Information for Free-Response Question 1

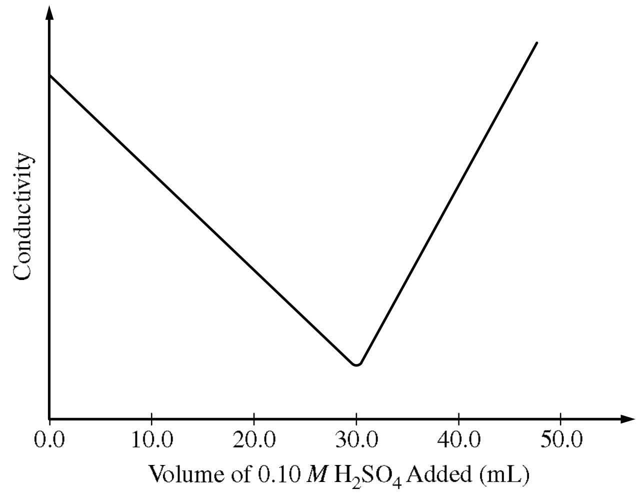
Timing	The student should spend approximately 20 minutes on this question.
Essential Knowledge/ Big Ideas	1.E.2 Conservation of atoms makes it possible to compute the masses of substances involved in physical and chemical processes. Chemical processes result in the formation of new substances, and the amount of these depends on the number and the types and masses of elements in the reactants, as well as the efficiency of the transformation. Big Idea 3: Changes in matter involve the rearrangement and/or reorganization of atoms and/or the transfer of electrons. 3.A.1 A chemical change may be represented by a molecular, ionic, or net ionic equation. 6.C.3 The solubility of a substance can be understood in terms of chemical equilibrium.
Science Practices	1.5 The student can re-express key elements of natural phenomena across multiple representations in the domain. 4.2 The student can design a plan for collecting data to answer a particular scientific question. 5.1 The student can analyze data to identify patterns or relationships. 7.1 The student can connect phenomena and models across spatial and temporal scales.
Learning Objectives	1.19 The student can design, and/or interpret data from, an experiment that uses gravimetric analysis to determine the concentration of an analyte in a solution. 3.1 Students can translate among macroscopic observations of change, chemical equations, and particle views. 3.2 The student can translate an observed chemical change into a balanced chemical equation and justify the choice of equation type (molecular, ionic, or net ionic) in terms of utility for the given circumstances. 6.23 The student can interpret data regarding the relative solubility of salts in terms of factors (common ions, pH) that influence the solubility.

Characteristics of a STRONG Response	Part (a) The student is able to write a correct equation for the neutralization reaction and a correct equation for the precipitation reaction. The equations are balanced net ionic equations with appropriate charges on the ions. Part (b) The student is able to identify either the Ba^{2+} ion or the OH^- ion as the chemical species that enable the solution to conduct electricity. The student is able to use the precipitation reaction to explain that the concentration of Ba^{2+} decreases as solid $BaSO_4$ is formed and use the neutralization reaction to explain that OH^- decreases due to reaction with the strong acid. Part (c) The student can use the graph to calculate the molarity of the original solution of $Ba(OH)_2$. In determining the original $Ba(OH)_2$ solution molarity, the student can calculate the number of moles of the titrant added at the equivalence point. The student can use this information to calculate the correct original concentration of $Ba(OH)_2$. Part (d) The student understands that the concentrations of Ba^{2+} and SO_4^{2-} are equal and correctly uses the expression $K_{sp} = [Ba^{2+}] \times [SO_4^{2-}] = 1.0 \times 10^{-10}$ to determine the concentration. The student is able to correctly calculate the K_{sp}. The student understands that the concentration of Ba^{2+} and SO_4^{2-} is equal. The student uses the equation $K_{sp} = [Ba^{2+}] \times [SO_4^{2-}] = 1.0 \times 10^{-10}$. Part (e) The student can explain the decrease in Ba^{2+} ion by using equilibrium reasoning, either by applying Le Chatelier's principle to the dissolution reaction for $BaSO_4$ or by referring to the common ion effect.
Characteristics of a GOOD Response	Part (a) The student is able to write an equation for the neutralization reaction and an equation for the precipitation reaction. The equations may not be balanced. Part (b) The student is able to identify either the Ba^{2+} ion or OH^- ion as the chemical species that will enable the solution to conduct electricity. The student uses only one reaction to explain the decrease in conductivity, including only the decrease in Ba^{2+} via the precipitation reaction or the decrease in OH^- via the neutralization reaction. Part (c) The student can determine the number of moles of titrant needed at the equivalence point, however he or she cannot successfully use this information to calculate the correct original concentration of $Ba(OH)_2$. Part (d) The student attempts to use the K_{sp} expression to calculate the solubility. However, the student makes an error in the solubility computation, such as failing to take the square root of K_{sp} to get the concentration. Part (e) The student can explain the decrease in Ba^{2+} ion by using equilibrium reasoning, either by applying Le Chatelier's principle to the dissolution reaction for $BaSO_4$ or by referring to the common ion effect. However, additional factors are included that contradict the student's earlier statements.

Characteristics of a WEAK Response	Part (a) The student is able to write the neutralization reaction but has difficulty with the precipitation reaction. The precipitation reaction may be written in combination with the neutralization reaction, as in $Ba(OH)_2 + H_2SO_4 \rightarrow BaSO_4 + 2\ H_2O$. Part (b) The student incorrectly identifies the species responsible for the conductivity. The student is unable to explain the decrease in conductivity based on the reactions from part (a). Part (c) The student can determine the number of moles of titrant needed at the equivalence point, however he or she cannot successfully use this information to calculate the correct original concentration of $Ba(OH)_2$. Part (d) The student is not able to connect the experimental situation to the solubility of $BaSO_4$. Part (e) The student uses stoichiometry, instead of equilibrium reasoning, to explain the change in Ba^{2+} concentration.

Scoring Guidelines for Free-Response Question 1

Question 1
(10 Points)



A student performs an experiment in which the conductivity of a solution of $Ba(OH)_2$ is monitored as the solution is titrated with 0.10 *M* H_2SO_4. The original volume of the $Ba(OH)_2$ solution is 25.0 mL. A precipitate of $BaSO_4$ ($K_{sp} = 1.0 \times 10^{-10}$) formed during the titration. The data collected from the experiment are plotted in the graph above.

(a) As the first 30.0 mL of 0.10 *M* H_2SO_4 are added to the $Ba(OH)_2$ solution, two types of chemical reactions occur simultaneously. On the lines provided below, write the balanced net-ionic equations for (i) the neutralization reaction and (ii) the precipitation reaction.

(i) Equation for neutralization reaction: ______________________________

(ii) Equation for precipitation reaction: ______________________________

$Ba^{2+}(aq) + SO_4^{2-}(aq) \rightarrow BaSO_4(s)$ $H^+(aq) + OH^-(aq) \rightarrow H_2O(l)$	1 point is earned for <u>each</u> correct product. 1 point is earned for the correct reactants with atoms <u>and</u> charges balanced in <u>both</u> reactions.

