Student Performance Q&A:

2012 AP® Chemistry Free-Response Questions

The following comments on the 2012 free-response questions for AP® Chemistry were written by the Chief Reader, Larry Funck of Wheaton College in Wheaton, Ill. They give an overview of each free-response question and of how students performed on the question, including typical student errors. General comments regarding the skills and content that students frequently have the most problems with are included. Some suggestions for improving student performance in these areas are also provided. Teachers are encouraged to attend a College Board workshop to learn strategies for improving student performance in specific areas.

Question 1

What was the intent of this question?

This question assessed students' understanding of and ability to solve problems and explain concepts that pertain to a weak acid/strong base titration. Part (a) asked students to provide evidence that HA is a weak acid. Part (b) required students to write a balanced net-ionic equation for the reaction between HA and NaOH. Part (c) asked students to calculate the number of moles of HA titrated. In part (d) students were asked to calculate the molar mass of HA. In part (e) students were given the ionization equation and the K_a value for the weak acid and were asked to determine the pH of HA before addition of any NaOH. Part (f) assessed students' understanding of the titration process by asking them to calculate $[H_3O^+]$ at a point in the titration before the equivalence point.

How well did students perform on this question?

The mean score was 3.79 out of 10 possible points.

Overall students did reasonably well when answering this question. They were generally successful on parts (a) through (e), but part (f) proved more challenging for the majority of students. In part (a) many students noted that HA was a weak acid, citing the pH at the equivalence point being 8.62 instead of the 7.00 that would have resulted from a strong acid–strong base titration. Some students expanded their answer by explaining that the basic pH was the result of $A^- + H_2O \rightarrow OH^- + HA$. In part (b) many students were able to successfully write the net-ionic equation representing the reaction between HA and OH^-.

A majority of students correctly calculated the number of moles of HA in part (c) and successfully used that number in part (d) to calculate the molar mass of HA. In part (e) most students were able to set up the K_a expression correctly, substitute appropriately, calculate the correct $[H_3O^+]$, and calculate the correct pH. Many times part (e) was the only part of the question where points were earned.

Part (f) proved the most challenging for the students. A limited number of students were able to successfully calculate the number of moles of HA and A^- after the reaction. Some students appropriately substituted into either the K_a expression or versions of the Henderson-Hasselbalch equation. If this point was earned, it was common to earn the third point for the calculation of $[H_3O^+]$.

What were common student errors or omissions?

Part (a):

- Citing that the base was "strong," overriding the "weak" acid
- Noting that excess hydroxide ion caused the basic pH but implying that the hydroxide ion was from NaOH instead of from the hydrolysis of the product
- Stating only the definition of a weak acid
- Confusing acid strength (strong vs. weak) and concentration (molarity)
- Giving the volume at equivalence as the reason for HA being weak
- Identifying the initial pH of the acid being lower than 3.72 as evidence for strength
- Looking at the data table and using a change in pH argument

Part (b):

- Writing the net-ionic equation for a strong acid-strong base titration
- Showing ionization of the weak acid
- Ignoring charges on OH^- and/or A^-
- Identifying an incorrect stoichiometry

Part (c):

- Calculating the number of moles as 0.10 moles instead of 0.0100 moles by incorrectly moving the decimal for volume conversion
- Using the volume at the end of the titration instead of the volume at the equivalence point
- Using $[H^+] = 10^{-pH}$ with data from the table
- Attempting some sort of ICE table calculation to determine the number of moles of HA

Part (d):

- Multiplying grams and moles instead of dividing
- Calculating molarity instead of moles

Part (e):

- Ignoring the weak acid equilibrium and simply calculating the pH of the 0.200 M solution
- Forgetting to multiply the K_a value by [HA] before taking the square root when solving
- Rounding the value of $[H_3O^+]$ to one significant digit before calculating pH

Part (f):

- Ignoring the stoichiometry between the acid and base
- Diluting 50.0 mL of 0.200 M HA to 80.0 mL and ignoring the reaction
- Calculating the correct values of HA and A^- after the reaction but forgetting the substitution of the new values into the K_a expression

- Not clearly identifying moles of A^-
- Setting up the K_a expression and solving for $[H_3O^+]$ as in part (e)
- Using a combination of moles and molarity (ignoring units) when substituting into the equation
- Using Henderson-Hasselbalch and reporting pH but not $[H_3O^+]$
- Abusing Henderson-Hasselbalch with a variety of values
- Using the dilution formula, $M_1V_1 = M_2V_2$, to solve for the concentration of $[H_3O^+]$

Based on your experience of student responses at the AP Reading, what message would you like to send to teachers that might help them to improve the performance of their students on the exam?

Suggestions for teachers:

- Allow ample opportunities for students to perform titrations while recording pH values past the equivalence point.
- Analyze and discuss the meaning of laboratory data.
- Require students to show work and methods for solving problems, stressing process over memorization.
- Distinguish between amount (moles) and concentration (molarity).
- Reinforce that "[ ]" notation represents molar concentration.
- Provide opportunities for students to write statements of explanation using correct scientific vocabulary and reasoning using evidence to support their claim.
- Demonstrate tools such as ICE or RICE tables when solving equilibrium problems.
- Emphasize that stoichiometry occurs during a titration followed by equilibrium if either the acid or the base is weak.

