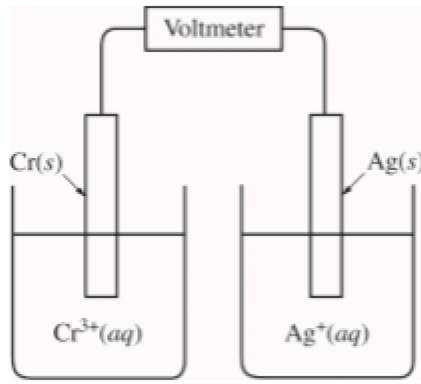
ELECTROCHEMISTRY AP PROBLEMS

2018 AP® CHEMISTRY FREE-RESPONSE QUESTIONS



6. A student sets up a galvanic cell at 298 K that has an electrode of Ag(*s*) immersed in a 1.0 *M* solution of $Ag^+(aq)$ and an electrode of Cr(*s*) immersed in a 1.0 *M* solution of $Cr^{3+}(aq)$, as shown in the diagram above.

   (a) The student measures the voltage of the cell shown above and discovers that it is zero. Identify the missing component of the cell, and explain its importance for obtaining a nonzero voltage.

Half-Reaction	$E°$ (V)
$Ag^+(aq) + e^- \rightarrow Ag(s)$	+ 0.80
$Cr^{3+}(aq) + 3\,e^- \rightarrow Cr(s)$	?

   (b) The student adds the missing component to the cell and measures E°_{cell} to be +1.54 V. As the cell operates, Ag^+ ions are reduced. Use this information and the information in the table above to do the following.

   (i) Calculate the value of $E°$ for the half-reaction $Cr^{3+}(aq) + 3\,e^- \rightarrow Cr(s)$.

   (ii) Write the balanced net-ionic equation for the overall reaction that occurs as the cell operates.

   (iii) Calculate the value of $\Delta G°$ for the overall cell reaction in J/mol_{rxn}.

7. A student wants to determine the concentration of H_2O_2 in a solution of $H_2O_2(aq)$. The student can use one of two titrants, either dichromate ion, $Cr_2O_7^{2-}(aq)$, or cobalt(II) ion, $Co^{2+}(aq)$. The balanced chemical equations for the two titration reactions are shown below.

Dichromate as titrant: $Cr_2O_7^{2-}(aq) + 3\ H_2O_2(aq) + 8\ H^+(aq) \rightarrow 2\ Cr^{3+}(aq) + 3\ O_2(g) + 7\ H_2O(l)$

Cobalt(II) as titrant: $2\ Co^{2+}(aq) + H_2O_2(aq) + 2\ H^+(aq) \rightarrow 2\ Co^{3+}(aq) + 2\ H_2O(l)$

The half-reactions and the $E°$ values for the systems related to the titrations above are given in the following table.

Half-Reaction	$E°$ (V) at 298 K
$Co^{3+}(aq) + e^- \rightarrow Co^{2+}(aq)$	1.84
$H_2O_2(aq) + 2\ H^+(aq) + 2\ e^- \rightarrow 2\ H_2O(l)$	1.77
$Cr_2O_7^{2-}(aq) + 14\ H^+(aq) + 6\ e^- \rightarrow 2\ Cr^{3+}(aq) + 7\ H_2O(l)$	1.33
$O_2(g) + 2\ H^+(aq) + 2\ e^- \rightarrow H_2O_2(aq)$	0.70

(a) Use the information in the table to calculate the following.

(i) $E°$ for the reaction between $Cr_2O_7^{2-}(aq)$ and $H_2O_2(aq)$ at 298 K

(ii) $E°$ for the reaction between $Co^{2+}(aq)$ and $H_2O_2(aq)$ at 298 K

(b) Based on the calculated values of $E°$, the student must choose the titrant for which the titration reaction is thermodynamically favorable at 298 K.

(i) Which titrant should the student choose? Explain your reasoning.

(ii) Calculate the value of $\Delta G°$, in kJ/mol$_{rxn}$, for the reaction between the chosen titrant and $H_2O_2(aq)$.