(b) The conductivity of the $Ba(OH)_2$ solution decreases as the volume of added 0.10 *M* H_2SO_4 changes from 0.0 mL to 30.0 mL.

(i) Identify the chemical species that enable the solution to conduct electricity as the first 30.0 mL of 0.10 *M* H_2SO_4 are added.

$Ba^{2+}(aq)$ and/or $OH^-(aq)$	1 point is earned for either ion.

(ii) On the basis of the equations you wrote in part (a), explain why the conductivity decreases.

As the titration approaches the equivalence point, $Ba^{2+}(aq)$ ions are removed from solution by the precipitation reaction, <u>and</u> $OH^-(aq)$ ions are removed from solution by the neutralization reaction.	1 point is earned for each correct explanation. <u>Note</u>: response must refer to <u>both</u> reactions for full credit.

(c) Using the information in the graph, calculate the molarity of the original $Ba(OH)_2$ solution.

moles $Ba(OH)_2$ = moles H_2SO_4 (at equivalence point) moles $H_2SO_4 = \frac{0.10 \text{ mol}}{1.0 \text{ L}} \times 0.030 \text{ L} = 0.0030 \text{ mol}$ $[Ba(OH)_2] = \frac{\text{mol } Ba(OH)_2}{\text{volume of original solution}} =$ $\frac{0.0030 \text{ mol}}{0.025 \text{ L}} = 0.12\ M$	1 point is earned for the correct determination of the number of moles of titrant added at the equivalence point (can be implicit). 1 point is earned for the correct calculation of the original concentration of $Ba(OH)_2(aq)$.

(d) Calculate the concentration of $Ba^{2+}(aq)$ in the solution at the equivalence point (after exactly 30.0 mL of 0.10 M H_2SO_4 are added).

$K_{sp} = [Ba^{2+}] \times [SO_4^{2-}] = 1.0 \times 10^{-10}$ $[Ba^{2+}] = [SO_4^{2-}]$ $[Ba^{2+}] = \sqrt{1.0 \times 10^{-10}} = 1.0 \times 10^{-5}\ M$	1 point is earned for the correct calculation based on K_{sp}.

(e) The concentration of $Ba^{2+}(aq)$ in the solution decreases as the volume of added 0.10 M H_2SO_4 increases from 30.0 mL to 31.0 mL. Explain.

Because of the common ion effect, adding sulfate ions to an equilibrium reaction involving sulfate ions will cause the reaction to consume the added ions as a new equilibrium is established. Consequently, more $BaSO_4(s)$ is formed, causing the $Ba^{2+}(aq)$ concentration to decrease.	1 point is earned for a correct explanation, which must use an equilibrium argument (for example, citing the common ion effect or Le Chatelier's principle) rather than a stoichiometric argument.

Information for Free-Response Question 2

Timing	The student should spend approximately 20 minutes on this question.
Essential Knowledge	5.B.3 Chemical systems undergo three main processes that change their energy: heating/cooling, phase transitions, and chemical reactions. 5.B.4 Calorimetry is an experimental technique that is used to measure the change in energy of a chemical system. 6.A.2 The current state of a system undergoing a reversible reaction can be characterized by the extent to which reactants have been converted to products. The relative quantities of reaction components are quantitatively described by the reaction quotient, Q. 6.A.4 The magnitude of the equilibrium constant, K, can be used to determine whether the equilibrium lies toward the reactant side or the product side.
Science Practices	2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 2.3 The student can estimate numerically quantities that describe natural phenomena. 4.2 The student can design a plan for collecting data to answer a particular scientific question. 5.1 The student can analyze data to identify patterns or relationships.
Learning Objectives	5.6 The student is able to use calculations or estimations to relate energy changes associated with heating/cooling a substance to the heat capacity, relate energy changes associated with a phase transition to the enthalpy of fusion/vaporization, relate energy changes associated with a chemical reaction to the enthalpy of the reaction, and relate energy changes to $P\Delta V$ work. 5.7 The student is able to design and/or interpret the results of an experiment in which calorimetry is used to determine the change in enthalpy of a chemical process (heating/cooling, phase transition, or chemical reaction) at constant pressure. 6.2 The student can, given a manipulation of a chemical reaction or set of reactions (e.g., reversal of reaction or addition of two reactions), determine the effects of that manipulation on Q or K. 6.7 The student is able, for a reversible reaction that has a large or small K, to determine which chemical species will have very large versus very small concentrations at equilibrium.

Characteristics of a STRONG Response	Part (a) The student is able to analyze the provided data to assess the level of precision in the measurements and correctly conclude that it is not sufficient to report an answer to two significant figures due to the choice of glassware. The student can correctly list two changes to the procedure that will result in a more precise result: using the more precise volumetric glassware and increasing the concentration of the reactant solutions. The explanation includes that using the more precise glassware allows the volume (50.0 mL) to be measured to three significant figures. The explanation also articulates that using the more concentrated solutions results in a greater release of energy without a larger volume of solution to heat, which increases the temperature change to a level where three significant figures can be maintained. Part (b) The student is able to calculate the enthalpy of reaction in kJ/mol with correct sign or direction of energy flow, given the provided solution quantities and amount of energy released. The calculation includes the correct calculation of moles of reaction (given that the coefficients in the reaction are all 1), as well as dividing the heat released by the moles of reaction. The answer is reported with the proper sign (negative) or indication of direction of energy flow (released). The student can articulate that the calorimeter and thermometer absorb energy from the reaction, resulting in a calculated value of the reaction enthalpy that is lower (less exothermic) than it would be had the energy absorbed by the calorimeter and thermometer been taken into account. The student can identify the net ionic equation for the chemical reaction and correctly determine that it is the reverse of the equation for K_w, resulting in a K value that is very large. The student can articulate that reactions with very large K values go essentially to completion. Part (c) The student is able to determine a specific procedural error that would result in a higher calculated reaction enthalpy by reasoning which experimental variants would result in a higher than expected value of the temperature change. Highlighted errors may include an erroneously low initial temperature recording, an erroneously high final temperature recording (or both), or using the more concentrated solutions in place of the 1.00 M solutions and not realizing it. Justification includes correct mapping of variables and articulation that the highlighted error would result in a larger temperature change, which in turn results in a higher calculated value for the reaction enthalpy.