Suggestions for students:

- Use correct vocabulary, specifically endpoint, equivalence point, and equilibrium.
- Be sure that numerical answers are reasonable.
- Show work clearly and label all numbers with appropriate units.
- Differentiate between moles and molarity in calculations.
- Use the calculator for all calculations; bring extra batteries.
- Follow the written instructions to respond to the question on the lined pages provided and not in the question itself.
- Round calculations to appropriate significant figures at the end of the problem.

Question 2

What was the intent of this question?

This question assessed students' understanding of and ability to solve problems and explain concepts that pertain to the reaction of gaseous reactants and products. Parts of the question required calculation. Students were presented with a known pressure of an unknown gaseous hydrocarbon in a rigid vessel at a constant temperature. Part (a) required students to calculate the number of moles of the unknown gaseous hydrocarbon. Part (b) required students to determine the partial pressure of oxygen gas given the total pressure after the addition of some oxygen gas to the vessel. Part (c) required students to calculate the partial pressure of the oxygen gas that reacted in the hydrocarbon combustion reaction given the partial pressures of the CO_2 gas and H_2O gas that formed. Part (d) required students to write the balanced equation based on the partial pressures both given and calculated and determine the formula of the hydrocarbon. Part (e) required students to calculate the mass of the hydrocarbon that reacted, and part (f) required students to predict the pH in the reaction vessel after it had cooled and drops of liquid water formed on the inside of the container.

How well did students perform on this question?

The mean score was 4.05 out of a possible 10 points.

Students generally answered parts (a) and (b) correctly. The points in part (c) were the most frequently missed. Many students earned a point in part (d) for any balanced combustion equation and 2 points in part (e) for using the number of moles from part (a) and using a consistent molar mass from part (d) to calculate the number of grams of hydrocarbon that reacted. Part (f) required no calculations and was a commonly earned point. It is interesting to note that part (f) was an independent point relative to the other 9 points in the question.

A range of approaches were used in parts (b), (c), and (d) for correct answers. For part (b) the correct answer could be arrived at by calculating the total moles based on the total pressure, subtracting the moles of hydrocarbon (calculated in part (a)) from the total moles to get the moles of oxygen added, and then using the mole fraction of oxygen gas times the total pressure to get the pressure of the added oxygen gas. This was a lot of work for the correct answer. For part (c) students could arrive at the correct answers using $PV = nRT$ for moles of carbon dioxide and moles of water, then calculate the moles of oxygen gas consumed using stoichiometric ratios for O_2 from the chemical formulas of water and carbon dioxide, summing those calculated moles of oxygen gas and then plugging that total moles of oxygen gas back into $PV = nRT$ to arrive at the pressure of oxygen gas consumed. It was a lot more work taking this route.

For part (d) many students saw the relationship of partial pressures of hydrocarbon, CO_2 and H_2O (0.200 atm : 0.600 atm : 0.800 atm) to determine the stoichiometric coefficients in the balanced chemical equation (1 : 3 : 4) and then were able to determine the formula of the hydrocarbon and the coefficient of oxygen gas in the balanced chemical equation. In part (c) some students recognized that the coefficient of O_2 was 5 so 1.00 atm of oxygen gas was consumed.

Using information consistent with part (d), students commonly earned 2 points in part (e) for the number of grams of hydrocarbon that reacted. Some students did not use partial pressures to determine the formula of the hydrocarbon but rather used mole calculations to determine the empirical formula for the hydrocarbon. Knowing the formula for the hydrocarbon, they were able to balance the equation.

What were common student errors or omissions?

Part (a):

- Solving the equation $PV = nRT$ incorrectly
- Using the incorrect value of R
- Forgetting to convert degrees Celsius to Kelvin
- Using the incorrect conversion factor for converting degrees Celsius to Kelvin
- Calculating the answer to the expression written incorrectly

Part (b):

- Using a ratio of $P_{O_2} : P_{total}$ = 0.857 to represent the partial pressure of oxygen gas
- Mistaking mole fraction for partial pressure
- Confusing moles with atmospheres of pressure

Part (c):

- Not recognizing that pressure is proportional to moles
- Thinking that moles of water and carbon dioxide summed up is equal to moles of oxygen gas
- Calculating moles of atoms of O rather than moles of oxygen gas
- Thinking that partial pressures in a reaction mixture are conserved
- Neglecting to justify the formula of the hydrocarbon

Part (d):

- Balancing the equation with 6 moles of O_2, which reflected using the total pressure of oxygen gas from part (b) rather than the consumed oxygen gas from part (c)
- Not recognizing that it takes 2 moles of water to form 1 mole of oxygen gas
- Not recognizing that for each mole of water formed, 2 hydrogens are needed from the hydrocarbon
- Not realizing that hydrocarbons contain only carbon and hydrogen
- Not realizing that hydrocarbons are not any random combination of Cs and Hs.
- Not realizing that combustion requires oxygen gas as a reactant
- Not knowing that excess oxygen does not go on the products side of the reaction equation
- Thinking that total pressure stayed the same before and after in a gaseous reaction

Part (e):

- Not recognizing that the moles of the hydrocarbon had already been calculated in part (a)
- Using the coefficient from the balanced equation in part (d) and molar mass to calculate the grams of hydrocarbon that reacted
- Confusing the moles actually produced or consumed in a reaction with the stoichiometric coefficients in the balanced equation
- Confusing mass with molar mass

Part (f):

- Not picking one of the choices given
- Stating that "acidic" does not indicate the pH
- Stating that water always has a pH of 7
- Thinking that condensation equals pH change

Based on your experience of student responses at the AP Reading, what message would you like to send to teachers that might help them to improve the performance of their students on the exam?

