AP® CHEMISTRY
2010 SCORING GUIDELINES

Question 6
(9 points)

$$2\ Al(s) + 3\ Zn^{2+}(aq) \rightarrow 2\ Al^{3+}(aq) + 3\ Zn(s)$$

Respond to the following statements and questions that relate to the species and the reaction represented above.

(a) Write the complete electron configuration (e.g., $1s^2\,2s^2\,\ldots$) for Zn^{2+}.

$1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,3d^{10}$	One point is earned for the correct configuration.

(b) Which species, Zn or Zn^{2+}, has the greater ionization energy? Justify your answer.

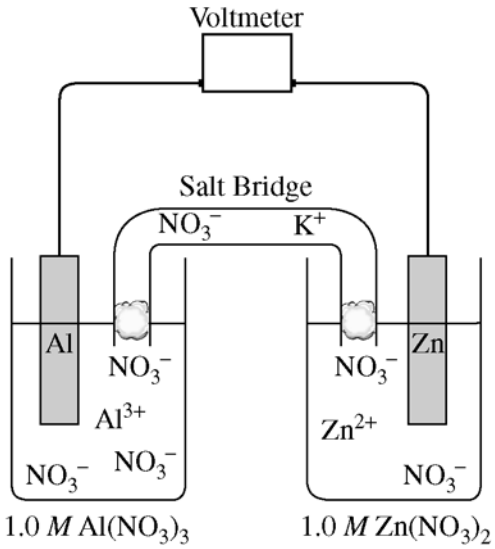
Zn^{2+} has the greater ionization energy. The electron being removed from Zn^{2+} experiences a larger effective nuclear charge than the electron being removed from Zn because Zn^{2+} has two fewer electrons shielding the nucleus. ***OR*** It takes more energy to remove a negatively charged electron from a positive ion than from a neutral atom.	One point is earned for identifying Zn^{2+} with justification.

(c) Identify the species that is oxidized in the reaction.

Al(*s*)	One point is earned for identifying Al.

Question 6 (continued)

The diagram below shows a galvanic cell based on the reaction. Assume that the temperature is 25°C.



(d) The diagram includes a salt bridge that is filled with a saturated solution of KNO_3. Describe what happens in the salt bridge as the cell operates.

As the cell operates, NO_3^- ions flow toward the Al half-cell and K^+ ions flow toward the Zn half-cell.	One point is earned for correctly indicating the direction of ion flow.

(e) Determine the value of the standard voltage, $E°$, for the cell.

$E° = (-0.76\text{ V}) - (-1.66\text{ V}) = 0.90\text{ V}$	One point is earned for the correct $E°$.

(f) Indicate whether the value of the standard free-energy change, $\Delta G°$, for the cell reaction is positive, negative, or zero. Justify your answer.

$\Delta G°$ is negative since $E°$ is positive and $\Delta G° = -n\mathcal{F}E°$. ***OR*** $\Delta G°$ must be negative because the reaction is spontaneous under standard conditions.	One point is earned for indicating that $\Delta G°$ is negative. One point is earned for a correct justification.

Question 6 (continued)

(g) If the concentration of $Al(NO_3)_3$ in the $Al(s)/Al^{3+}(aq)$ half-cell is lowered from $1.0\,M$ to $0.01\,M$ at 25°C, does the cell voltage increase, decrease, or remain the same? Justify your answer.

Lowering $[Al^{3+}]$ causes an increase in the cell voltage. The value of Q will fall below 1.0 and the log term in the Nernst equation will become negative. This causes the value of E_{cell} to become more positive. ***OR*** A decrease in a product concentration will increase the spontaneity of the reaction, increasing the value of E_{cell}.	One point is earned for indicating that E_{cell} increases. One point is earned for the correct justification.

$$2\ Al(s) + 3\ Zn^{2+}(aq) \rightarrow 2\ Al^{3+}(aq) + 3\ Zn(s)$$

6A,

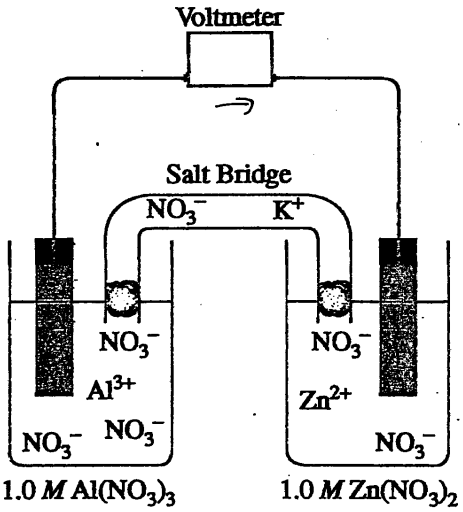
6. Respond to the following statements and questions that relate to the species and the reaction represented above.

(a) Write the complete electron configuration (e.g., $1s^2 2s^2 \ldots$) for Zn^{2+}.

(b) Which species, Zn or Zn^{2+}, has the greater ionization energy? Justify your answer.