Characteristics of a GOOD Response	Part (a) The student is able to evaluate the experimental results to determine that the data are insufficient to report a conclusion with two significant figures due to the choice of imprecise volumetric glassware. The student can propose one change to the procedure that will result in three significant figures and correctly explain how the proposed change will increase the precision of the results. The student may have difficultly listing or explaining how the second change would result in a calculation with precision to three significant figures. Part (b) The student is able to calculate the moles of reaction from the data provided and set up the ratio between heat released and the moles of reaction. The student can articulate that the calorimeter and thermometer absorb energy and will decrease calculated enthalpy of reaction. The student may be able to determine the net ionic equation for the reaction but may have difficulty recognizing the relationship between this reaction and the reaction associated with K_w. Part (c) The student can articulate the connection between the temperature change and the magnitude of the enthalpy change and reason that a larger ΔT term is necessary. The student may have difficulty identifying an experimental error that will result in a larger value for ΔT.
Characteristics of a WEAK Response	Part (a) The student may be able to identify that the experimental data are not sufficient to report an answer to two significant figures but may have difficulty justifying why the data are insufficient. The student may incorrectly conclude that the data are sufficient to report the answer to two significant figures. The student may be able to suggest one change to the experimental conditions to increase the level of precision beyond one significant figure, or the student may be able to list a change but be unable to explain how it will increase the precision. Part (b) The student may be able to set up the ratio between heat released and moles of reaction or may calculate the moles of reaction incorrectly. The student may omit the sign or direction of the energy flow in the calculated ΔH term. The student may be able to reiterate that the thermometer and calorimeter absorb energy but may incorrectly predict the effect on the reaction enthalpy. The student is unable to identify the net ionic equation's relationship to K_w or to use that relationship to justify that the reaction is likely to go to completion. Part (c) The student may be able to articulate the relationship between a larger ΔT value and a larger ΔH value, or the student may incorrectly assign an inverse relationship. The student may suggest an experimental error that moves the ΔH value in the wrong direction (i.e., results in a smaller temperature change rather than larger) or may suggest an experimental error that does not affect ΔH (e.g., using larger volumes of the 1.00 M solutions).

Scoring Guidelines for Free-Response Question 2

Question 2
(10 Points)

A student is given the task of determining the enthalpy of reaction for the reaction between HCl(*aq*) and NaOH(*aq*). The following materials are available.

1.00 *M* HCl(*aq*)	1.00 *M* NaOH(*aq*)	distilled water
2.00 *M* HCl(*aq*)	2.00 *M* NaOH(*aq*)	goggles
insulated cups with covers	gloves	lab coat
thermometer (± 0.1°C)	stirring rod	

The student may select from the glassware listed in the table below.

Glassware Items	Precision
250 mL Erlenmeyer flasks	± 25 mL
100 mL beakers	± 10 mL
100 mL graduated cylinders	± 0.1 mL

(a) The student selects two 100 mL beakers, uses them to measure 50 mL each of 1.00 *M* HCl(*aq*) solution and 1.00 *M* NaOH(*aq*) solution, and measures an initial temperature of 24.5°C for each solution. Then the student pours the two solutions into an insulated cup, stirs the mixture, covers the cup, and records a maximum temperature of 29.9°C.

(i) Is the experimental design sufficient to determine the enthalpy of reaction to a precision of two significant figures? Justify your answer.

No. The use of the beakers to measure 50 mL ±10 mL of solutions limits the precision of the volume measurements and of the calculations to ±20% or 1 significant figure.	1 point is earned for the correct answer with the correct explanation.

(ii) List two specific changes to the experiment that will allow the student to determine the enthalpy of reaction to a precision of three significant figures. Explain.

Use graduated cylinders to measure the volumes of acid and base allowing a volume precision of ±0.1 mL or 3 significant figures for a volume of 50.0 mL. AND Use the 2.00 *M* HCl and 2.00 *M* NaOH solutions (instead of 1.00 *M*) to get a larger ΔT, thereby improving the relative precision in ΔT to ±1%.	1 point is earned for the change of glassware to graduated cylinders with a proper explanation. 1 point is earned for using the 2.00 *M* solutions for improved relative precision in temperature. <u>Note</u>: doubling the volumes will not increase ΔT or significantly improve volume precision.

(b) A second student is given two solutions, 75.0 mL of 1.00 *M* HCl and 75.0 mL of 1.00 *M* NaOH, each at 25.0°C. The student pours the solutions into an insulated cup, stirs the mixture, covers the cup, and records the maximum temperature of the mixture.

(i) The student calculates the amount of heat evolved in the experiment to be 4.1 kJ. Calculate the student's experimental value for the enthalpy of reaction, in kJ/mol_{rxn}.

$75.0\text{ mL} \times \frac{1.00\text{ mol HCl (or NaOH)}}{1000\text{ mL}} = 0.0750\text{ mol HCl (or NaOH)}$	1 point is earned for the correct calculation of moles of reactants.
$\Delta H = \frac{-4.1\text{ kJ}}{0.0750\text{ mol of reactants}} = -55\text{ kJ/mol}_{rxn}$	1 point is earned for the correct substitution and answer.

(ii) The student assumes that the thermometer and the calorimeter do not absorb energy during the reaction. Does this assumption result in a calculated value of the enthalpy of reaction that is higher than, lower than, or the same as it would have been had the heat capacities of the thermometer and calorimeter been taken into account? Justify your answer.

The calculated value of the enthalpy of reaction will be <u>lower</u> (smaller or less negative) than it would have been had the thermometer and calorimeter been taken into account.	1 point is earned for the correct prediction.
The thermometer and calorimeter will absorb some of the heat of reaction. This lost heat is ignored in the original calculation of ΔH_{rxn}, making it smaller in magnitude (less negative). OR The actual heat capacity of the system is the sum of the heat capacities of the water, thermometer, and calorimeter. The assumed heat capacity of the system (water only) is less than the actual value, resulting in a lower (less negative) calculated value of ΔH_{rxn}.	1 point is earned for an acceptable justification.

(iii) One assumption in interpreting the results of the experiment is that the reaction between HCl(*aq*) and NaOH(*aq*) goes to completion. Justify the validity of this assumption in terms of the equilibrium constant for the reaction.

$H^+ + OH^- \rightarrow H_2O$, the reaction between HCl(*aq*) and NaOH(*aq*), is the <u>reverse</u> of $H_2O \rightarrow H^+ + OH^-$, the autoionization of water (for which $K = K_w = 1.0 \times 10^{-14}$). Thus the value of K for the neutralization reaction is the reciprocal of K_w, or 1.0×10^{14}, a very large number. Thus the neutralization reaction goes virtually to completion.	1 point is earned for the correct justification.

(c) A third student calculates a value for the enthalpy of reaction that is significantly higher than the accepted value.

(i) Identify a specific error in procedure made by the student that will result in a calculated value for the enthalpy of reaction that is higher than the accepted value. (Vague statements like "human error" or "incorrect calculations" will not earn credit.)

The student read the thermometer incorrectly in such a way to result in a calculated value of ΔT that was too high (either read T_i too low or read T_f too high). OR The student mistakenly used 2.00 *M* acid and 2.00 *M* base, thinking they were both 1.00 *M*.	1 point is earned for an acceptable procedural error that results in a higher calculated value.

(ii) Explain how the error that you identified in part (c)(i) leads to a calculated value for the enthalpy of reaction that is higher than the accepted value.