Suggestions for teachers:

- Be sure that students understand what partial pressure means — "partial" refers to the gas "part" in a mixture.
- Ask students to write what they know in the form of a data table. Given the data, is there an equation that can be used to solve the problem? Don't always be concerned with the answer but rather focus on the process of arriving at the answer.
- Practice gas laws using partial pressure calculations.
- Teach the concept of proportionality relating to the gas laws. P or V is proportional to n and/or T.
- Make sure students can distinguish when only molar mass is called for and when this needs to be converted to a physical mass.
- Teach acidic and basic oxides.
- Give students questions that have more than one part and that develop a flow of data and answers from one part to the next.
- Teach students that H^+ is the species that determines the pH of a solution. The acid is not in itself acidic; it is the dissociation of the acid that actually causes the pH to be less than 7. Remind students that carbonic acid is an acid that is in equilibrium with a gas, CO_2.

Suggestions for students:

- Even for simple calculations, show your work. Often points are given for the setup, substituting the numbers into that setup, and then the final calculation. A correct answer with no supporting data often will not earn all possible points.
- Recognize the difference between proportional and equal to in relationship to the gas laws.
- Read the problem carefully and follow the instructions. "Use [certain data] to calculate ______" means that the given data should be in the calculation. "Explain your prediction" usually means that a correct prediction *without* an explanation will not earn a point.
- Answer the question asked. When a choice of pH is asked for, make sure your answer is one of the choices given.
- Justify your answers in writing. When you are asked to determine the formula of the hydrocarbon, show how you arrived at the answer.
- When answering a question with many parts, do not assume that you must start from scratch for each part's answer.
- You may encounter questions that sound strange or unfamiliar. Use the knowledge you have to try to determine what a plausible approach might be. Nothing you put down will earn less credit than a blank page will.

Question 3

What was the intent of this question?

This question assessed students' understanding of fundamental concepts of thermodynamics and kinetics. Part (a) presented students with standard entropy values for reactants and products and required them to calculate $\Delta S°$ for the reaction. In part (b) students were asked to calculate $\Delta H°$ for the reaction from a table of average bond enthalpies and structural formulas for all species. Part (c) required students to interpret the temperature change of an insulated container in which the reaction occurs. The focus of the question changed from thermodynamics to kinetics in parts (d) through (f). In part (d) students were presented with data from which to determine initial and final reactant concentrations and were told that the decomposition reaction is first order. Students were first required to determine the initial concentration of reactant and to apply the concentrations to the integrated rate law for first-order reactions to determine the value of the rate constant, k, with appropriate units. Students were then required to determine the initial reaction rate for the conditions given and, finally, to predict whether a graph of $1/[CH_3CH_2NH_2]$ versus time would be linear or curved and to explain their reasoning.

How well did students perform on this question?

The mean score was 3.20 out of a possible 9 points.

Though the points in parts (a) through (c) were earned more often than those in parts (d) and (e), it was common for students to earn some of the available credit on the later parts of the question regardless of their performance on the earlier parts. In this sense, the question had little carryover from part to part and offered students an opportunity to earn credit on each part.

Students did quite well in part (a). Parts (b) and (c) were more challenging, with student responses showing a range of errors and misconceptions. In part (b) students varied in their approach to the problem. Many students attempted to calculate the total bond enthalpies in the reactant and product molecules, but some used the structural diagrams that were given to include only the bond enthalpies for those bonds that were broken or formed. Students had difficulty in part (c), where they were asked to use their answer to part (b) to predict the sign of the temperature change of the contents of a container as the reaction occurred. Credit was earned if the predicted temperature change was consistent with the +/– sign of the answer to part (b), regardless of whether the terms "endothermic" and "exothermic" were used correctly.

In parts (d) and (e) the questions changed from thermodynamics to kinetics, and the points were earned less frequently. These parts presented more challenges for the students, as their general grasp of the concepts of kinetics was weaker than their grasp of thermodynamics. Most students earned 1 point in part (d) for converting the moles of $CH_3CH_2NH_2$ and volume to concentration, but frequently this was the only point earned in parts (d) and (e).

Part (f) presented a very accessible opportunity for students to earn credit, regardless of their performance in parts (d) and (e), and was often the only point earned in the kinetics parts of the question.

What were common student errors or omissions?

Part (a):

- Reversing the order of operands
- Incorrect math

Part (b):

- Attributing signs incorrectly. Students were used to the formalism $\Delta H^\circ = \Sigma H^\circ_{\text{products}} - \Sigma H^\circ_{\text{reactants}}$, and by summing the bond enthalpies of the products and subtracting the bond enthalpy of the reactant they obtained a value of –49 kJ/mol rather than +49 kJ/mol.
- Not accounting for the breaking of the C-C single bond. Although students accounted for the 614 kJ/mol bond enthalpy of the C=C bond, they frequently did not break the C-C bond.

