution}} = 0.895 \text{ mole} \cdot \text{L}^{-1}$$

$$m_{\text{solution}} := \frac{3 \cdot \text{mole}_{\text{sodium_sulfate}}}{\text{mass}_{\text{water}}} \quad m_{\text{solution}} = 0.846 \text{ mole} \cdot \text{kg}^{-1}$$

NOTE: Multiply moles by 3, because sodium sulfate is a salt that dissociates into three ions ($\text{Na}_2\text{SO}_4 \rightarrow 2\text{Na}^{1+} + \text{SO}_4^{2-}$) in water

a. Calculate the boiling point of this mixture

$$K_b := 0.512 \cdot \text{K} \cdot \text{kg} \cdot \text{mole}^{-1}$$

$$\Delta T_b := m_{\text{solution}} \cdot K_b$$

$$\Delta T_b = 0.433 \cdot \text{K}$$

$$T_{b_pure} := 373.15 \cdot \text{K}$$

$$T_{b_mixture} := T_{b_pure} + \Delta T_b$$

$$T_{b_mixture} = 373.583 \cdot \text{K}$$

b. Calculate the vapor pressure of this mixture

$$\text{mole}_{\text{water}} := \frac{\text{mass}_{\text{water}}}{\text{MW}_{\text{water}}}$$

$$\text{mole}_{\text{water}} = 13.852 \cdot \text{mol}$$

$$X_{\text{water}} := \frac{\text{mole}_{\text{water}}}{\text{mole}_{\text{water}} + \text{mole}_{\text{sodium_sulfate}}}$$

$$X_{\text{water}} = 0.995$$

$$P_{\text{mixture}} := X_{\text{water}} \cdot P_{\text{water_pure}}$$

$$P_{\text{mixture}} = 3.151 \cdot 10^3 \text{ Pa}$$

c. Calculate the freezing point of this mixture

$$K_f := 1.86 \cdot \text{K} \cdot \text{kg} \cdot \text{mole}^{-1}$$

$$\Delta T_f := m_{\text{solution}} \cdot K_f$$

$$\Delta T_f = 1.574 \cdot \text{K}$$

$$T_{f_pure} := 273.15 \cdot \text{K}$$

$$T_{f_mixture} := T_{f_pure} - \Delta T_f$$

$$T_{f_mixture} = 271.576 \cdot \text{K}$$

d. Calculate the osmotic pressure of this mixture at 25 C.

$$R := 8.314510 \cdot \text{joule} \cdot \text{K}^{-1} \cdot \text{mole}^{-1}$$

$$T := (273.15 + 25) \cdot \text{K}$$

$$\Pi := M_{\text{solution}} \cdot R \cdot T$$

$$\Pi = 2.219 \cdot 10^6 \text{ Pa}$$

4. You are examining forensics data for a court case and need to identify an analgesic (pain killer). It could be either acetylsalicylic acid (aspirin), ibuprofen (advil) or acetaminophen (tylenol). A mixture of the unknown is prepared by mixing 10.0 grams of unknown and diluting to 250 mL with ethanol. The density of this solution is 0.80 g mL⁻¹. Identify the unknown based upon the following:

a. The boiling point of this mixture is 78.8 °C.

b. The osmotic pressure of this mixture is 480 Pa at 25 °C.

Boiling Point Elevation:

$$\text{BP}_{\text{ethanol}} := (273.15 + 78.5) \cdot \text{K}$$

$$\text{BP}_{\text{mixture}} := (273.15 + 78.8) \cdot \text{K}$$

$$\Delta T := \text{BP}_{\text{mixture}} - \text{BP}_{\text{ethanol}}$$

$$\Delta T = 0.3 \cdot \text{K}$$

$$\Delta T = m \cdot K_b$$

$$K_b := 1.22 \cdot \text{K} \cdot \text{kg} \cdot \text{mole}^{-1}$$

$$m_{\text{mixture}} := \frac{\Delta T}{K_b}$$

$$m_{\text{mixture}} = 0.246 \cdot \text{mol} \cdot \text{kg}^{-1}$$

$$\text{mass}_{\text{mixture}} := 250 \cdot \text{mL} \cdot 0.80 \cdot \text{gm} \cdot \text{mL}^{-1}$$

$$\text{mass}_{\text{mixture}} = 0.2 \cdot \text{kg}$$

$$\text{mass}_{\text{unknown}} := 10.0 \cdot \text{gm}$$

$$\text{mass}_{\text{solvent}} := \text{mass}_{\text{mixture}} - \text{mass}_{\text{unknown}}$$

$$\text{mole}_{\text{unknown}} := m_{\text{mixture}} \cdot \text{mass}_{\text{solvent}}$$

$$\text{mole}_{\text{unknown}} = 0.047 \cdot \text{mol}$$

$$\text{MW}_{\text{unknown}} := \frac{\text{mass}_{\text{unknown}}}{\text{mole}_{\text{unknown}}}$$

$$\text{MW}_{\text{unknown}} = 214.035 \text{ gm} \cdot \text{mole}^{-1}$$

Osmotic Pressure:

$$\Pi := 480400 \cdot \text{Pa}$$

$$T := (273.15 + 25) \cdot \text{K}$$

$$R := 8.31415 \cdot \text{joule} \cdot \text{K}^{-1} \cdot \text{mole}^{-1}$$

$$\Pi = C \cdot R \cdot T$$

$$C_{\text{unknown}} := \frac{\Pi}{R \cdot T}$$

$$C_{\text{unknown}} = 193.798 \cdot \text{m}^{-3} \cdot \text{mol}$$

$$C_{\text{unknown}} = 0.194 \cdot \text{mol} \cdot \text{liter}^{-1}$$

$$V_{\text{mixture}} := 250 \cdot \text{mL}$$

$$\text{mole}_{\text{unknown}} := C_{\text{unknown}} \cdot V_{\text{mixture}}$$

$$\text{mole}_{\text{unknown}} = 0.048 \cdot \text{mol}$$

$$\text{MW}_{\text{unknown}} := \frac{\text{mass}_{\text{unknown}}}{\text{mole}_{\text{unknown}}}$$

$$\text{MW}_{\text{unknown}} = 206.4 \cdot \text{gm} \cdot \text{mole}^{-1}$$