The calculation of the molar enthalpy of reaction may be expressed as Molar $\Delta H_{rxn} = -\dfrac{\text{mass}_{soln} \times c \times \Delta T}{n_{rxn}}$. If there is a measurement error that results in a ΔT that is too high, the magnitude (i.e., the absolute value) of the calculated molar enthalpy of reaction will be too high.	1 point is earned for an explanation that is consistent with the stated procedural error.

Information for Free-Response Question 3

Timing	The student should spend approximately 20 minutes on this question.
Essential Knowledge	2.A.2 The gaseous state can be effectively modeled with a mathematical equation relating various macroscopic properties. A gas has neither a definite volume nor a definite shape; because the effects of attractive forces are minimal, we usually assume that the particles move independently. 6.A.3 When a system is at equilibrium, all macroscopic variables, such as concentrations, partial pressures, and temperature, do not change over time. Equilibrium results from an equality between the rates of the forward and reverse reactions, at which point $Q = K$. 6.B.1 Systems at equilibrium respond to disturbances by partially countering the effect of the disturbance (Le Chatelier's principle).
Science Practices	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 2.3 The student can estimate numerically quantities that describe natural phenomena. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objectives	2.6 The student can apply mathematical relationships or estimation to determine macroscopic variables for ideal gases. 6.4 The student can, given a set of initial conditions (concentrations or partial pressures) and the equilibrium constant, K, use the tendency of Q to approach K to predict and justify the prediction as to whether the reaction will proceed toward products or reactants as equilibrium is approached. 6.5 The student can, given data (tabular, graphical, etc.) from which the state of a system at equilibrium can be obtained, calculate the equilibrium constant, K. 6.6 The student can, given a set of initial conditions (concentrations or partial pressures) and the equilibrium constant, K, use stoichiometric relationships and the law of mass action (Q equals K at equilibrium) to determine qualitatively and/or quantitatively the conditions at equilibrium for a system involving a single reversible reaction. 6.8 The student is able to use Le Chatelier's principle to predict the direction of the shift resulting from various possible stresses on a system at chemical equilibrium.

Characteristics of a STRONG Response	Part (a) The student is able to provide the correct setup and correct calculations: $\text{moles}_{SO_2Cl_2} = \frac{m}{\boldsymbol{M}} = \frac{4.32\text{ g}}{134.96\text{ g/mol}} = 0.0320\text{ mol}$ $p_{SO_2Cl_2} = \frac{nRT}{V} = \frac{(0.0320\text{ mol})(0.0821\text{ L·atm/mol·K})(400.\text{ K})}{1.50\text{ L}}$ $= 0.701\text{ atm}$ Part (b) The student is able to provide the correct setup and correct calculation of pressure. **Pressures at equilibrium at 400. K:** $SO_2Cl_2(g) \rightarrow SO_2(g) + Cl_2(g)$ Total $0.701 - x$ x x $0.701 + x$ $p_{total} = 0.701 + x = 1.26\text{ atm}$ $x = p_{SO_2} = p_{Cl_2} = 0.56\text{ atm}$ $p_{SO_2Cl_2} = 0.701 - x = 0.14\text{ atm}$ Part (c) The student can correctly set up and calculate the following: $K_p = \frac{p_{SO_2} \cdot p_{Cl_2}}{p_{SO_2Cl_2}}$ $K_p = \frac{(0.56)(0.56)}{0.14} = 2.2$ Part (d) The student is able to effectively articulate that at a higher temperature, K_p will increase. The student can also reason that according to Le Chatelier's principle, raising the temperature of an endothermic reaction at equilibrium increases the value of K_p and produces more products. Part (e) The student can reason that the amount of SO_2Cl_2 in the container will decrease. The student can also reason that initially $Q_p = 1.0 < 2.2. = K_p$, thus the reaction will consume SO_2Cl_2 as it proceeds in the forward direction towards equilibrium.

Characteristics of a GOOD Response	Part (a) The student is able to provide a correct setup for the calculations but potentially provides a wrong answer: $\text{moles}_{SO_2Cl_2} = \frac{m}{\boldsymbol{M}} = \frac{4.32\text{ g}}{134.96\text{ g/mol}} = 0.0320\text{ mol}$ $p_{SO_2Cl_2} = \frac{nRT}{V} = \frac{(0.0320\text{ mol})(0.0821\text{ L·atm/mol·K})(400.\text{ K})}{1.50\text{ L}}$ $= 0.701\text{ atm}$ Part (b) The student is able to provide a correct set up but potentially makes mistakes in the calculation of pressure. Pressures at equilibrium at 400. K: $SO_2Cl_2(g) \rightarrow SO_2(g) + Cl_2(g)$ Total $0.701 - x$ x x $0.701 + x$ $p_{total} = 0.701 + x = 1.26\text{ atm}$ $x = 0.56\text{ atm}$ Part (c) The student can provide the correct setup but potentially makes mistakes in the calculations: $K_p = \frac{p_{SO_2} \cdot p_{Cl_2}}{p_{SO_2Cl_2}}$ $K_p = \frac{(0.56)(0.56)}{0.14} =$ [incorrect number] Part (d) The student is able to reason only that at a higher temperature, K_p will <u>increase</u> due to Le Chatelier's principle. Part (e) The student can qualitatively reason that the amount of SO_2Cl_2 in the container will <u>decrease</u>.
Characteristics of a WEAK Response	Part (a) The student is able to provide a correct mole calculation but makes mistakes in the formula used to calculate pressure: $\text{moles}_{SO_2Cl_2} = \frac{m}{\boldsymbol{M}} = \frac{4.32\text{ g}}{134.96\text{ g/mol}} = 0.0320\text{ mol}$ Part (b) The student is able to provide a correct setup, but does not perform any calculations. Pressures at equilibrium at 400. K: $SO_2Cl_2(g) \rightarrow SO_2(g) + Cl_2(g)$ $0.701 - x$ x x Part (c) The student can provide a less detailed, partially correct setup and performs no calculations. For example, $K = (P_B)\,(P_C)\,/\,(P_A)$ Part (d) The student may predict that K_p will <u>decrease</u>. Part (e) The student can predict the change in SO_2Cl_2 but may provide a less correct rationale for the prediction such as: The amount of SO_2Cl_2 in the container will <u>decrease</u> because the reaction is endothermic.

Scoring Guidelines for Free-Response Question 3

Question 3
(10 Points)

$$SO_2Cl_2(g) \rightleftarrows SO_2(g) + Cl_2(g)$$

A 4.32 g sample of liquid SO_2Cl_2 is placed in a rigid, evacuated 1.50 L reaction vessel. As the container is heated to 400. K, the sample vaporizes completely and starts to decompose according to the equation above. The decomposition reaction is endothermic.

(a) If no decomposition occurred, what would be the pressure, in atm, of the $SO_2Cl_2(g)$ in the vessel at 400. K ?