Part (c):

- Attributing a positive (negative) value of $\Delta H°$ to a temperature increase (decrease)
- Not referring to the answer to part (b) and using exothermic or endothermic incorrectly
- Not differentiating between the reaction system and the surroundings (e.g., “reaction gains heat so temperature increases”)
- Calculating $\Delta G°$ and erroneously basing the temperature change on spontaneity

Parts (d) and (e):

- Not converting from initial moles of $CH_3CH_2NH_2$ and volume to initial concentration (or erroneously changing the given concentration at $t = 20$ minutes)
- Determining the average reaction rate rather than the instantaneous rate
- Not differentiating between the *rate constant* and the *reaction rate*
- Using the average reaction rate and the differential rate law (rather than the integrated rate law) to determine the rate constant
- Using the given temperature rather than the elapsed time in the integrated rate law
- Incorrect or missing units in part (d)
- Poor mathematics

Part (f):

- Not explaining a correct response (e.g., restating that the graph would give a curve because the reaction was first order)

Based on your experience of student responses at the AP Reading, what message would you like to send to teachers that might help them to improve the performance of their students on the exam?

Suggestions for teachers:

- Continue to stress that bond breaking is endothermic and requires energy ($\Delta H > 0$), and bond formation is exothermic and releases energy ($\Delta H < 0$).
- In the laboratory, reinforce the connection between thermodynamic quantities (ΔH, ΔS, ΔG) and observables:
    - $\Delta H_{rxn} \leftrightarrow$ heat released/absorbed (assume no work done) $\leftrightarrow$ temperature change.
    - $\Delta S_{rxn} \leftrightarrow$ change in disorder of system $\leftrightarrow$ gas evolved/absorbed.
    - $\Delta G_{rxn} \leftrightarrow$ spontaneity of reaction or work done by system (for electrochemical cells).
- Stress the direction of heat flow for endothermic and exothermic reactions.
- Differentiate among the quantities (and units) of amount (moles), volume (liters), and concentration (mol/L), and stress that kinetic and equilibrium calculations must be performed with concentration.
- Provide practice substituting appropriate quantities into integrated rate law expressions and solving algebraically.
- Stress appropriate units of rate constants and reaction rates.
- Offer practice sketching and interpreting graphs of [ ], 1/[ ], and ln[ ] versus time for zero, first-, and second-order decomposition reactions.

Suggestions for students:

- Read the question and be sure to answer the question that is asked.
- Show setup for all calculations.
- Check that your numerical answers are reasonable (e.g., that the correct exponent has been included in scientific notation).
- Include units as appropriate. If no units are specified, use the most convenient units.
- Be sure that an explanation or justification goes beyond a restatement of information given in the problem.

Question 4

What was the intent of this question?

This question assessed students' ability to communicate their knowledge of chemical processes. Important skills tested included writing chemical formulas for substances and balancing equations. Additional aspects of the question evaluated general understanding of chemical concepts presented to students in both the classroom and the laboratory.

How well did students perform on this question?

The mean score was 8.58 out of 15 possible points.

What were common student errors or omissions?

Part (a):

- Writing the strong acid as a nonionized species
- Writing a complete balanced molecular equation instead of a net-ionic equation
- Leaving spectator ions in the final equation
- Balancing positives on the reactant side with negatives on the product side of the reaction
- Not realizing the decomposition of carbonic acid into CO_2 and H_2O, or omitting the negative charge on the equally acceptable product, hydrogen carbonate ion
- Not applying solubility rules and therefore assuming that $SrCl_2$ is insoluble and consequently precipitates from the solution
- Confusing what the student sees as the reaction that is occurring with inferences or measurements (dissolving is observed as the reaction progresses, dissociation is an inference of how the particles separate)
- Stating that the metal Sr dissolves or dissociates instead of saying that the compound $SrCO_3$ dissolves in the acid
- Not knowing formulas for the strong acids and thus writing $HClO_3$, among other combinations of H, Cl, and O, for HCl
- Writing incorrect symbols, such as Sn, St, S, Sb, or Sc for Sr, and C, CO, CO_2, CO_4, or Ca with various possibilities for charge for carbonate
- Using the following words for dissolve: “degrades,” “deteriorates,” “disintegrates,” “decomposes,” “disappears,” “produces a fizzing sound,” “evaporates,” “melts,” “sublimates,” “breaks apart,” “goes away,” etc.

- Instead of supplying an observation, supplying a confirmation test for Sr or CO_2, such as a red flame color, or extinguishing a flame
- Some common responses:
  $SrCO_3 + 2\ HCl \rightarrow H_2CO_3 + SrCl_2$
  $Sr^{2+} + H^+ + 2\ Cl^- \rightarrow CO_2 + SrCl_2 + H_2O$
  $SrCO_3 + 2\ H^+ \rightarrow H_2 + CO_2 + SrO$
  $SrCO_3 + 2\ Cl^- \rightarrow CO_3^{2-} + SrCl_2$
  $SrCO_3 + 2\ H^+ \rightarrow CO_2 + Sr^{2-} + H_2O$
  $SrCO_3 + H^+ \rightarrow HCO_3 + Sr^{2+}$
  $SrCO_3 + HCl \rightarrow HSr + ClCO_3$
  $SrCO_3 \rightarrow Sr^{2+} + CO_3^{2-}$
  $SrCO_3 \rightarrow CO_2 + SrO$
  $2\ H^+ + CO_3^{2-} \rightarrow H_2CO_3$