(c) Identify the species that is oxidized in the reaction.

The diagram below shows a galvanic cell based on the reaction. Assume that the temperature is 25°C.



(d) The diagram includes a salt bridge that is filled with a saturated solution of KNO_3. Describe what happens in the salt bridge as the cell operates.

(e) Determine the value of the standard voltage, $E°$, for the cell.

(f) Indicate whether the value of the standard free-energy change, $\Delta G°$, for the cell reaction is positive, negative, or zero. Justify your answer.

(g) If the concentration of $Al(NO_3)_3$ in the $Al(s)/Al^{3+}(aq)$ half-cell is lowered from 1.0 *M* to 0.01 *M* at 25°C, does the cell voltage increase, decrease, or remain the same? Justify your answer.

6a Zn^{2+}: $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10}$

6b. Zn^{2+} Zn^{2+} has already had two electrons removed so there is less electron shielding. There are the same number of protons for less electrons. Zn^{2+} has a completely filled 3d orbital. Zn^{+2} has one less shell.

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6A2

ADDITIONAL PAGE FOR ANSWERING QUESTION 6

than Zn since the $4s^2$ have already been removed. Zn^{+2} has a stronger pull on the electrons.

6c. Al Change from 0 to 3^+

6d. NO_3^- goes to the anode (Al) while K^+ goes to the cathode (Zn). In the anode, Al becomes Al^{+3}, making the anode more positive, drawing the negative anion NO_3^- while the cathode becomes negative attracting the cation, K^+ and losing NO_3^-.

6e. $E^\circ = E_{Al} + E_{Zn}$
$= 1.66 - 0.76$
$= \boxed{0.90\,V}$

6f. It is negative since $\mathcal{E}^\circ$ is positive. The reaction is spontaneous so ΔG is negative.

6g. $\mathcal{E} = \mathcal{E}^\circ - \frac{0.0591}{n} \log Q$. The cell voltage increases. The equilibrium shifts right by LeChatelier's. The voltage increases. Q is < 1.
log Q negative $\mathcal{E} = \mathcal{E}^\circ + A$ when A is positive $\mathcal{E}$ increases.

$\log Q = \log \frac{0.01}{1} = -2 < 0$

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$$2\ Al(s) + 3\ Zn^{2+}(aq) \rightarrow 2\ Al^{3+}(aq) + 3\ Zn(s)$$

6 B

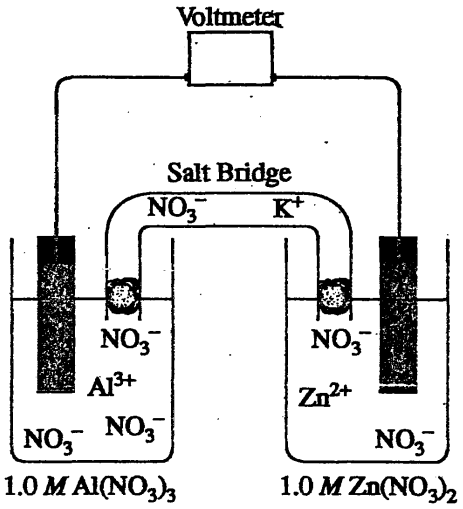
6. Respond to the following statements and questions that relate to the species and the reaction represented above.

(a) Write the complete electron configuration (e.g., $1s^2\,2s^2\ldots$) for Zn^{2+}.

(b) Which species, Zn or Zn^{2+}, has the greater ionization energy? Justify your answer.

(c) Identify the species that is oxidized in the reaction.

The diagram below shows a galvanic cell based on the reaction. Assume that the temperature is 25°C.



(d) The diagram includes a salt bridge that is filled with a saturated solution of KNO_3. Describe what happens in the salt bridge as the cell operates.

(e) Determine the value of the standard voltage, $E°$, for the cell.

(f) Indicate whether the value of the standard free-energy change, $\Delta G°$, for the cell reaction is positive, negative, or zero. Justify your answer.

(g) If the concentration of $Al(NO_3)_3$ in the $Al(s)/Al^{3+}(aq)$ half-cell is lowered from 1.0 *M* to 0.01 *M* at 25°C, does the cell voltage increase, decrease, or remain the same? Justify your answer.

6. a) $1s^2 2s^2 2p^6 3s^2 3p^6 4s^1 3d^{10} = Zn^{2+}$

b) Zn because it is easier to remove the first electron than the third electron.

c) Al

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d) The salt bridge completes the circuit by allowing for free flow of cations and anions in solution. The cations flow towards the cathode and the anions flow towards the anode.

e) $E°cell = -0.76 + 1.66 = 0.90V$

$E°_{red,Al^{3+}} = -1.66V$

$E°_{red,Zn^{2+}} = -0.76V$

$+1.66$
-0.76
0.90

f) Negative because the reaction happens spontaneously.

g) Increase; To account for the loss of Ag^{3+}, more Al would lose their electrons and turn into Al^{3+}.