Assuming no decomposition, $\text{moles}_{SO_2Cl_2} = \frac{m}{M} = \frac{4.32 \text{ g}}{134.96 \text{ g/mol}} = 0.0320 \text{ mol}$	1 point is earned for the correct calculation of moles of SO_2Cl_2 (may be implicit).
$p_{SO_2Cl_2} = \frac{nRT}{V} = \frac{(0.0320 \text{ mol})(0.0821 \text{ L·atm/mol·K})(400. \text{ K})}{1.50 \text{ L}}$ $= 0.701$ atm	1 point is earned for the correct calculation of the pressure.

(b) When the system has reached equilibrium at 400. K, the total pressure in the container is 1.26 atm. Calculate the partial pressures, in atm, of $SO_2Cl_2(g)$, $SO_2(g)$, and $Cl_2(g)$ in the container at 400. K.

Pressures at equilibrium at 400. K: $SO_2Cl_2(g) \rightarrow SO_2(g) + Cl_2(g)$ Total $0.701 - x$ x x $0.701 + x$	1 point is earned for the correct setup.
$p_{total} = 0.701 + x = 1.26$ atm $x = p_{SO_2} = p_{Cl_2} = 0.56$ atm $p_{SO_2Cl_2} = 0.701 - x = 0.14$ atm	1 point is earned for the correct calculation of pressures.

(c) For the decomposition reaction at 400. K,

(i) write the equilibrium-constant expression for K_p for the reaction, and

$K_p = \frac{p_{SO_2} \cdot p_{Cl_2}}{p_{SO_2Cl_2}}$	1 point is earned for the correct K_p expression. Note: the pressure subscripts must be specific (i.e., SO_2, Cl_2, and SO_2Cl_2 — NOT, e.g., A, B, C, and D).

(ii) calculate the value of the equilibrium constant, K_p.

$K_p = \frac{(0.56)(0.56)}{0.14} = 2.2$	1 point is earned for the correct calculation of K_p that is consistent with the K_p expression stated in part (c)(i) and with the partial pressures calculated in part (b).

(d) The temperature of the equilibrium mixture is increased to 425 K. Will the value of K_p increase, decrease, or remain the same? Justify your prediction.

At a higher temperature, K_p will <u>increase</u>. According to Le Chatelier's principle, raising the temperature of an endothermic reaction at equilibrium adds a thermal stress that increases the value of K_p and produces more products.	1 point is earned for the correct prediction. 1 point is earned for a proper justification in terms of Le Chatelier's principle.

(e) In another experiment, the original partial pressures of $SO_2Cl_2(g)$, $SO_2(g)$, and $Cl_2(g)$ are 1.0 atm each at 400. K. Predict whether the amount of $SO_2Cl_2(g)$ in the container will increase, decrease, or remain the same. Justify your prediction.

The amount of SO_2Cl_2 in the container will <u>decrease</u>. Initially $Q_p = 1.0 < 2.2. = K_p$, thus the reaction will consume SO_2Cl_2 as it proceeds in the forward direction to reestablish equilibrium.	1 point is earned for the correct prediction. 1 point is earned for an acceptable justification. <u>Note</u>: the justification must consider the relative values of Q_p and K_p.

Information for Free-Response Question 4

Timing	The student should spend approximately 7–8 minutes on this question.
Essential Knowledge/ Enduring Understanding	4.B.1 Elementary reactions can be unimolecular or involve collisions between two or more molecules. 4.B.2 Not all collisions are successful. To get over the activation energy barrier, the colliding species need sufficient energy. Also, the orientations of the reactant molecules during the collision must allow for the rearrangement of reactant bonds to form product bonds. 4.C Many reactions proceed via a series of elementary reactions.
Science Practices	6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices. 6.5 The student can evaluate alternative scientific explanations. 7.1 The student can connect phenomena and models across spatial and temporal scales.
Learning Objectives	4.4 The student is able to connect the rate law for an elementary reaction to the frequency and success of molecular collisions, including connecting the frequency and success to the order and rate constant, respectively. 4.5 The student is able to explain the difference between collisions that convert reactants to products and those that do not in terms of energy distributions and molecular orientation. 4.7 The student is able to evaluate alternative explanations, as expressed by reaction mechanisms, to determine which are consistent with data regarding the overall rate of a reaction, and data that can be used to infer the presence of a reaction intermediate.
Characteristics of a STRONG Response	Part (a)(i) The student is able to connect the collision energy to the activation energy of the reaction. The reasoning is based on a clear understanding that a successful molecular collision must have energy sufficient to overcome the activation energy. The student may draw connections to the energy profile of the reaction by, for instance, noting that the collision energy must be sufficient to reach the transition state. The student may also draw connections between the activation energy and specific processes occurring in the reaction, for instance, by noting that the collision energy must be sufficient to begin breaking the F–F bond. Part (a)(ii) The student is able to identify the relative orientation of the molecules as a factor that is distinct from the collision energy and that influences the success of the collision. The student explanation connects the orientation required for a successful collision to processes occurring in the reaction. Such explanations may note that the orientation must allow for weakening of the F-F bond and formation of the N-F bond or draw particulate level diagrams comparing a successful and unsuccessful collision.

	Part (b) The student is able to • identify the first step in the mechanism as the rate-limiting step • generate the rate law for the first step in the mechanism, based on the coefficients of the reactants in the step and • connect the rate law of the overall reaction to the rate law of the first step in the mechanism, based on the first step being rate limiting
Characteristics of a GOOD Response	Part (a)(i) The student correctly states that the collision energy must be larger than the activation energy but does not connect the activation energy to the bond breaking and formation processes occurring in the reaction. Part (a)(ii) The student is able to identify the relative orientation of the molecules in the collision as a factor in establishing the success of the reaction; however, the explanation simply restates that orientation is important as opposed to drawing connections between orientation and the bond breaking and formation processes occurring in the reaction. Part (b) The student is able to identify the first step in the mechanism as rate limiting and write the rate law for the overall reaction based on the coefficients of the reactants in the first step. However, the student explanation does not make a clear distinction between the rate law of individual steps in the reaction mechanism and the rate law of the overall reaction.
Characteristics of a WEAK Response	Part (a)(i) The student may be able to state that the collision energy must be large but is unable to connect this to the concept of activation energy and instead reasons vaguely that more energy means more successful reactions. The student does not draw connections between the energy needed for a successful reaction and the bond breaking and formation processes occurring in the reaction. Part (a)(ii) The student is not able to identify relative orientation as a factor and instead chooses factors such as temperature or volume, which are not properties of the individual collision. The explanation may confuse the factors that influence the overall rate of a reaction, such as temperature and concentration, with the factors that lead to successful collision. Part (b) The student may recall that slow steps in a mechanism are rate limiting but be unable to use this to determine the rate law for the overall reaction.

Scoring Guidelines for Free-Response Question 4

Question 4
(4 Points)

$$2\,NO_2(g) + F_2(g) \rightarrow 2\,NO_2F(g)$$

It is proposed that the reaction represented above proceeds via the mechanism represented by the two elementary steps shown below.