Part (b):

- Assuming that either or both Mg metal and O_2 gas are ions with +2 and –2 charges, respectively
- Assuming all combustion reactions yield H_2O and CO_2
- Writing Mn for Mg
- Writing O for molecular oxygen
- Common responses:
  $Mg + O_2 \rightarrow MgO_2$
  $Mg + O_2 \rightarrow MgO$
  $2\ Mg + O_2 \rightarrow 2\ Mg^{2+}O^{2-}$
  $2\ Mg^{2+} + O_2 \rightarrow 2\ MgO$
  $2\ Mg^{2+} + O_2^{2-} \rightarrow 2\ MgO$
  $2\ Mg + O_2^{2-} \rightarrow 2\ MgO$
  $2\ Mg^{2+} + O_2^{-} \rightarrow 2\ MgO$
  $2\ Mg + O_2 + 4\ H^+ \rightarrow 2\ H_2O + 2\ Mg$
  $2\ Mg + 2\ O_2 \rightarrow 2\ MgO + O_2$
  $Mg + O_2 \rightarrow H_2O + CO_2$
  $Mg + O_2 + 2\ H^+ \rightarrow H_2O + CO_2$
  $Mg + O_2 + H_2 \rightarrow H_2O + CO_2$
  $Mg + O_2 \rightarrow H_2O + CO_2 + MgO$
  $2\ Mg + O_2 \rightarrow Mg^{2+} + O_2^{2-}$
  $4\ e^- + Mg^{2+} \rightarrow H_2O + 4\ e^-$
  $4\ e^- + 2\ H^+ + Mg + O_2 \rightarrow H_2O + MgO$

Part (c):

- Writing a strong base as a nonionized species
- Not using the parentheses around the hydroxide ion

- Writing a totally molecular equation
- Not knowing and applying solubility rules (metal hydroxides are insoluble; Group I compounds, like the common NaCl, are soluble)
- Writing complex ions even after being told that there is a precipitate
- Assuming that either sodium or hydroxide is in excess because NaOH is a strong base
- Writing N or Nb for Ni
- Common responses:
  $NiCl_2 + NaOH \rightarrow Ni(OH)_2 + NaCl$
  $NiCl_2 + NaOH \rightarrow NiOH + NaCl_2$
  $NiCl + NaOH \rightarrow NiOH + NaCl$
  $NiCl_2 + 2\ NaOH \rightarrow Ni(OH)_2 + Na_2Cl$
  $NiCl + 2\ NaOH \rightarrow NiOH_2 + 2\ NaCl$
  $NiCl + NaOH \rightarrow NiNa + ClOH$
  $NiCl_2 + 2\ NaOH \rightarrow Ni(OH_2) + 2\ NaCl$
  $NiCl_2 + NaOH \rightarrow NaNi + ClOH$
  $NiCl_2 + 2\ OH^- \rightarrow Ni(OH)_2 + 2\ Cl^-$
  $Ni^{2+} + 2\ OH^- \rightarrow NiO + H_2O$
  $Ni^{2+} + 2\ OH^- \rightarrow NiOH_2$
  $Ni^{2+} + OH^- \rightarrow Ni(OH)_2$
  $Ni^+ + OH^- \rightarrow NiOH$
  $Ni^+ + OH^- \rightarrow NiOH^-$
  $Ni^{3+} + 3\ OH^- \rightarrow Ni(OH)_3$
  $NiCl_2 \rightarrow Ni^{2+} + Cl_2$
  $NiCl_2 \rightarrow Ni + Cl_2$

All parts:

- Writing molecular reactions
- Not checking both charge and mass balance
- Writing miscellaneous charges on the reactant or product species
- Supplying responses for part (ii) that were not based on the equations written in part (i) of each question
- Penmanship that made it difficult to determine what was intended

Based on your experience of student responses at the AP Reading, what message would you like to send to teachers that might help them to improve the performance of their students on the exam?

Suggestions for teachers:

- Give students practice in using the symbolic language of chemistry (e.g., strontium is not St; Mn is not magnesium; chloride is not the same as chlorine and is not represented as Cl or Cl_2; and C, CO, CO_4, and Ca with various possibilities for charge are not carbonate).
- Help students understand the nature of the ionic bonded compounds as a metal combination with a nonmetal so they do not bond two metals together.

- Remind students that independent atoms do not have net charges (i.e., Mg atoms vs. Mg^{2+} ions), and metals generally do not have negative charges, as in Sr^- or Sr^{2-}.
- Offer practice and reinforcement of balancing of net ionic equations, emphasizing that both mass and charge require balance. Some students misunderstand and want to balance positive charge on one side of the equation with negative charge on the other side of the equation. Have students get into the habit of routinely checking for both charge and mass balance.
- Help students understand the significance of correct symbolic reporting when writing chemical formulas for molecules, atoms, and ions in solution. Stress that all soluble ionic compounds should be dissociated, and any of the six strong acids (or seven according to some texts) should be ionized. All other species, such as elements, solid forms of compounds, and molecular compounds, should not be written as separate ions. Students should cancel out (if written) spectator ions that are present in both the reactants and the products.
- Distinguish between an observation and a measurement or an inference. Instead of asking for an observation, it may be prudent to ask, "What did you see or notice as the reaction occurred?" Many people define observations as detecting changes by using the senses, such as seeing, hearing, and smelling. Processes like dissociation, ionization, and breaking ionic bonds, however, are not observations. Temperature and pH and are usually considered measurements.
- Do a lab or demonstration for the decomposition of a carbonate salt, and then have students write observations and balance the equation; additionally, requiring drawings of particulate representations or having students select particulate representations would reinforce the concepts and provide for a deeper understanding.
- Carefully provide instructions for observing the burning of magnesium ribbon, then have students observe the reaction and write and balance the equations for the reaction with oxygen and the reaction with nitrogen. Again, require students to select or draw particulate representations.
- Demonstrate or introduce a lab precipitating various polyatomic ions (carbonates, hydroxides, etc.) by adding one solution to another, and use these reactions to reinforce solubility rules.
- Require students to write equations for reactions performed during all appropriate class demonstrations and experiments to reinforce the skills, patterns, and concepts, and to achieve a deeper understanding of the chemistry.

