2022

AP® CollegeBoard

AP® Chemistry

Sample Student Responses and Scoring Commentary

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Free-Response Question 3

- ☑ Scoring Guidelines
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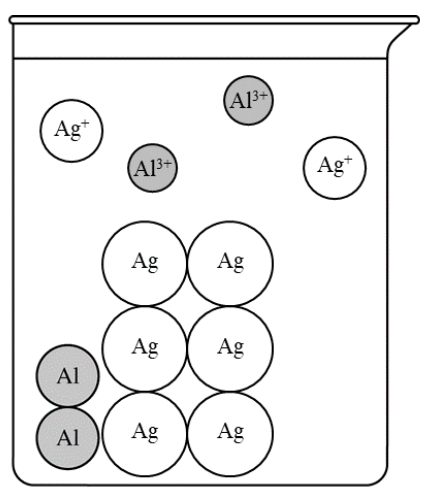
Question 3: Long Answer — 10 points

(a)	For a correct electron configuration: Accept one of the following: • $1s^2 2s^2 2p^6 3s^2 3p^1$ • $[Ne]\ 3s^2 3p^1$	**1 point**
(b)	For a correct explanation: *The highest occupied electron shell (n=3) of* Al *is at a greater average distance from the nucleus than the highest occupied electron shell (n=2) of* Al^{3+}.	**1 point**
(c)	For the correct steps to dissolve the solute in water (steps may be consolidated): *2. Partially fill the volumetric flask with some distilled water* *3. Add the weighed* $AgNO_3(s)$ *to the volumetric flask* *4. Swirl to dissolve the solid*	**1 point**
	For the correct step to ensure quantitative dilution: *5. After the solid is dissolved, fill the flask to the calibration (*200.00 mL*) mark and mix.*	**1 point**
	Total for part (c)	**2 points**
(d)	For a drawing that shows product formation and indicates the conservation of matter: 4 Al *and* 8 Ag *particles in the beaker on right (see sample drawing below)*	**1 point**
	For a drawing that shows product formation and conservation of charge: 2 Ag^+ *ions and* 2 Al^{3+} *ions in the beaker on the right (see sample drawing below)*	**1 point**
	For a drawing that shows product formation and correct phases of matter for all species: 6 Ag *atoms that are solid and* 2 Al^{3+} *ions that are aqueous in the beaker on the right*	**1 point**



	Total for part (d)	**3 points**

(e)	For the correct calculated value: Accept one of the following: • $E° = 0.80\text{ V} + 1.66\text{ V} = 2.46\text{ V}$ • $E^\circ_{cell} = E^\circ_{red} - E^\circ_{ox} = 0.80\text{ V} - (-1.66\text{ V}) = 2.46\text{ V}$	**1 point**
(f)	For the correct answer and a valid justification: *Negative. The reaction has a positive value of $E°$, indicating that it is thermodynamically favorable and would therefore have a negative value of $\Delta G°$. ($\Delta G° = -nFE°$)*	**1 point**
(g)	For the correct answer and a valid justification: Accept one of the following: • *Zero. The observation that the reaction stops progressing implies that $E_{cell} = 0$, indicating that there is no longer a driving force for the reaction.* • *Zero. The observation that reaction stops progressing implies that equilibrium is established, and $\Delta G = 0$ at equilibrium.*	**1 point**

Total for question 3 10 points

Question 3

Begin your response to QUESTION 3 on this page.

3. Answer the following questions relating to the element aluminum, Al.

(a) Write the complete ground-state electron configuration of an Al atom.

$1s^2 2s^2 2p^6 3s^2 3p^1$

(b) Based on principles of atomic structure, explain why the radius of the Al atom is larger than the radius of the Al^{3+} ion.

Al atom has 3 occupied energy levels compared to Al^{+3} which has 2 occupied energy levels, so the outermost e^- of Al are farther away from the nucleus, than the outermost e^- of Al^{+3}, giving it a larger radius.

A student plans to combine solid aluminum with an aqueous solution of silver ions. The student determines the mass of solid $AgNO_3$ needed to prepare the solution with a specific concentration.

(c) In the following table, briefly list the steps necessary to prepare 200.0 mL of an aqueous solution of $AgNO_3$ using only equipment selected from the choices given. Assume that all appropriate safety measures are already in place. Not all equipment or lines in the table may be needed.

