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Topic 3.10: Solubility

Worksheet · AP Chemistry

UNIT 3 · PROPERTIES OF SUBSTANCES AND MIXTURES

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How to Use This Worksheet

Work in order. Section A checks the ideas: the three energy steps of dissolving, like dissolves like, saturation, and the effects of temperature and pressure. Section B builds the calculations: energy cycles, the solubility curve and Henry's law. Section C combines energetics, entropy and precipitation in exam style.

Every value you need is stated in the question, so each question can be answered from the text alone.

Do not look at the answer key until you have attempted every question.

Section A: Recall and Concepts

A1. An ionic solid dissolves in water in three conceptual steps: the ions are separated from the crystal, the water molecules are separated to make room, and the ions are surrounded by water. (a) State the name given to the energy change of the first step for an ionic solid. (b) State whether each of the three steps absorbs or releases energy. (c) State which step carries a special name when the solvent is water, and give the general name used for any solvent. (d) State what the sum of the three steps gives, and what its sign tells you.

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A2. For each solute, choose the better solvent, water or hexane, and justify the choice by naming the dominant attractions formed. (a) Sodium chloride, NaCl. (b) Iodine, I_2. (c) Methanol, CH_3OH. (d) Octane, C_8H_{18}.

A3. A saturated solution of KNO_3 stands in contact with undissolved solid at the bottom of the beaker at a steady temperature. (a) State what saturated means for this solution. (b) Explain, at the particle level, why the concentration does not change even though ions are still moving between the solid and the solution. (c) The beaker is warmed. State what is seen, and explain it using the fact that dissolving KNO_3 is endothermic. (d) A second solution is cooled slowly until it holds more dissolved KNO_3 than the equilibrium amount, with no solid forming. Name this state, and state what happens when a seed crystal is dropped in.

A4. (a) Explain why a warm bottle of soda goes flat faster than a cold bottle once opened. (b) Explain why soda is bottled under a high pressure of CO_2, in terms of the concentration of dissolved gas. (c) State the effect of that same high pressure on the amount of solid NaCl that can dissolve in the drink. (d) State the effect of doubling the partial pressure of a gas above a liquid on its solubility, naming the law involved.

A5. Predict whether each compound is soluble or insoluble in water, giving the anchor pattern or the energy reason. (a) Potassium nitrate, KNO_3. (b) Silver chloride, AgCl. (c) Barium sulfate, $BaSO_4$. (d) Calcium carbonate, $CaCO_3$. (e) Sodium carbonate, Na_2CO_3.

Section B: Core Practice

B1. For sodium chloride, the lattice energy is +787 kJ/mol, the hydration enthalpy of Na^+ is -406 kJ/mol and the hydration enthalpy of Cl^- is -378 kJ/mol. (a) Calculate the total hydration enthalpy

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change when one mole of NaCl dissolves. (b) Calculate the enthalpy of solution of NaCl. (c) State whether dissolving NaCl is endothermic or exothermic, and predict whether the solution warms, cools, or barely changes temperature. (d) Use the size of your answer to part (b) to explain why the solubility of NaCl changes only slightly between 25 °C and 100 °C.

B2. Two ionic salts have the following data, in kJ/mol. Salt P: lattice energy +812, total hydration enthalpy -690. Salt Q: lattice energy +590, total hydration enthalpy -655. (a) Calculate the enthalpy of solution of each salt. (b) State which salt dissolves exothermically. (c) State which salt's energetics favour dissolving more strongly, and name the second factor that must also be considered before solubility can be predicted. (d) A student claims salt P cannot dissolve at all, because its enthalpy of solution is positive. Evaluate the claim.

B3. The solubility of KNO_3, in grams per 100 g of water, is 31.6 at 20 °C, 63.9 at 40 °C and 110 at 60 °C. A solution containing 100 g of water is saturated at 60 °C. (a) State the mass of KNO_3 dissolved. (b) The solution is cooled to 20 °C and crystals form. Calculate the mass of crystals. (c) The mixture is then warmed to 40 °C. Calculate the mass of solid that redissolves and the mass that remains. (d) State whether the mixture after part (c) is saturated, unsaturated or supersaturated, and how you can tell.