Suggestions for students:

- Memorize and practice formulas and charges for common polyatomic ions.
- Know basic solubility rules (e.g., Group I elements all form soluble compounds). Knowing this simple rule and then being told that a precipitate forms in part (c)(i) should have allowed students to eliminate NaCl as a product in the net-ionic equation.
- Remember that the answer box should contain only the final, balanced chemical equation. It is not acceptable to write miscellaneous charges over formulas in the box (e.g., MgO^{2-}). The box should not contain oxidation numbers, scratch work, or extra equations.
- Be very familiar with the list of common strong acids and strong bases and know that all other acids and bases are weak. Many students incorrectly indicated that HCl is a weak acid, or that NaOH is a weak base.
- Reduce the stoichiometric coefficients to lowest whole numbers. Fractional coefficients should be multiplied for lowest whole numbers.

Question 5

What was the intent of this question?

This question asked students to explain the behavior of various aggregations of iodine and bromine in terms of enthalpy and entropy changes and solubility tendencies. In addition, they were asked to represent the I_3^- ion as a Lewis electron-dot diagram. Part (a) asked students to explain why the enthalpy of formation of $I_2(g)$ exceeds that of $Br_2(g)$. They were instructed to identify the type of particle interactions involved and to provide a reason for the difference in magnitude of these interactions. Part (b) asked students to predict which of the two processes in part (a) would have a greater change in entropy and to provide a justification for their prediction. Part (c) asked students to predict whether $IBr(l)$ or $Br_2(l)$ would have a greater molar enthalpy of vaporization and to justify their predictions. Part (d) described an experimental procedure and observation involving the combination of water, hexane (C_6H_{14}), and a crystal of solid I_2. Students were asked to explain the observation and to reference the relative strengths of interactions between the two solvents and the crystal. In part (e) students were told a small crystal of $KI(s)$ was added to the combination of chemicals described in part (d). In part (e)(i) students were asked to draw the complete Lewis electron-dot diagram for the I_3^- ion. Finally, in part (e)(ii) they were asked to state which solvent layer would contain the higher concentration of I_3^- and to explain why.

How well did students perform on this question?

The mean score was 3.27 out of a possible 8 points.

Students generally attempted all parts of this question. The most common points were earned in part (a) for simply stating solid to gas conversions require more energy to complete than liquid to gas conversions (1 point only) and part (d) for explaining the hexane layer turned purple because the I_2 was dissolved in the C_6H_{14} .

What were common student errors or omissions?

Part (a):

- Rather than beginning by identifying a type of particle interaction, jumping to the second part of the question and simply stating that the enthalpy change from solid to gas is greater than the enthalpy change from liquid to gas
- Not giving a reason for the difference in the magnitude of the interactions
- Using general, vague, or incorrect terms to describe the interactions, such as “stronger attractions,” “Van der Waals forces,” or “IMF’s” rather than “London Dispersion Forces”
- Stating general trends for the differences in magnitude (“more massive particles exert greater LDF’s”) rather than giving an explanation for the trend (“larger electron clouds lead to increased polarizability”)

Part (b):

- Not giving an adequate justification for the answer
- Confusing the definitions for entropy and enthalpy.
- Stating that a solid to gas conversion involves a greater increase in entropy than a liquid to gas without any explanation of what entropy means. An increased number of microstates, increased randomness, disorder, or degrees of freedom would have been appropriate but often did not appear in student responses.

Part (c):

- Making errors and omissions similar to those in part (a)
- Thinking that IBr(*l*) has a greater molar enthalpy of vaporization because it somehow averages the enthalpy values for $I_2(s)$ and $Br_2(g)$ owing to combining the two different types of atoms

Part (d):

- Not understandinging what dissolving means. The terms "reacts with," "bonds with," "dissociates in," and "breaks up in" were commonly used to explain why the purple I_2 ended up in the hexane. Good explanations of the interactions between the two solvents, water and hexane, and the solid iodine were very rare.
- Not even attempting a discussion of the interactions, preferring simply to state "like dissolves like" along with a recitation of the relative polarities of each of the three species

Part (e):

- In part (e)(i), not including the brackets and the charge that indicate the structure is an ion
- Using nonconventional methods to draw a reasonable structure with 22 electrons and three lone pairs on the central iodine atom (e.g., two dots at the end of a line for a lone pair and lone pairs with a balloonlike region drawn around them; drawing bent or cyclic structures despite being told that even though I_3^- was linear)
- In part (e)(ii), erroneously thinking that the nonpolar I_3^- ion dissolved in the nonpolar hexane or the I_3^- ion dissolved in the water because it is a polar ion