- Solid $AgNO_3$
- Distilled water
- Balance
- Weighing paper and scoop
- 200.00 mL volumetric flask
- 50.0 mL graduated cylinder
- 250 mL beakers
- Pipet

Step	Step Description
1.	Use weighing paper to measure the determined mass of solid $AgNO_3$ on a balance.
2.	Pour the solid $AgNO_3$ into the 200.00 mL volumetric flask
3.	Fill the volumetric flask with distilled water up to the 200.00mL graduation.
4.	Shake the flask to ensure that all $AgNO_3$ dissolves while making sure
	nothing spills.

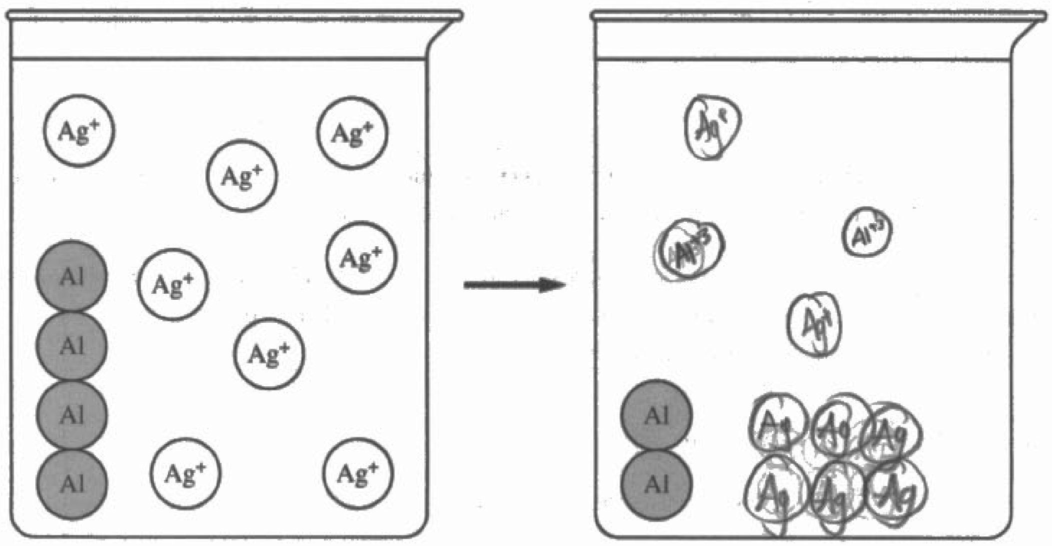
Question 3

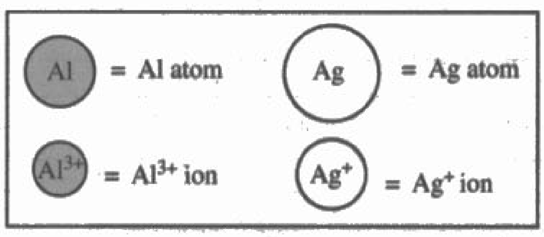
Continue your response to **QUESTION 3** on this page.

After preparing the solution, the student places some of the solution into a beaker and adds a sample of aluminum. The reaction represented by the following equation occurs.

$$1\ Al(s) + 3\ Ag^{+}(aq) \rightarrow Al^{3+}(aq) + 3\ Ag(s)$$

(d) The following diagram gives an incomplete particulate representation of the reaction. The beaker on the left represents the system before the mixture reacts. Complete the drawing on the right to represent the system after the reaction has occurred. Be sure to include 1) the correct type and number of particles based on the number shown on the left and 2) the relative spacing to depict the appropriate phases.





The student finds the standard reduction potentials given in the table, which are related to the reaction that occurs.

Half-Reaction	$E°$
$Ag^{+}(aq) + e^{-} \rightarrow Ag(s)$	0.80 V
$Al^{3+}(aq) + 3e^{-} \rightarrow Al(s)$	−1.66 V

Question 3

Continue your response to **QUESTION 3** on this page.

(e) Using the standard reduction potentials, calculate the value of $E°$ for the reaction.

$E° = 0.80v + 1.66v = \boxed{2.46v}$

(f) Based on the value of $E°$, would the standard free energy change of the reaction under standard conditions, $\Delta G°$, be positive, negative, or zero? Justify your answer.

ΔG° would be negative because a positive E° value means the reaction is thermodynamically favorable, which corresponds to a negative ΔG° as negative ΔG° values mean the rxn is favorable.