B4. The Henry's law constant for CO_2 in water at 25 °C is 3.4×10^{-2} mol per litre per atm. (a) Calculate the concentration of dissolved CO_2 in a drink sealed under a CO_2 partial pressure of 3.0 atm. (b) Calculate the mass of CO_2 dissolved in 1.00 L of the drink at that pressure. The molar mass of CO_2 is 44.01 g/mol. (c) The drink is opened and left in air, where the partial pressure of CO_2 is 4.0×10^{-4} atm. Calculate the new equilibrium concentration. (d) Calculate the percentage of the originally dissolved CO_2 that must escape.

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B5. Methanol and ethanol are miscible with water in all proportions. The solubility of 1-butanol in water is about 7.9 g per 100 g of water, and of 1-hexanol about 0.60 g per 100 g of water. (a) State the trend in solubility as the alcohol chain lengthens. (b) Explain the trend using the structure of the alcohols: one -OH group and a hydrocarbon chain of growing length. (c) Predict where the solubility of 1-pentanol falls relative to the values for 1-butanol and 1-hexanol. (d) State which of these alcohols mixes most readily with octane, and why.

B6. Classify each mixture or state using the correct term, with a reason. (a) Olive oil and water, shaken and then left, form two layers. (b) Oxygen gas mixed with nitrogen gas in a cylinder. (c) A solution standing over undissolved solid, its concentration constant over several days. (d) Chalk dust stirred into water, which stays cloudy and slowly settles.

Section C: Exam Style

C1. Ammonium nitrate is the salt in instant cold packs. Its enthalpy of solution is +25.7 kJ/mol. (a) State the two energy costs and the one energy release involved when it dissolves in water, with the sign of each. (b) Explain why the pack feels cold when the salt dissolves. (c) Explain how the salt can dissolve spontaneously even though the process absorbs heat. (d) Calculate the heat absorbed when 0.50 mol of ammonium nitrate dissolves. (e) Predict the effect of warming on the maximum mass of ammonium nitrate that can dissolve, and justify the prediction.

C2. A bottle of soda is sealed under a CO_2 partial pressure of 4.0 atm. The Henry's law constant for CO_2 in water at 25 °C is 3.4×10^{-2} mol per litre per atm. (a) Calculate the concentration of dissolved CO_2 in the sealed bottle. (b) The bottle is opened and left standing in air, where the partial pressure of CO_2 is 4.0×10^{-4} atm. Calculate the equilibrium concentration now. (c) Calculate the percentage of the dissolved CO_2 that escapes. (d) Explain, at the particle level, why an opened warm bottle

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goes flat faster than an opened cold bottle. (e) A student shakes an opened bottle and it goes flat sooner. State what shaking changes and what it cannot change.

C3. Solutions of silver nitrate, $AgNO_3$, and sodium chloride, NaCl, are mixed. A white solid forms at once. (a) Name the solid, and the two ions that combine to form it. (b) State which two ions remain dissolved, and what interaction keeps them in solution. (c) Explain, using lattice energy and hydration energy, why the solid in part (a) does not stay dissolved, while $AgNO_3$ and NaCl each dissolve readily on their own. (d) A saturated solution of the solid from part (a) contains 0.0019 g of it per litre. Calculate the mass, in milligrams, dissolved in 500 mL of the solution. (e) A drop of the clear liquid standing above the settled solid is evaporated on a watch glass and leaves a faint white residue. Explain what this shows about calling the solid insoluble.

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Answer Key

A1. (a) The lattice energy. (b) Separating the ions from the crystal absorbs energy; separating water molecules to make room absorbs energy; forming ion-dipole attractions as water surrounds the ions releases energy. (c) The third step: it is called hydration when the solvent is water, and solvation for any solvent. (d) The enthalpy of solution. A negative sum means dissolving releases heat overall (exothermic); a positive sum means it absorbs heat (endothermic).