Step I:	$NO_2 + F_2 \rightarrow NO_2F + F$	*(slow)*
Step II:	$NO_2 + F \rightleftarrows NO_2F$	*(fast reversible)*

(a) Step I of the proposed mechanism involves the collision between NO_2 and F_2 molecules. This step is slow even though such collisions occur very frequently in a mixture of $NO_2(g)$ and $F_2(g)$. Consider a specific collision between a molecule of NO_2 and a molecule of F_2.

(i) One factor that affects whether the collision will result in a reaction is the magnitude of the collision energy. Explain.

Successful molecular collisions must have sufficient energy in order to result in reaction. Only collisions with sufficient energy to overcome the activation energy barrier, E_a, will be able to reach the transition state and begin to break the F–F bond.	1 point is earned for a correct explanation that makes reference to the activation energy of the reaction.

(ii) Identify and explain one other factor that affects whether the collision will result in a reaction.

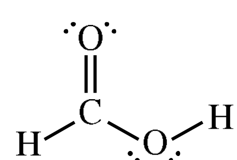
For a collision to be successful, the molecules must have the correct orientation.	1 point is earned for identifying the relative orientation of the colliding molecules.
Only collisions with the correct orientation will be able to begin to form an N–F bond and begin to break an F–F bond as the transition state is approached (that is, the molecules must contact each other at very specific locations on their surfaces for the transition state to be accessible).	1 point is earned for an explanation that makes reference to specific parts (atoms or bonds) of the reacting molecules.

(b) Consider the following potential rate laws for the reaction. Circle the rate law below that is consistent with the mechanism proposed above. Explain the reasoning behind your choice in terms of the details of the elementary steps of the mechanism.

rate = $k[NO_2]^2[F_2]$ rate = $k[NO_2][F_2]$

The rate law that is consistent with the mechanism is the one on the right above (rate = $k[NO_2][F_2]$). Step I is the slower step and the rate-determining step in the mechanism. Since Step I is an elementary reaction, its rate law is given by the stoichiometry of the reacting molecules, $rate_{Step\ I} = k_1[NO_2][F_2]$.	1 point is earned for identifying the correct rate law with a proper explanation. The explanation must correlate the overall rate law with the rate law derived from the stoichiometry of the slow step in the mechanism. Note: a statement relating the coefficients of the reactants in Step I to the exponents in the rate law indicates a correct understanding.

Information for Free-Response Question 5

Timing	The student should spend approximately 7–8 minutes on this question.
Essential Knowledge	2.C.4 The localized electron bonding model describes and predicts molecular geometry using Lewis diagrams and the VSEPR model.
Science Practice	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Learning Objective	2.21 The student is able to use Lewis diagrams and VSEPR to predict the geometry of molecules, identify hybridization, and make predictions about polarity.
Characteristics of a STRONG Response	Part (a)(i) The student is able to • identify the number of electron domains around the carbon atom (i.e., the steric number, SN, of the carbon atom) as 3 • connect SN = 3 to an ideal trigonal planar geometry, and therefore an ideal angle of 120° • reason about expected deviations from the ideal bond angle in terms of the presence of a double bond between the carbon and oxygen atoms Part (a)(ii) The student is able to • identify the steric number of the nitrogen atom as SN = 4 • connect SN = 4 to an ideal tetrahedral geometry, and therefore an ideal angle of 109.5° • reason about expected deviations from the ideal bond angle in terms of the presence of a lone pair of electrons on the nitrogen atom OR The student is able to note that there are resonance structures for the molecule. Part (b) The student is able to generate the Lewis structure for formic acid shown below, based on the requirements that the carbon atom has the same steric number, SN = 3, as in methanamide, and each atom must satisfy the octet rule. All bonds are drawn with the correct order, including the double bond between carbon and oxygen, and all lone pairs are shown correctly. 

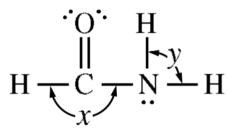
Characteristics of a GOOD Response	Part (a)(i) The student is able to identify the steric number of the carbon atom as SN = 3, and connect this to a trigonal planar geometry with an ideal angle of 120°. However, deviations from the ideal bond angle are not considered. Therefore, the student gives an angle of 120° but does not give any justification. Part (a)(ii) The student is able to identify the steric number of the nitrogen atom as SN = 4 and connect this to a tetrahedral geometry with an ideal angle of 109.5°. However, deviations from the ideal bond angle are not considered. Therefore, the student gives an angle of 109.5° but does not give any justification. Part (b) The student is able to generate a structure with the connectivity of formic acid, but fails to draw all bonds in the correct order, or fails to include all lone pairs.
Characteristics of a WEAK Response	Part (a)(i) The student has difficulty in determining the steric number of the carbon atom and using this to predict a molecular geometry. For instance, the student may incorrectly conclude that the carbon atom has a steric number of 4 due to the double bond between the C and O. Part (a)(ii) The student has difficulty in determining the steric number of the nitrogen atom and using this to predict a molecular geometry. Part (b) The student is able to generate a structure with the correct number of atoms but with one or more of the following flaws • some atoms have too few or too many electrons to satisfy the octet rule • the connectivity of the atoms is not that of formic acid • the number of electrons is not equal to the 18 valence electrons

Scoring Guidelines for Question 5

Question 5
(4 Points)

Methanamide, CH_3NO, is a liquid at 25°C.

(a) The complete Lewis electron-dot diagram for methanamide is shown below.



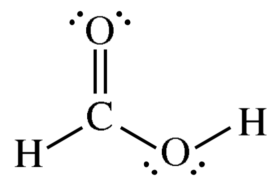
(i) In the molecule, angle *x* is not 180°. Estimate the observed angle. Justify your answer.

Angle *x* is approximately 120°. Three electron domains around the carbon atom will maximally separate the electrons and minimize the energy when the bond angles are 120°.	1 point is earned for the correct angle with justification. <u>Note</u>: accept 120° ± 10° for the angle (i.e., 110° ≤ *x* ≤ 130°.) Also accept steric number (SN) = 3 or trigonal planar geometry for the justification in part (i) only.)

(ii) In the molecule, angle *y* is not 90°. Explain why in terms of electron domains (VSEPR model).

Angle *y* is approximately 109.5°. Four electron domains around the nitrogen atom will maximally separate the electrons and minimize the energy when the bond angles are 109.5°. OR Angle *y* is approximately 120°. Considering possible resonance structures involving a double bond between the C and N atoms, there are three electron domains around the nitrogen atom. In this case, minimization of energy leads to bond angles of approximately 120°.	1 point is earned for the correct justification for an angle different than 90°. <u>Note</u>: the justification need not give a specific bond angle, but it must mention the repulsion of 4 electron domains (or 3 electron domains, if resonance structures are mentioned).