(g) Once the reaction appears to stop progressing, would the change in free energy, ΔG, be positive, negative, or zero? Justify your answer.

ΔG would be 0 because once the reaction stops progressing, the reaction is at equilibrium, which corresponds to ΔG=0 as the forwards & backwards reactions are equally favorable.

Question 3

Begin your response to QUESTION 3 on this page.

3. Answer the following questions relating to the element aluminum, Al.

(a) Write the complete ground-state electron configuration of an Al atom. ← not ion

Al: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^1$

(b) Based on principles of atomic structure, explain why the radius of the Al atom is larger than the radius of the Al^{3+} ion.

Since the Al^{+3} ion has more protons than the Al atom, the orbitals have a stronger attraction to the nucleus which is filled with more protons. This attraction causes the orbitals to pull in and become closer the to nucleus, making the Al^{+3} ion smaller.

A student plans to combine solid aluminum with an aqueous solution of silver ions. The student determines the mass of solid $AgNO_3$ needed to prepare the solution with a specific concentration.

(c) In the following table, briefly list the steps necessary to prepare 200.0 mL of an aqueous solution of $AgNO_3$ using only equipment selected from the choices given. Assume that all appropriate safety measures are already in place. Not all equipment or lines in the table may be needed.

- ~~Solid $AgNO_3$~~
- Weighing paper and scoop ?
- ~~250 mL beakers~~
- ~~Distilled water~~
- ~~200.00 mL volumetric flask~~
- Pipet ×
- Balance ?
- 50.0 mL graduated cylinder ×

Step	Step Description
1.	Use weighing paper to measure the determined mass of solid $AgNO_3$ on a balance.
2.	Measure out 200mL of distilled water using a 200mL volumetric flask.
3.	Mix the solid $AgNO_3$ and 200mL of distilled water together in a 250mL beaker

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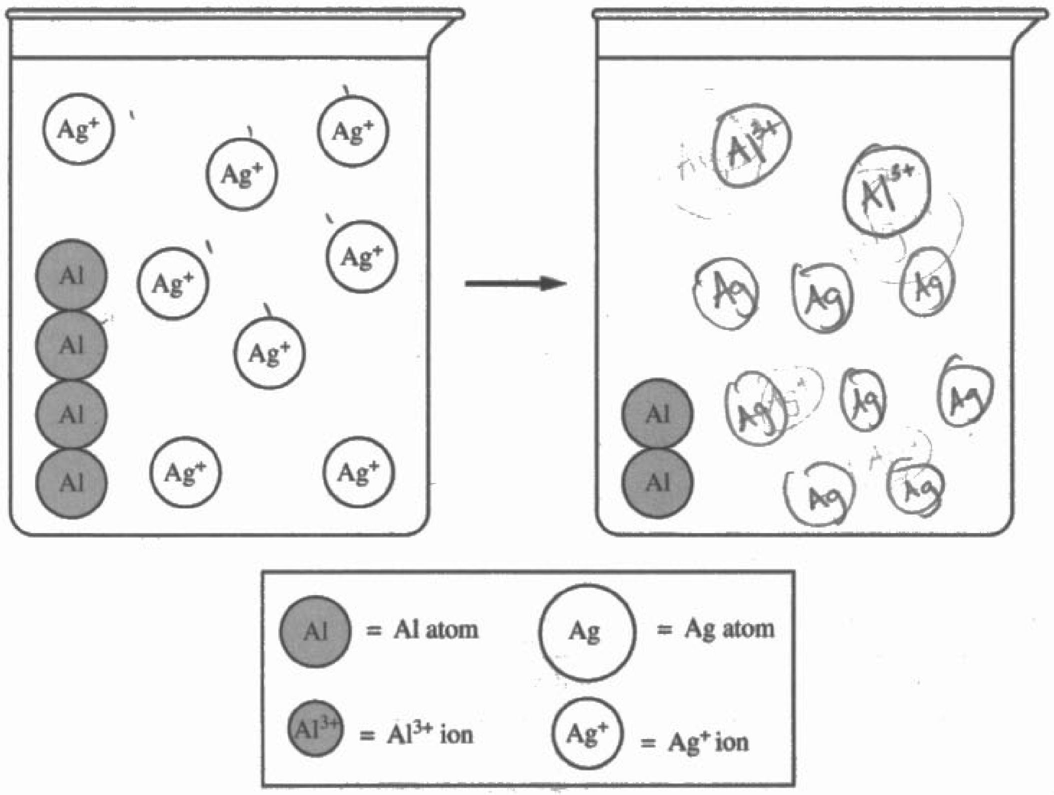
Question 3

Continue your response to **QUESTION 3** on this page.