A2. (a) Water. NaCl is ionic, and the ion-dipole attractions between water and the Na^+ and Cl^- ions repay the cost of separating the lattice. (b) Hexane. I_2 is nonpolar and held only by dispersion forces, which hexane matches; dissolving in water would break hydrogen bonds that iodine cannot repay. (c) Water. Methanol's -OH group hydrogen bonds with water as strongly as with itself, so the two liquids are miscible. (d) Hexane. Octane is a nonpolar hydrocarbon held by dispersion forces; hexane provides matching attractions, while water cannot compensate for its disrupted hydrogen bonding.

A3. (a) It holds the maximum equilibrium amount of dissolved KNO_3 at that temperature; no more can dissolve. (b) Ions keep leaving the solid and crystallizing back onto it at equal rates. The two flows cancel, so the concentration stays constant: a dynamic equilibrium, not a stopped process. (c) Some of the undissolved solid dissolves. Dissolving KNO_3 is endothermic, so heat acts like a reactant: warming shifts the balance toward the dissolved state, and the solution can hold more. (d) Supersaturated. The seed crystal gives the excess solute a surface to build on, so the excess crystallizes out rapidly until the solution is just saturated.

A4. (a) Gas solubility falls as temperature rises. In the warm bottle the dissolved CO_2 particles have more kinetic energy and escape from the liquid more readily, so the gas leaves faster and less can stay dissolved. (b) By Henry's law the concentration of a dissolved gas is proportional to its partial pressure above the liquid, so bottling under a high CO_2 pressure forces a high concentration of CO_2 into the drink. (c) Essentially no effect: pressure has a negligible influence on the solubility of a solid. (d) It doubles. Henry's law makes the dissolved concentration directly proportional to the partial pressure, so twice the pressure gives twice the concentration at equilibrium.

A5. (a) Soluble: all nitrates are soluble. (b) Insoluble: silver chloride is the standing exception among chlorides, because its lattice energy far exceeds what hydration can repay. (c) Insoluble: barium sulfate is the standing exception among sulfates. (d) Insoluble: carbonates are generally insoluble, and calcium is not a Group 1 metal. (e) Soluble: sodium is a Group 1 metal, and Group 1 carbonates are the exception to the carbonate pattern.

B1. (a) -406 + (-378) = -784 kJ/mol. (b) +787 + (-784) = +3 kJ/mol, matching the measured value of about +3.9 kJ/mol. (c) Very slightly endothermic. The temperature barely changes: only about 3 to 4 kJ per mole is absorbed, the small leftover of two terms near 800 kJ/mol that almost cancel. (d)

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With an enthalpy of solution so close to zero, heat is neither a significant reactant nor a product, so temperature has little leverage on the equilibrium. The solubility rises only slightly, from about 36 g to about 40 g per 100 g of water between 25 °C and 100 °C.

B2. (a) Salt P: +812 + (-690) = +122 kJ/mol. Salt Q: +590 + (-655) = -65 kJ/mol. (b) Salt Q. (c) Salt Q: it releases energy overall, while salt P must find +122 kJ/mol from somewhere. The second factor is entropy, the disorder gained when the crystal disperses. (d) The reasoning is wrong, even if the conclusion may hold for this salt. A positive enthalpy of solution does not forbid dissolving: ammonium nitrate absorbs +25.7 kJ/mol and dissolves readily, because the entropy increase pays the difference. For salt P the gap is +122 kJ/mol, far larger than the entropy gains from dissolving usually supply, so P is expected to be insoluble in practice, but for that quantitative reason rather than the student's absolute one.

B3. (a) 110 g. (b) At 20 °C the water can hold 31.6 g, so the mass crystallized is 110 - 31.6 = 78.4 g. (c) At 40 °C the water can hold 63.9 g, so the mass redissolved is 63.9 - 31.6 = 32.3 g. The mass remaining as solid is 78.4 - 32.3 = 46.1 g. (d) Saturated. Undissolved solid remains in contact with the solution, so the solution holds the maximum equilibrium amount for 40 °C.