(b) Consider a molecule with the formula CH_2O_2. The structure of this molecule has a geometry around the carbon atom similar to the geometry around carbon in methanamide. In the box provided below, draw the complete Lewis electron-dot diagram for the molecule.



2 points are earned for a correct Lewis electron-dot diagram for formic acid.

Notes: 1 point is earned for the correct skeletal structure for formic acid with the C=O double bond (i.e., containing all five bonding pairs) but missing one or more lone pairs.

Also, 1 point is earned for a Lewis electron-dot diagram representing

(i) the correct molecular formula (CH_2O_2)

(ii) with three electron domains and at least three bonded pairs of electrons around the carbon atom, with no more than three bonded pairs of electrons around any oxygen atom, and

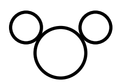
(iii) the proper distribution of all 18 electrons in accordance with the octet rule.

Information for Free-Response Question 6

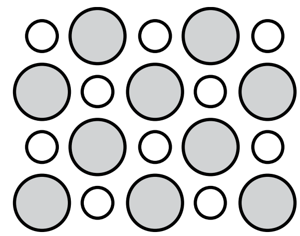
Timing	The student should spend approximately 7–8 minutes on this question.
Essential Knowledge	2.A.3 Solutions are homogenous mixtures in which the physical properties are dependent on the concentration of the solute and the strengths of all interactions among the particles of the solutes and solvent. 3.C.3 Electrochemistry shows the interconversion between chemical and electrical energy in galvanic and electrolytic cells.
Science Practices	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain. 5.1 The student can analyze data to identify patterns or relationships.
Learning Objectives	2.8 The student can draw and/or interpret representations of solutions that show the interactions between the solute and solvent. 3.13 The student can analyze data regarding galvanic or electrolytic cells to identify properties of the underlying redox reactions.
Characteristics of a STRONG Response	Part (a) The student is able to provide a sketch that shows: (1) one Li^+ ion and one Cl^- ion separated from each other, labeled, and charged; (2) each ion surrounded by at least two water molecules; (3) the water molecules are drawn as bent molecules with oxygen in the middle, and are oriented with the oxygen end pointed towards the Li^+ and the hydrogen end point toward the Cl^- ion. Part (b) The student is able to identify the following species at the cathode with the proper justification: $H_2(g)$ and $OH^-(aq)$ The hydrogen atoms in H_2O are reduced to H_2 at the cathode because this reaction has a less negative standard reduction potential than the reduction of lithium ions to $Li(s)$.
Characteristics of a GOOD Response	Part (a) The student is able to provide a sketch that shows: (1) one Li^+ ion and one Cl^- ion separated from each other, labeled and charged; and (2) the water molecules are drawn as bent molecules with oxygen in the middle, but the molecules are not oriented correctly around the two ions. Part (b) The student is able to identify one species at the cathode with the following justification: H_2 is produced at the cathode because this reaction is more favorable.
Characteristics of a WEAK Response	Part (a) The student is able to provide a sketch that shows: (1) LiCl with the two atoms attached to one another and/or at the bottom of the container; and (2) the water molecules are drawn as bent molecules with oxygen in the middle, but the molecules are not oriented correctly around the LiCl. Part (b) The student is able to correctly identify one species at the cathode with an incorrect justification such as: H_2 is produced at the cathode because it is a gas and forms bubbles.

Scoring Guidelines for Question 6

Question 6
(4 Points)



H_2O molecule

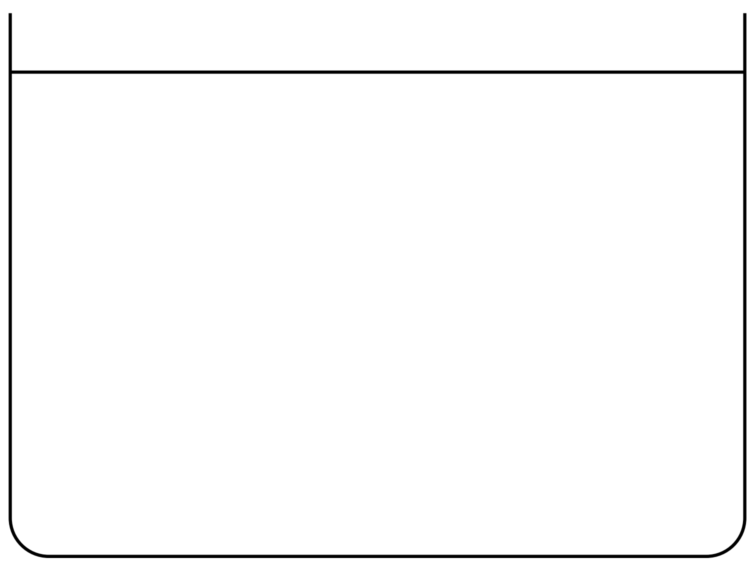


LiCl crystal

The structures of a water molecule and a crystal of LiCl(*s*) are represented above. A student prepares a 1.0 *M* solution by dissolving 4.2 g of LiCl(*s*) in enough water to make 100 mL of solution.

(a) In the space provided below, show the interactions of the components of LiCl(*aq*) by making a drawing that represents the different particles present in the solution. Base the particles in your drawing on the particles shown in the representations above. Include only one formula unit of LiCl and no more than ten molecules of water. Your drawing must include the following details.

- identity of ions (symbol and charge)
- the arrangement and proper orientation of the particles in the solution



LiCl (*aq*)

The sketch should clearly show: 1. a clear representation of at least one Li^+ ion and one Cl^- ion separated from each other, labeled, and charged; 2. each ion surrounded by at least two H_2O molecules; and 3. H_2O molecules with the proper orientation around each ion (i.e., the oxygen end of the water molecules closer to the lithium ion and the hydrogen end of the water molecules closer to the chloride ion).	1 point is earned for a correctly drawn and labeled particulate representation of the ions. (Representation must indicate that the smaller ion is Li^+. Representations that include more than one formula unit of LiCl (dissolved or undissolved) are acceptable as long as at least one of the formula units is separated into its ions and the ions are correctly labeled with their respective identities and charges.) 1 point is earned for a correctly drawn particulate representation of water molecules of hydration surrounding the ions. 1 point is earned for correctly representing the orientation of the water molecules of hydration with the proper polarity.

(b) The student passes a direct current through the solution and observes that chlorine gas is produced at the anode. Identify the chemical species produced at the cathode and justify your answer using the information given in the table below.

Half-reaction	Standard Reduction Potential at 25°C (V)
$Li^+(aq) + e^- \rightarrow Li(s)$	− 3.05
$2\ H_2O(l) + 2\ e^- \rightarrow H_2(g) + 2\ OH^-(aq)$	− 0.83

$H_2(g)$ and $OH^-(aq)$ The hydrogen atoms in H_2O are reduced to H_2 at the cathode because this reaction has a higher (more favorable or less negative) standard reduction potential than the reduction of lithium ions to Li(*s*).	1 point is earned for correctly identifying either of the chemical species produced at the cathode with the proper justification. <u>Note</u>: the justification must clearly indicate that "higher" means "less negative." A "lower magnitude" negative value also earns the point.