All parts:

- Confusing the terms *inter*molecular and *intra*molecular, often using them interchangeably. Some students clearly believed that changes of state involve breaking covalent bonds.
- Using the term "bond" in a wide variety of ways. While intermolecular forces may indeed be considered weak bonds of a sort, many students did not communicate a clear distinction between these types of forces and strong covalent or ionic bonds. In fact, many did a good job of describing the latter when they likely meant the former.
- Not demonstrating mastery of chemical vocabulary

Based on your experience of student responses at the AP Reading, what message would you like to send to teachers that might help them to improve the performance of their students on the exam?

Suggestions for teachers:

- Emphasize penmanship and spelling.
- When asking students to compare two substances, insist that they always talk about both and clearly indicate which one they are referring to in turn (avoid ambiguities like "dissolves in *it*"). Simply discussing one substance and expecting the reader to infer information regarding the other often will not receive credit.
- Do not accept incorrect terminology from students. Provide practice defining and applying chemical terms in a variety of contexts.
- Encourage students to explain and justify answers for all types of questions and to support claims with evidence.

- The value of precise and concise answers that use correct terminology cannot be overstated. It is important to emphasize this to students and to provide an arena for them to practice communicating in this fashion frequently.
- Intra- and intermolecular interactions are difficult for students to distinguish and describe. Assist students in this endeavor by:
    - Teaching the major binding forces (ionic, covalent, metallic) separately from the intermolecular forces;
    - Having students consider both force types and put them into categories;
    - Having students illustrate attractions within and between molecules and clearly indicate which are intra- and which are intermolecular forces; and
    - Having students practice explaining differences in data using the various types of interactions.
- Avoid using the term "Van der Waals forces" as synonymous with "London dispersion forces." This descriptor is more correctly used as an umbrella term to cover all the weak intermolecular interactions.
- Avoid using molar mass as a predictive tool for the strength of London dispersion forces. While it often works, it is not always successful (a good example is neon vs. methane).

Suggestions for students:

- Write legibly and place all answers in the lined spaces provided instead of squeezing words in between the question parts.
- Read the entire question, and answer what is being asked. Underline key phrases and box or outline exactly what you are being asked to do. For example, "identify the type of particle interactions involved and a reason for the difference in magnitude of those interactions" does not mean give a general reason for the enthalpy change of formation of I2(s) exceeding that of Br2(l).
- Communicate clearly and precisely. Vague, unclear, and rambling answers often make it impossible to determine whether students fully understand the chemistry required in the question.
- When asked to provide a justification for an answer, it is not adequate to simply provide a statement of fact. Justify implies give an explanation as to why something occurs.
- When drawing Lewis electron-dot diagrams:
    - Determine the total number of electrons in the diagram first.
    - Use the open area on the page to refine the diagram.
    - Draw dots firmly and clearly and try to avoid erasures.
    - Clearly indicate only the final diagram in the box.

Question 6

What was the intent of this question?

This electrochemistry question was divided into three parts. The first component asked students to consider observations of electrochemical reactions to determine the relative reactivities of three metals: Q, X, and Pb. The second component asked students to write chemical equations and determine particular electrochemical values for an electrochemical cell. The third component asked students to predict potential difference changes and justify these changes. In part (a) students were asked to analyze observations of three equations involving three different metals and the respective ions to create a list showing the least reactive metal to the most reactive metal. In part (b) students were asked to write the half-reaction occurring at the anode in the electrochemical cell. In part (c)(i) students were asked to calculate the standard reduction potential for the half-reaction that occurs at the cathode. In part (c)(ii) students were asked to identify the unknown metal (X). A table of standard reduction potentials was provided on the exam. In part (d) students were asked what happens to the mass of each electrode. In part (e)(i) students were asked to identify the potential difference of the electrochemical cell if the salt bridge lost contact with the solution and to justify the prediction. In part (e)(ii) students were asked to identify the potential difference of the electrochemical cell if sodium sulfate solution was spilled into the anode compartment and to justify the prediction. In part (e)(iii) students were asked to identify the potential difference of the electrochemical cell after the switch had been closed approximately one day and to justify the prediction.

How well did students perform on this question?

The mean score was 3.97 out of a possible 9 points.

Students generally attempted all parts of the question. If parts were omitted, it was generally part (e). The most commonly missed points were in parts (e)(i), (e)(ii), and (e)(iii).

What were common student errors or omissions?