B4. (a) $C = kP = 3.4 \times 10^{-2} \times 3.0 = 0.102$ mol/L. (b) Mass = 0.102 × 44.01 = 4.49 g. (c) $C = 3.4 \times 10^{-2} \times 4.0 \times 10^{-4} = 1.36 \times 10^{-5}$ mol/L. (d) The fraction escaping is (0.102 - 0.0000136) ÷ 0.102 = 0.9999, so about 99.99 percent of the dissolved CO_2 escapes.

B5. (a) Solubility falls sharply as the chain lengthens: complete miscibility for the one and two carbon alcohols, then 7.9 g per 100 g of water at four carbons and only 0.60 g at six. (b) Every alcohol has one -OH group, which hydrogen bonds with water and favours dissolving. The hydrocarbon chain is nonpolar: it disrupts water's hydrogen bonding network without repaying it. As the chain grows, the -OH group becomes a smaller share of the molecule, so the nonpolar character takes over. (c) Between the two values, at roughly 2 g per 100 g of water (the measured value is about 2.2 g). (d) 1-Hexanol. Its long hydrocarbon chain makes dispersion forces the dominant interaction, matching nonpolar octane most closely.

B6. (a) Immiscible. Oil is nonpolar and water is polar; mixing offers no attractions to repay breaking water's hydrogen bonds, so the liquids separate into layers. (b) A homogeneous solution. Gas particles mix completely and uniformly in all proportions. (c) A saturated solution at dynamic equilibrium: dissolving and crystallizing run at equal rates, which holds the concentration constant. (d) A heterogeneous mixture, a suspension, not a solution. The chalk particles never dissolved, which is why the mixture stays cloudy and settles on standing.

C1. (a) Costs: separating the NH_4^+ and NO_3^- ions from the crystal (lattice energy, positive) and separating water molecules to make room (positive). Release: hydration of the ions as ion-dipole attractions form (negative). (b) The three steps sum to +25.7 kJ/mol, so dissolving draws heat in from the water and the pack. Their temperature falls, and that is the cold that is felt. (c) Dissolving disperses the ordered ions of the crystal throughout the solution, a large increase in entropy. That

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increase drives the process spontaneously even while it absorbs heat. (d) Heat absorbed = 0.50 × 25.7 = 12.85 kJ, about 12.9 kJ. (e) It increases. Because dissolving is endothermic, heat acts as a reactant, so warming shifts the balance toward the dissolved state and more salt can dissolve.

C2. (a) C = $3.4 \times 10^{-2} \times 4.0 = 0.136$ mol/L. (b) C = $3.4 \times 10^{-2} \times 4.0 \times 10^{-4} = 1.36 \times 10^{-5}$ mol/L. (c) The fraction escaping is (0.136 - 0.0000136) ÷ 0.136 = 0.9999, so about 99.99 percent escapes. (d) At the higher temperature the dissolved CO_2 particles move faster, escape the liquid more readily, and the equilibrium solubility of the gas is lower. The warm drink therefore loses its gas faster and more completely; in the cold drink more CO_2 can remain dissolved. (e) Shaking changes the rate: it speeds the escape of gas toward equilibrium. It cannot change the equilibrium amount dissolved, which is set by the temperature and the CO_2 partial pressure above the drink.

C3. (a) Silver chloride, AgCl, formed from Ag^+ ions and Cl^- ions. (b) Na^+ and NO_3^- remain dissolved, held in solution by ion-dipole attractions to water, their hydration. (c) In AgCl the electrostatic attractions holding the lattice together are stronger than the ion-dipole attractions hydration can offer in return, so water cannot pay the cost of separating the ions and they stay locked in the solid. For $AgNO_3$ and NaCl the balance is close enough, with entropy helping, that hydration repays the lattice cost and the ions disperse. (d) Mass in 500 mL = 0.0019 × 0.500 = 0.00095 g, which is 0.95 mg. (e) It shows that insoluble does not mean zero solubility. The saturated solution still holds a tiny equilibrium concentration of dissolved Ag^+ and Cl^- ions, which is what the residue came from; insoluble means sparingly soluble, with the equilibrium lying far toward the solid.

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