After preparing the solution, the student places some of the solution into a beaker and adds a sample of aluminum. The reaction represented by the following equation occurs.

$$Al(s) + 3\ Ag^{+}(aq) \rightarrow Al^{3+}(aq) + 3\ Ag(s)$$

(d) The following diagram gives an incomplete particulate representation of the reaction. The beaker on the left represents the system before the mixture reacts. Complete the drawing on the right to represent the system after the reaction has occurred. Be sure to include 1) the correct type and number of particles based on the number shown on the left and 2) the relative spacing to depict the appropriate phases.



The student finds the standard reduction potentials given in the table, which are related to the reaction that occurs.

Half-Reaction	$E°$
$3Ag^{+}(aq) + e^{-} \rightarrow 3Ag(s)$	0.80 V
$Al^{3+}(aq) + 3e^{-} \rightarrow Al(s)$	−1.66 V

· 3 = 2.4

= 1.66

flip

Question 3

Continue your response to **QUESTION 3** on this page.

(e) Using the standard reduction potentials, calculate the value of $E°$ for the reaction.

Ag: 2.4 V

Al: + 1.66 V

$E°_{rxn}$ = 4.06 V

(f) Based on the value of $E°$, would the standard free energy change of the reaction under standard conditions, $\Delta G°$, be positive, negative, or zero? Justify your answer.

The value of $\Delta G°$ would be negative because since $E°$ is positive, ~~and~~ Faraday's constant is positive, and the number of moles is negative, from the equation $\Delta G° = -nFE°$, $\Delta G°$ would be negative.

(g) Once the reaction appears to stop progressing, would the change in free energy, ΔG, be positive, negative, or zero? Justify your answer.

The change in ΔG once the reaction stopped progressing would be the same because all of the previous quantities for n, F, and $E°$ would stay the same, even if the reaction stopped.

Question 3

Begin your response to QUESTION 3 on this page.

3. Answer the following questions relating to the element aluminum, Al.

(a) Write the complete ground-state electron configuration of an Al atom.

$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^1$

(b) Based on principles of atomic structure, explain why the radius of the Al atom is larger than the radius of the Al^{3+} ion.

The radius of Al atom is larger than the radius of the Al^{3+} ion because the Al^{3+} ions means that it lost 3 electrons making the radius smaller.

A student plans to combine solid aluminum with an aqueous solution of silver ions. The student determines the mass of solid $AgNO_3$ needed to prepare the solution with a specific concentration.

(c) In the following table, briefly list the steps necessary to prepare 200.0 mL of an aqueous solution of $AgNO_3$ using only equipment selected from the choices given. Assume that all appropriate safety measures are already in place. Not all equipment or lines in the table may be needed.

- Solid $AgNO_3$
- Distilled water
- Balance
- Weighing paper and scoop
- 200.00 mL volumetric flask
- 50.0 mL graduated cylinder
- 250 mL beakers
- Pipet

Step	Step Description
1.	Use weighing paper to measure the determined mass of solid $AgNO_3$ on a balance.
2.	Place $AgNO_3$ (s) and distilled water in 250 mL beakers