Part (a):

- Listing Q, X, and Pb as ions rather than metals, commonly as a mixture of one or two ions with one or two metals (Q^{2+}, X, Pb or X^{2+}, Q, Pb^{2+})
- Listing one of the metals as a diatomic molecule (X_2)
- Incorrectly listing the metals from most active to least active

Part (b):

- Identifying the anode half reaction as a reduction ($Pb^{2+} + 2\,e^- \rightarrow Pb$)
- Identifying the species at the anode as X ($X \rightarrow X^{2+} + 2\,e^-$ or $X^{2+} + 2\,e^- \rightarrow X$)
- Writing the full electrochemical reaction ($X^{2+} + Pb \rightarrow X + Pb^{2+}$)
- Including spectator ions in the equation or indicating lead nitrate is insoluble ($Pb(NO_3)_2 \rightarrow Pb^{2+} + 2\,NO_3^-$) and not balancing the equation

Part (c):

- Calculating 0.60 V. This value was calculated in the following manner: If the reaction identified in part (b) was $Pb^{2+} + 2\,e^- \rightarrow Pb$, E°_{red} would be equal to –0.13 V, and 0.47 V = $E^\circ_{red} + E^\circ_{ox}$. E°_{ox} would then represent the standard oxidation potential for X (E°_{ox} = 0.60 V). However, this value represents the E°_{ox} for X, and therefore the standard reduction potential for X would be –0.60 V.
- Calculating and making mathematical errors
- Trying to use a variety of equations provided in the exam booklet
- Identifying a metal in part (c)(ii) without using the value calculated in part (c)(i)
- Identifying the metal as an ion. Students specifically were asked to name the metal, and many answers included copper(II) or Cu^{2+}.

- Identifying the metal as a diatomic molecule (X_2)
- Identifying X as a nonmetal

Part (d):

- Not including descriptions of both electrodes
- Stating there were no changes in mass at the electrodes (or stating that both increase or both decrease) during the reaction
- Indicating mass increase or decrease was due to the mass of an electron

Part (e):

- Stating that when the salt bridge loses contact, electrons no longer can flow through the salt bridge
- Stating that the salt bridge maintains neutrality (what kind of neutrality is at issue)
- Stating that the salt bridge balances the system (no specific information provided)
- Stating that the electron flow stopped
- Indicating that the ions in the salt bridge only flow in one direction
- Using only an equilibrium explanation based on Le Chatelier's Principle. This system is not at equilibrium; Pb^{2+} has been removed through precipitation, and therefore the reaction is more thermodynamically driven to proceed. But because the switch is open the reaction does not proceed, resulting in an increased potential difference.
- Describing an increase or decrease in the mass of electrodes as resulting in a changed potential difference (the quantity of electrode is irrelevant)
- Using the Nernst equation to explain the problem, inverting the concept; stating that a decrease in $[Pb^{2+}]$ will decrease the cell potential
- Indicating that the Na^+ would increase the potential difference because Na has a larger standard reduction potential
- Indicating that more ions increases the potential difference
- Indicating that SO_4^{2-} ions react directly with solid Pb electrode to form $PbSO_4(s)$
- Stating that a decrease in concentration will result in a decrease in the potential difference. A decrease in $[Pb^{2+}]$ will cause an increase in potential difference.
- Describing an increase or decrease in the mass of electrodes as resulting in a changed potential difference (the quantity of electrode is irrelevant)
- No change because a closed circuit stops the reaction
- Stating this was a battery

Based on your experience of student responses at the AP Reading, what message would you like to send to teachers that might help them to improve the performance of their students on the exam?

Suggestions for teachers:

- Establish what reactions take place at the anode and cathode; electrons do not cause the anode and cathode mass changes; electrons are involved in the oxidation and reduction reactions which cause these mass changes.
- Emphasize what moves through the salt bridge; electrons do not move through, nor does the mass of the electrodes.

- Emphasize that ions do not move (to a large extent) from the anode compartment to the cathode compartment (and vice versa) through the salt bridge; the ions in the salt bridge move into these compartments to maintain electrical neutrality.
- Emphasize the different functions of the various components of the electrochemical cell.
- Discuss the appropriate use of Le Chatelier's Principle. This principle does not describe every reaction, only those at equilibrium. In this diagram, the switch was open, and reducing the $[Pb^{2+}]$ does not cause an immediate reaction to occur. The potential for the reaction to occur is thermodynamically enhanced; therefore the voltmeter will read a higher potential difference.
- When considering the activities of metals, emphasize that when comparing species, it must be done with similar species, for example, compare metals with other metals and compare ions with other ions.
- Have students practice writing and interpreting explanations. Peer review of each other's explanations helps to develop a sense of a well-written explanation.
- Perform labs with electrochemical cells.
- Ask students to analyze data from electrochemistry labs.
- Ask students to draw models to enhance their explanations.
- Students should understand how to use variations of the standard potential equation. For example:
    - $E^\circ_{cell} = E^\circ_{red} + E^\circ_{ox}$. Use of this form will require students to obtain values from the standard reduction potential table and reverse the sign for the oxidation reaction.
    - $E^\circ_{cell} = E^\circ_{cathode} - E^\circ_{anode}$. Use of this form will require students to obtain values from the standard reduction potential table. No sign reversal is necessary.

Suggestions for students:

- It is not always correct to use catch phrases such as "the mass of the anode will decrease, the mass of the cathode will increase." Use these statements to interpret the reactions of the electrochemical cell, and adjust the statement according to evidence and written reactions.
- Consistency is important. Consider your prior answers: for example, if in part (b) the reaction was listed as $Pb \rightarrow Pb^{2+} + 2e^-$, then be sure to answer the next questions based on the written reaction. If the next answers do not make sense, reconsider your original proposal.
- Clearly state your ideas. Particular words (such as neutrality) have multiple meanings and must be more specifically defined. Use clear, unambiguous language so the reader knows what you are trying to say.
- Answer the specific question. If the question asks about mass, mass should be part of the answer.