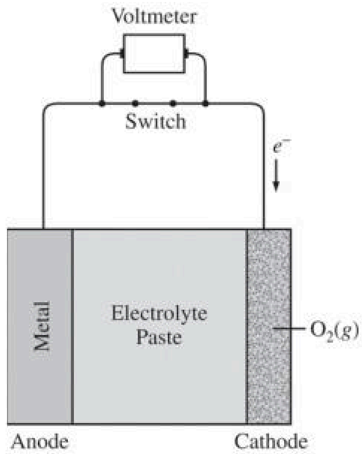
While cleaning up after the experiment, the student wishes to dispose of the unused solid I_2 in a responsible manner. The student decides to convert the solid I_2 to $I^-(aq)$ anion. The student has access to three solutions, $H_2O_2(aq)$, $Na_2S_2O_3(aq)$, and $Na_2S_4O_6(aq)$, and the standard reduction table shown below.

Half reaction	$E°$ (V)
$S_4O_6^{2-}(aq) + 2\,e^- \rightarrow 2\,S_2O_3^{2-}(aq)$	0.08
$I_2(s) + 2\,e^- \rightarrow 2\,I^-(aq)$	0.54
$O_2(g) + 2\,H^+(aq) + 2\,e^- \rightarrow H_2O_2(aq)$	0.68

(e) Which solution should the student add to $I_2(s)$ to reduce it to $I^-(aq)$? Circle your answer below. Justify your answer, including a calculation of $E°$ for the overall reaction.

$H_2O_2(aq)$ $\qquad$ $Na_2S_2O_3(aq)$ $\qquad$ $Na_2S_4O_6(aq)$

(f) Write the balanced net-ionic equation for the reaction between I_2 and the solution you selected in part (e).



1. Metal-air cells are a relatively new type of portable energy source consisting of a metal anode, an alkaline electrolyte paste that contains water, and a porous cathode membrane that lets in oxygen from the air. A schematic of the cell is shown above. Reduction potentials for the cathode and three possible metal anodes are given in the table below.

Half Reaction	*E* at pH 11 and 298 K (V)
$O_2(g) + 2\ H_2O(l) + 4\ e^- \rightarrow 4\ OH^-(aq)$	+0.34
$ZnO(s) + H_2O(l) + 2\ e^- \rightarrow Zn(s) + 2\ OH^-(aq)$	−1.31
$Na_2O(s) + H_2O(l) + 2\ e^- \rightarrow 2\ Na(s) + 2\ OH^-(aq)$	−1.60
$CaO(s) + H_2O(l) + 2\ e^- \rightarrow Ca(s) + 2\ OH^-(aq)$	−2.78

(a) Early forms of metal-air cells used zinc as the anode. Zinc oxide is produced as the cell operates according to the overall equation below.

$$2\ Zn(s) + O_2(g) \rightarrow 2\ ZnO(s)$$

(i) Using the data in the table above, calculate the cell potential for the zinc-air cell.

(ii) The electrolyte paste contains OH^- ions. On the diagram of the cell above, draw an arrow to indicate the direction of migration of OH^- ions through the electrolyte as the cell operates.

(b) A fresh zinc-air cell is weighed on an analytical balance before being placed in a hearing aid for use.

(i) As the cell operates, does the mass of the cell increase, decrease, or remain the same?

(ii) Justify your answer to part (b)(i) in terms of the equation for the overall cell reaction.

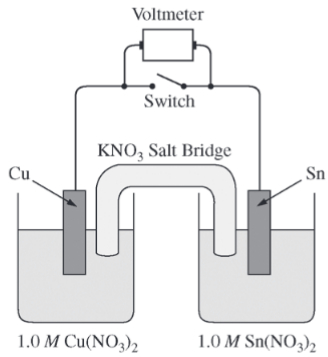
(c) The zinc-air cell is taken to the top of a mountain where the air pressure is lower.

(i) Will the cell potential be higher, lower, or the same as the cell potential at the lower elevation?

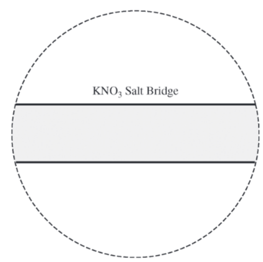
(ii) Justify your answer to part (c)(i) based on the equation for the overall cell reaction and the information above.

(d) Metal-air cells need to be lightweight for many applications. In order to transfer more electrons with a smaller mass, Na and Ca are investigated as potential anodes. A 1.0 g anode of which of these metals would transfer more electrons, assuming that the anode is totally consumed during the lifetime of a cell? Justify your answer with calculations.