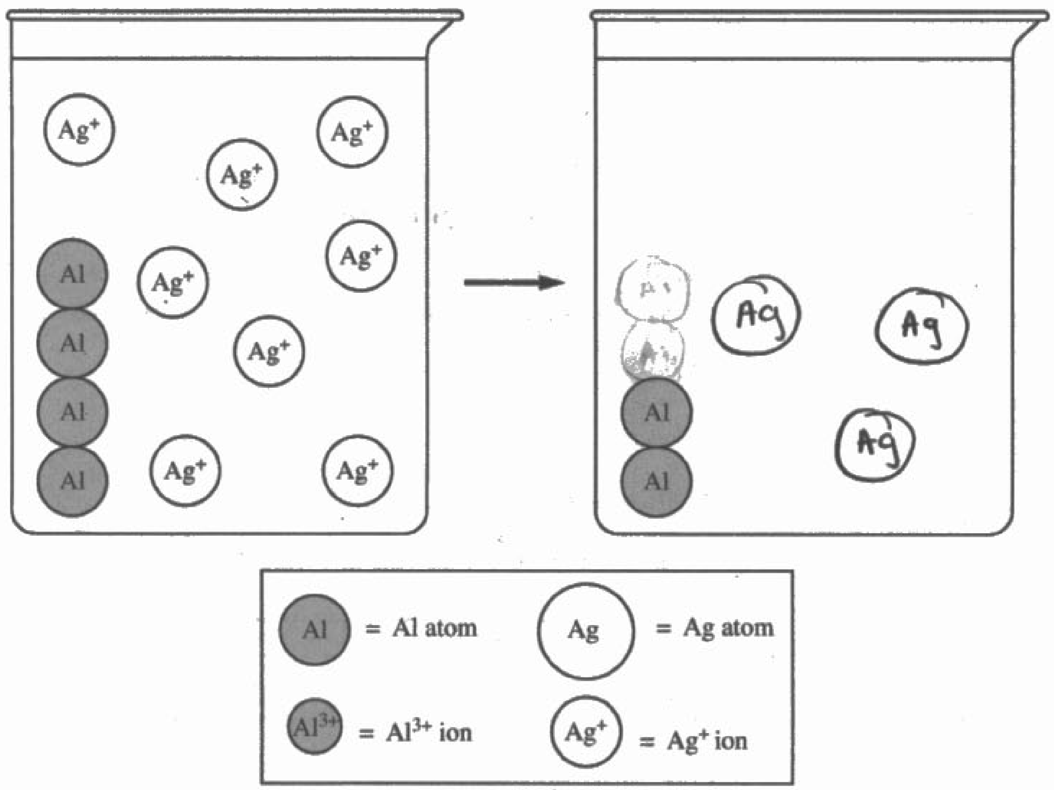
Question 3

Continue your response to QUESTION 3 on this page.

After preparing the solution, the student places some of the solution into a beaker and adds a sample of aluminum. The reaction represented by the following equation occurs.

$$Al(s) + 3\ Ag^{+}(aq) \rightarrow Al^{3+}(aq) + 3\ Ag(s)$$ ✓

(d) The following diagram gives an incomplete particulate representation of the reaction. The beaker on the left represents the system before the mixture reacts. Complete the drawing on the right to represent the system after the reaction has occurred. Be sure to include 1) the correct type and number of particles based on the number shown on the left and 2) the relative spacing to depict the appropriate phases.



The student finds the standard reduction potentials given in the table, which are related to the reaction that occurs.

Half-Reaction	$E°$
$Ag^{+}(aq) + e^{-} \rightarrow Ag(s)$	0.80 V
$Al^{3+}(aq) + 3e^{-} \rightarrow Al(s)$	−1.66 V

Question 3

Continue your response to **QUESTION 3** on this page.

(e) Using the standard reduction potentials, calculate the value of $E°$ for the reaction.

$$\frac{.80 + 1.66}{3} = 0.82$$

(f) Based on the value of $E°$, would the standard free energy change of the reaction under standard conditions, $\Delta G°$, be positive, negative, or zero? Justify your answer.

ΔG° will be positive because gallvanic cells are always positive.

(g) Once the reaction appears to stop progressing, would the change in free energy, ΔG, be positive, negative, or zero? Justify your answer.

The change in free energy will be negative once the reaction appears to stop progressing because Gibbs free energy will decrease and all the products and reactants will run out.

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Question 3

Note: Student samples are quoted verbatim and may contain spelling and grammatical errors.

Overview

Question 3 deals with the atomic structure and reactions of aluminum. Part (a) began by asking students for the electron configuration of the aluminum atom (SAP-1.A, 3.B). Part (b) then asked students to explain why the Al^{3+} cation is smaller than the Al atom using principles of atomic structure (SAP-2.A, 6.C). Each part was worth 1 point.

The question then turned to the analysis of the reaction between solid aluminum and silver ions. To prepare for the reaction, students were asked in part (c) to list the steps they would perform to make 200.0 mL of a $AgNO_3$ solution given the preweighed solid (SPQ-3.A, 2.C and 2.D) and a list of available equipment. Two points were possible for this procedure, the first for making a solution and the second for ensuring it contained a volume of 200.0 mL.