$$2\,Al(s) + 3\,Zn^{2+}(aq) \rightarrow 2\,Al^{3+}(aq) + 3\,Zn(s)$$

6C,

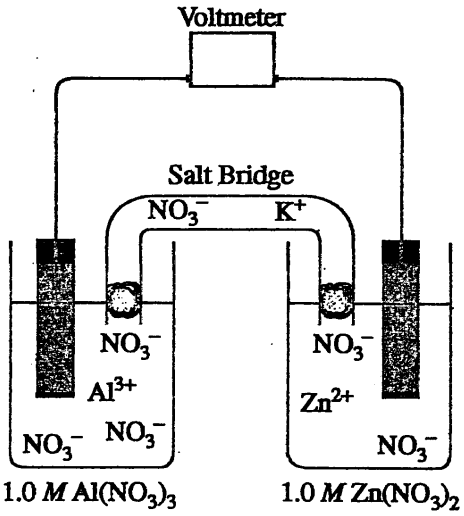
6. Respond to the following statements and questions that relate to the species and the reaction represented above.

(a) Write the complete electron configuration (e.g., $1s^2 2s^2 \ldots$) for Zn^{2+}.

(b) Which species, Zn or Zn^{2+}, has the greater ionization energy? Justify your answer.

(c) Identify the species that is oxidized in the reaction.

The diagram below shows a galvanic cell based on the reaction. Assume that the temperature is 25°C.



(d) The diagram includes a salt bridge that is filled with a saturated solution of KNO_3. Describe what happens in the salt bridge as the cell operates.

(e) Determine the value of the standard voltage, $E°$, for the cell.

(f) Indicate whether the value of the standard free-energy change, $\Delta G°$, for the cell reaction is positive, negative, or zero. Justify your answer.

(g) If the concentration of $Al(NO_3)_3$ in the $Al(s)/Al^{3+}(aq)$ half-cell is lowered from 1.0 *M* to 0.01 *M* at 25°C, does the cell voltage increase, decrease, or remain the same? Justify your answer.

6. a). $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^8$

b). Zn^{2+} because after 2 e^- have been removed, each electron feels a greater pull from the protons in the nucleus than the electrons in Zn feel.

c). Al is oxidized into Al^{3+} because each Al loses $3e^-$.

d). The salt bridge provides the solutions with positive and negative salts to balance the solution. K^+ or NO_3^- is dissolved in the solutions as needed.

e). red: ox:

$Al^{3+} + 3e^- \rightarrow Al$ $-1.66\,V$ $Al \rightarrow Al^{3+} + 3e^-$ $1.66V$

$Zn^{2+} + 2e^- \rightarrow Zn$ -0.76 $1.66 - 0.76 = \boxed{0.90V}$

f). Negative, because as the problem states, this is a galvanic, or spontaneous, cell, and ΔG is always negative if E° is positive or spontaneous. Also, $\Delta G = -n\mathcal{F}E^\circ$, and the number of moles and the Faraday constant cannot be negative, so if E° is positive, ΔG is negative.

g). The cell voltage remains the same, because no matter if the half-cell reaction is multiplied by 2 or 3 or 4, the E° does not change. The number of moles in the change of 1.0 M to 0.01 M does not affect the potential (E°) of each half-reaction.

AP® CHEMISTRY
2010 SCORING COMMENTARY

Question 6

Overview

This question started with two parts on atomic structure and then dealt mainly with matters of electrochemistry. In part (a) students were asked to complete the electron configuration for a *d*-block ion. In part (b) students were asked to compare the ionization energy of this ion with the corresponding neutral atom. The rest of the question dealt with a specific redox reaction and a galvanic cell based on this reaction. In part (c) students were asked to identify the species that is oxidized. In part (d) they were asked to describe what happens in the salt bridge as the cell operates. In part (e) students were asked to calculate $E°$ for the cell. In part (f) students were required to indicate the sign of $\Delta G°$ for the cell reaction and to justify their answer. In part (g) they were asked to predict the effect on E_{cell} if the concentration of one of the components in the cell reaction is reduced.

Sample: 6A
Score: 9

This response earned all 9 points: 1 point for part (a), 1 point for part (b), 1 point for part (c), 1 point for part (d), 1 point for part (e), 2 points for part (f), and 2 points for part (g). In part (b) Zn^{2+} is correctly identified as having the greater ionization energy, and this choice is justified based on the reduced electron shielding in the ion. In part (d) the direction of movement of both K^+ and NO_3^- ions is given; the direction of movement of either ion is sufficient to earn the point. The correct explanation in part (g) is based on a sign analysis using the Nernst equation.

Sample: 6B
Score: 7

This response did not earn the point in part (b). The response earned 1 point in part (g) for noting that the cell voltage would increase, but the second point was not earned because the explanation does not address either the Nernst equation or a change in reaction spontaneity.

Sample: 6C
Score: 5

This response did not earn the point in part (a). The point was not earned in part (d) because there is no description of ions moving. The points were not earned in part (g) because the answer given for the effect on the cell voltage is incorrect.