2014



3. A student is given a standard galvanic cell, represented above, that has a Cu electrode and a Sn electrode. As current flows through the cell, the student determines that the Cu electrode increases in mass and the Sn electrode decreases in mass.
   a) Identify the electrode at which oxidation is occurring. Explain your reasoning based on the student's observations.
   b) As the mass of the Sn electrode decreases, where does the mass go?
   c) In an expanded view of the center portion of the salt bridge shown in the diagram below, draw and label a particle view of what occurs in the salt bridge as the cell begins to operate. Omit solvent molecules and use arrows to show the movement of particles.



   d) A non-standard cell is made by replacing the 1.0 M solutions of $Cu(NO_3)_2$ and $Sn(NO_3)_2$ in the standard cell with 0.50 M solutions of $Cu(NO_3)_2$ and $Sn(NO_3)_2$. The volumes of solutions in the non-standard cell are identical to those in the standard cell.
      i. Is the cell potential of the nonstandard cell greater than, less than, or equal to the cell potential of the standard cell? Explain.
      ii. Both the standard and nonstandard cells can be used to power an electronic device. Would the nonstandard cell power the device for the same time, a longer time, or a shorter time as compared to the standard cell? Justify your answer.
   e) In another experiment, the student places a new Sn electrode into a fresh solution of $Cu(NO_3)_2$.

Half-Reaction	$E°$ (V)
$Cu^+ + e^- \rightarrow Cu(s)$	0.52
$Cu^{2+} + 2e^- \rightarrow Cu(s)$	0.34
$Sn^{4+} + 2e^- \rightarrow Sn^{2+}$	0.15
$Sn^{2+} + 2e^- \rightarrow Sn(s)$	–0.14

      i. Using information from the table above, write a net ionic equation for the reaction between the Sn electrode and the $Cu(NO_3)_2$ solution that would be thermodynamically favorable. Justify that reaction is thermodynamically favorable.
      ii. Calculate the value of $\Delta G°$ for the reaction. Include units in your answer.

2013

Answer the following questions involving the stoichiometry and thermodynamics of reactions containing aluminum species.

$$2\ Al_2O_3\ (l) + 3\ C\ (s) \rightarrow 4\ Al\ (l) + 3\ CO_2\ (g)$$

An electrolytic cell produces 235 g of Al(*l*) according to the equation above.

a) Calculate the number of moles of electrons that must be transferred in the cell to produce the 235 g of Al(*l*).

b) A steady current of 152 amp was used during the process. Determine the amount of time, in seconds, that was needed to produce the Al(*l*) .

c) Calculate the volume of $CO_2(g)$, measured at 301 K and 0.952 atm, that is produced in the process.

d) For the electrolytic cell to operate, the Al_2O_3 must be in the liquid state rather than in the solid state. Explain.

When Al(*s*) is placed in a concentrated solution of KOH at 25°C, the reaction represented below occurs.

$$2\ Al(s) + 2\ OH^-\ (aq) + 6\ H_2O(l) \rightarrow 2[Al(OH)_4]^-(aq) + 3\ H_2(g)$$

Half-reaction	$E°$ (V)
$[Al(OH)_4]^-(aq) + 3\ e^- \rightarrow Al(s) + 4\ OH^-(aq)$	−2.35
$2\ H_2O(l) + 2\ e^- \rightarrow H_2(g) + 2\ OH^-(aq)$	−0.83

e) Using the table of standard reduction potentials shown above, calculate the following:

i. $E°$, in volts, for the formation of $[Al(OH)_4]^-$ (*aq*) and $H_2(g)$ at 25°C

ii. $\Delta G°$, in kJ/mol_{rxn} , for the formation of $[Al(OH)_4]^-$ (*aq*) and $H_2(g)$ at 25°C

2012

In a laboratory experiment, Pb and an unknown metal Q were immersed in solutions containing aqueous ions of unknown metals Q and X. The following reactions summarize the observation:

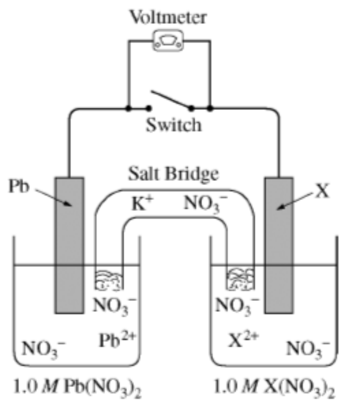
Observation 1: Pb (s) + X^{2+} (aq) → Pb^{2+} (aq) + X (s)

Observation 2: Q (s) + X^{2+} (aq) → no reaction

Observation 3: Pb (s) + Q^{2+} (aq) → Pb^{2+} (aq) + Q (s)

a) On the basis of the reactions indicated above, arrange the three metals, Pb, Q, and X, in order from least reactive to most reactive.