Information for Free-Response Question 7

Timing	The student should spend approximately 7–8 minutes on this question.
Essential Knowledge	2.B.3 Intermolecular forces play a key role in determining the properties of substances, including biological structures and interactions. 6.C.2 The pH is an important characteristic of aqueous solutions that can be controlled with buffers. Comparing pH to pK_a allows one to determine the protonation state of a molecule with a labile proton.
Science Practices	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.3 The student can estimate numerically quantities that describe natural phenomena. 5.1 The student can analyze data to identify patterns or relationships. 6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objectives	2.15 The student is able to explain observations regarding the solubility of ionic solids and molecules in water and other solvents on the basis of particle views that include intermolecular interactions and entropic effects. 6.19 The student can relate the predominant form of a chemical species involving a labile proton (i.e., protonated/deprotonated form of a weak acid) to the pH of a solution and the pK_a associated with the labile proton.
Characteristics of a STRONG Response	Part (a) The student can predict that In^-(*aq*) will be the predominant form of the acid in a buffer of pH of 7, based on • the ability of the buffer to maintain the pH at 7 and • the reasoning that since the solution pH is greater than the pK_a, the conjugate base form (In^-) will be the predominant form. Part (b) The student can explain the difference in color between the oil layers of the two beakers based on: • The yellow color of the oil layer is due to the presence of HIn in the oil layer. • Since HIn is neutral while In^- is charged, and since the oil layer is much less polar than water, HIn will be much more soluble than In^- in oil. • In beaker X, the pH of 3 in the buffer solution is less than pK_a, so the conjugate acid form (HIn) is the predominant form. Some of the HIn partitions into the oil layer, giving it a yellow color. • In beaker Y, the pH of 7 in the buffer solution is greater than pK_a, so the conjugated base form (In^-) is the predominant form. Since the charged In^- species is not soluble in oil, it remains in the buffer layer and the oil layer is colorless.

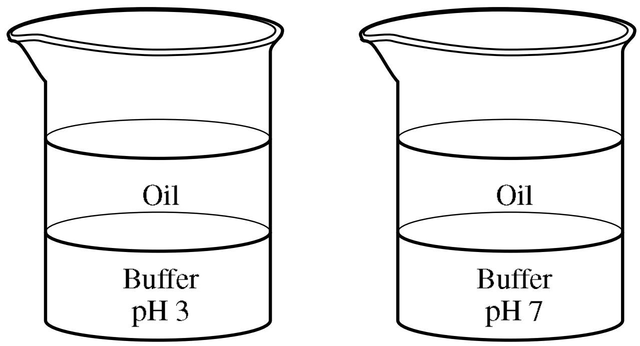
Characteristics of a GOOD Response	Part (a) The student connects pH to the relative concentrations of HIn and In^- through Le Chatelier's principle, with the low concentrations of H_3O^+ in a buffer with pH = 7 pushing the equilibrium towards In^-. However, the reasoning is not based on explicit comparison of pH and pK_a. Part (b) The student is able to reason about the differences between the two layers based on some of the relevant factors: • The yellow color of the oil layer is due to the presence of HIn in the oil layer. • Since HIn is neutral while In^- is charged, and since the oil layer is much less polar than water, HIn will be much more soluble in oil than In^-. • In beaker X, the pH of 3 in the buffer solution is less than pK_a, so the conjugate acid form (HIn) is the predominant form. Some of the HIn partitions into the oil layer, giving it a yellow color. • In beaker Y, the pH of 7 in the buffer solution is greater than pK_a, so the conjugated base form (In^-) is the predominant form. Since the charged In^- species is not soluble in oil, it remains in the buffer layer and the oil layer is colorless. However, key aspects of the reasoning are missing. For instance, the relative solubilities of HIn and In^- in oil and water may not be connected to forces between the particles. The larger concentration of HIn in beaker X than beaker Y may be connected to the difference in pH, but explicit comparisons to pK_a may be missing. The lack of a blue color in the oil layer in beaker Y may not be connected to the expected low solubility of In^- in oil.
Characteristics of a WEAK Response	Part (a) The student can reason in terms of an equilibrium between conjugate acid and base forms but is not able to connect the position of the equilibrium to the pH of the buffer solution. Part (b) The student may connect the yellow color of the oil layer in beaker Y to the presence of HIn and make vague connections between the presence of HIn and the pH of the buffer layer. However, the reasoning does not connect the relative concentrations of HIn and In^- to pH and pK_a. The reasoning also fails to connect the partitioning of HIn and In^- between water and oil to intermolecular forces.

Scoring Guidelines for Question 7

Question 7
(4 Points)

$$\underset{yellow}{HIn(aq)} + H_2O(l) \rightleftarrows \underset{blue}{In^-(aq)} + H_3O^+(aq)$$

The indicator HIn is a weak acid with a pK_a value of 5.0. It reacts with water as represented in the equation above. Consider the two beakers below. Each beaker has a layer of colorless oil (a nonpolar solvent) on top of a layer of aqueous buffer solution. In beaker X the pH of the buffer solution is 3, and in beaker Y the pH of the buffer solution is 7. A small amount of HIn is placed in both beakers. The mixtures are stirred well, and the oil and water layers are allowed to separate.



Beaker X Beaker Y

(a) What is the predominant form of HIn in the aqueous buffer in beaker Y, the acid form or the conjugate base form? Explain your reasoning.

The conjugate base form, $In^-(aq)$, is the predominant form of the indicator in the aqueous pH 7 buffer in beaker Y. This is because the pH is greater than the pK_a of HIn, causing the equilibrium to form a significant amount of products, $In^-(aq)$ and $H_3O^+(aq)$.	1 point is earned for correctly identifying $In^-(aq)$ as the predominant form in the aqueous layer of beaker Y because the solution is not acidic (may be implicit). 1 point is earned for stating that $pH > pK_a$ and that this causes the equilibrium to favor the products.

(b) In beaker X the oil layer is yellow, whereas in beaker Y the oil layer is colorless. Explain these observations in terms of both acid-base equilibria and interparticle forces.

At pH 3 the acid form $HIn(aq)$ predominates in the aqueous layer of beaker X because $pH < pK_a$. Since $HIn(aq)$ is a neutral molecule, some of it can dissolve in the oil layer of beaker X because of London dispersion interactions with the oil, causing the oil layer to be yellow. Since $In^-(aq)$ is charged, it will preferentially dissolve in the aqueous layer of beaker Y because of ion-dipole interactions with the water, leaving the oil layer colorless.	1 point is earned for explaining the yellow color in the oil layer of beaker X in terms of acid-base equilibrium and interparticle forces between HIn molecules and oil molecules. 1 point is earned for explaining the colorless oil layer of beaker Y in terms of interparticle forces between In^- ions and water molecules.