Students were then told that the solution was placed into a beaker containing aluminum and that a redox reaction occurred, producing solid silver and Al^{3+} ions. A particulate representation of the reactants was given, and students were asked to complete a particulate diagram in part (d) representing the species in the beaker after the reaction had occurred (TRA-1.C, 3.B; TRA-1.B, 3B; SAP-6.A, 3.C). Three points were possible for the particulate diagrams, as responses had to correctly show mass and charge balance between the diagrams and correct phases of matter for all species.

Parts (e), (f), and (g) were each worth 1 point and examined the thermodynamics of the reaction. In part (e) students were asked to calculate the value of $E°$ for the reaction from a given table of standard reduction potentials (ENE-5.A, 5.F). From the value of $E°$ calculated, students made a claim for the sign of $\Delta G°$ with justification (ENE-6.B, 5.C). Finally, students were asked to reason about the value of ΔG (or the driving force) of the reaction being positive, negative, or zero, after the reaction has been observed to stop progressing (ENE-6.C, 6.D).

Sample: 3A
Score: 9

This response earned 9 points. In part (a) the point was earned for the correct electron configuration. In part (b) the point was earned for correctly explaining that the difference in radii is a result of the outermost electrons in Al^{3+} existing in a lower energy level than the outermost electrons in Al. In part (c) the first point was earned because the procedure listed in the response does properly create a solution of $AgNO_3$ in the volumetric flask. The second point was not earned because the procedure listed does not properly create 200.0 mL of the solution. The procedure has water added to the mark before mixing, which would result in a volume different from 200.0 mL after the final mixing. In part (d) the first point was earned because the drawing indicates the conservation of matter. The second point was earned because the drawing indicates the consistency of charge particles. The third point was earned because the drawing indicates the correct phases of matter. In part (e) the point was earned because the calculation of $E°$ is correct. In part (f) the point was earned because the response states that the value of $\Delta G°$ is negative and gives the correct justification that because $E°$ is positive the reaction is thermodynamically favorable. In part (g) the point was earned because the response correctly states that ΔG will equal 0 because the reaction is at equilibrium when it stops progressing.

Question 3 (continued)

Sample: 3B
Score: 4

This response earned 4 points. In part (a) the point was earned for writing the correct electron configuration. In part (b) no point was earned because the response incorrectly states that the number of protons in Al^{3+} is greater than the number in Al. In part (c) the first point was earned because the response correctly describes the procedure to make an $AgNO_3$ solution. The second point was not earned because the solution produced does not have a volume of 200.0 mL (because the volumetric glassware is not correctly used). In part (d) the first point was earned because the diagram produced in the response shows conservation of particles (mass) of silver and aluminum. The second point was not earned because, although the diagram shows the formation of products (Ag(*s*) and Al^{3+} (*aq*)), the total positive charge is not consistent between the diagrams (too many silver atoms have been created). The third point was not earned because the phase of matter is incorrect for the Ag product. In part (e) no point was earned because the response incorrectly calculates the value of $E°$ from the given information. In part (f) the point was earned because the response states that the value of $\Delta G°$ is negative, along with the correct justification that because the value of $E°$ calculated in part (e) is positive, the reaction is thermodynamically favorable. In part (g) no point was earned because the response does not explicitly state whether the value of ΔG is positive, negative, or zero.

Sample: 3C
Score: 1

This response earned 1 point. In part (a) the point was earned for the correct electron configuration. In part (b) no point was earned because the response simply states that losing electrons makes the ion smaller, with no reference to the locations of the electrons in Al or Al^{3+}. In part (c) the first point was not earned because the procedure listed in the response does not create a solution of $AgNO_3$ (because no mixing occurs after the solid and water are combined). The second point was not earned because the use of a beaker will not produce a volumetric 200.0 mL solution. In part (d) the first point was not earned because the diagram in the response does not show conservation of silver or aluminum particles (mass). The second point was not earned because, although the product Ag is shown, no Al^{3+} is formed, and the total positive charge is not consistent between diagrams. The third point was not earned because the silver atoms are not shown in the proper phase of matter (solid). In part (e) no point was earned because the calculation of $E°$ is incorrect. In part (f) no point was earned because the response incorrectly states that $\Delta G°$ will be positive, and no proper justification based on the $E°$ value is given. In part (g) no point was earned because the response incorrectly states that ΔG will be negative when the reaction appears to stop progressing.