The diagram below shows an electrochemical cell that is constructed with a Pb electrode immersed in 100. mL of 1.0 M $Pb(NO_3)_2$ (aq) and an electrode made of metal X immersed in 100. mL of 1.0 M $X(NO_3)_2$ (aq). A salt bridge containing saturated aqueous KNO_3 connects the anode compartment to the cathode compartment. The electrodes are connected to an external circuit containing a switch, which is open. When a voltmeter is connected through the circuit as shown, the reading on the voltmeter is 0.47 V. When the switch is closed, electrons flow through the switch from the Pb electrode toward the X electrode.



b) Write the equation for the half-reaction that occurs at the anode.

c) The value of the standard potential for the cell, E°, is 0.47 V.
   i. Determine the standard reduction potential for the half-reaction that occurs at the cathode.
   ii. Determine the identity of metal X.

d) Describe what happens to the mass of each electrode as the cell operates.

e) During a laboratory session, students set up the electrochemical cell shown above. For each of the following three scenarios, choose the correct value of the cell voltage and justify your choice.
   1. A student bumps the cell setup, resulting in the salt bridge losing contact with the solution in the cathode compartment. Is V equal to 0.47 V or is V equal to 0?
   2. A student spills a small amount of 0.5 M Na_2SO_4 into the compartment with the Pb electrode, resulting in the formation of a precipitate. Is V less than 0.47 or is V greater than 0.47?
   3. After the laboratory session is over, a student leaves the switch closed. The next day, the student opens the switch and reads the voltmeter. Is V less than 0.47 or is V equal to 0.47?

2011

A fuel cell is an electrochemical cell that converts chemical energy stored in a fuel into electrical energy. A cell that uses H_2 as the fuel can be constructed based on the following half-reactions:

Half-reaction	E° (V)
$2\ H_2O + O_2 + 4\ e^- \rightarrow 4\ OH^-$	+ 0.40 V
$2\ H_2O + 2\ e^- \rightarrow H_2 + 2\ OH^-$	- 0.83 V

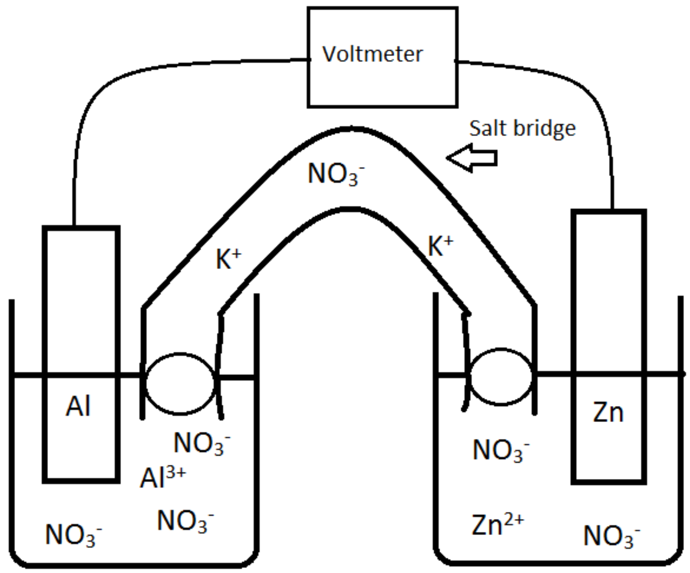
a) Write the equation for the overall cell reaction.
b) Calculate the standard potential at 298 K.
c) Assume that 0.93 mol of $H_{2\ (g)}$ is consumed as the cell operates for 600. seconds.
   ii) Calculate the number of moles of electrons that pass through the cell.
   iii) Calculate the average current, in amperes, that passes through the cell.
d) Some fuel cells use butane gas, C_4H_{10}, rather than hydrogen gas. The overall reaction that occurs in a butane fuel cell is $2\ C_4H_{10\ (g)} + 13\ O_{2\ (g)} \rightarrow 8\ CO_{2\ (g)} + 10\ H_2O_{\ (l)}$. What is one environmental advantage of using fuel cells that are based on hydrogen rather than hydrocarbons such as butane?

2010

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

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

a. Identify the species that is oxidized in the reaction.



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

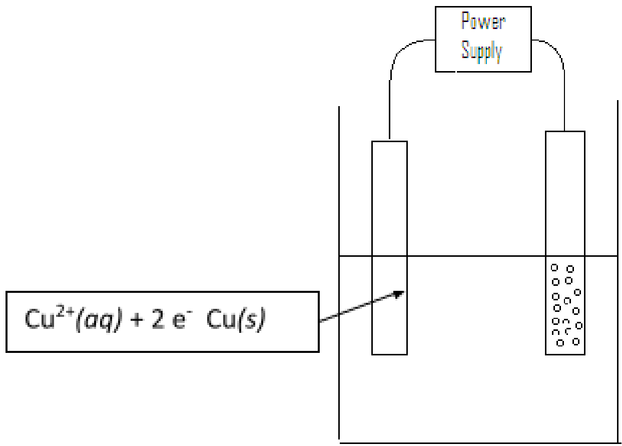
b. The diagram includes a salt bridge that is filled with a saturated solution of KNO_3. Describe what happens in the salt bridge as the cell operates.

c. Determine the value of the standard voltage, E°, for the cell.

d. Identify whether the value of the standard free-energy change, ΔG°, for the cell reaction is positive, negative, or zero. Justify your answer.

e. 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.

2007



An external direct-current power supply is connected to two platinum electrodes immersed in a beaker containing 1.0 M $CuSO_4$ (aq) at 25°C, as shown in the diagram above. As the cell operates, copper metal is deposited onto one electrode and O_2 (g) is produced at the other electrode. The two half-reactions for the overall reaction that occurs in the cell are shown in the table below.

Half-reaction	E° (V)
O_2 (g) + 4 H^+ + 4 e^- → 2 H_2O (l)	+ 1.23
Cu^{2+} + 2 e^- → Cu (s)	+ 0.34

(a) On the diagram, indicate the direction of electron flow in the wire.

(b) Write a balanced net ionic equation for the electrolysis reaction that occurs in the cell.

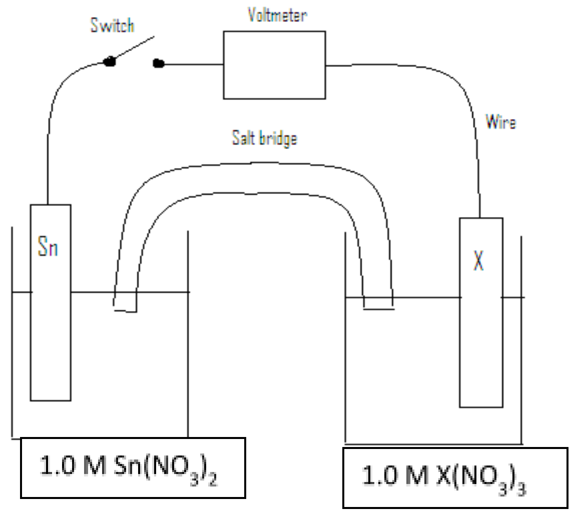
(c) Predict the algebraic sign of ΔG° for the reaction. Justify your prediction.

(d) Calculate the value of ΔG° for the reaction.

An electric current of 1.50 amps passes through the cell for 40.0 minutes.

(e) Calculate the mass, in grams, of the Cu (s) that is deposited on the electrode.

(f) Calculate the dry volume, in liters measured at 25°C and 1.16 atm, of the O_2 produced.



6. An electrochemical cell is constructed with an open switch, as shown in the diagram above. A strip of Sn and a strip of an unknown metal, X, are used as electrodes. When the switch is closed, the mass of the Sn electrode increases. The half-reactions are shown below:

Sn^{2+} (aq) + 2 e^- → Sn (s) $\quad$ E° = - 0.14 V

X^{3+} (aq) + 3 e^- → X (s) $\quad$ E° = **?**

(a) In the diagram above, label the electrode that is the cathode. Justify your answer.

(b) In the diagram above, draw an arrow indicating the direction of the electron flow in the external circuit when the switch is closed.

(c) If the standard cell potential, $E°_{cell}$ is + 0.60 V, what is the standard reduction potential, in volts, for the X^{3+}/X electrode?

(d) Identify metal X.

(e) Write a balanced net ionic equation for the overall chemical reaction occurring in the cell.

(f) In the cell, the concentration of Sn^{2+} is changed from 1.0 M to 0.50 M, and the concentration of X^{3+} is changed from 1.0 M to 0.10 M.

i. Substitute all the appropriate values for determining the cell potential, E_{cell}, into the Nernst equation. (Do <u>not</u> do any calculations.)

ii. On the basis of your response in part (f)(i), will the cell potential, E_{cell}, be greater than, less than, or equal to the original $E°_{cell}$? Justify your answer.