6. 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 observations.

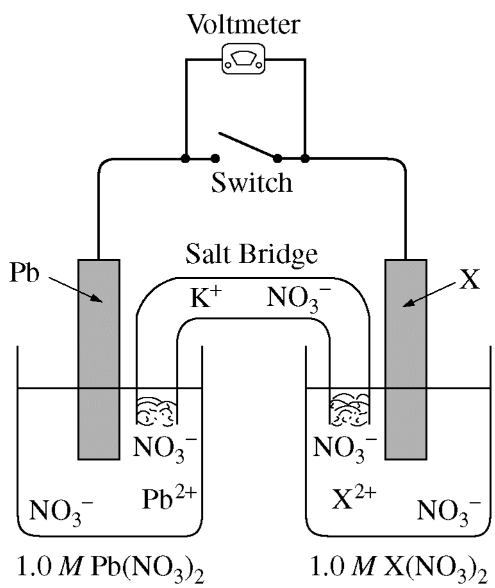
Observation 1: $Pb(s) + X^{2+}(aq) \rightarrow Pb^{2+}(aq) + X(s)$
Observation 2: $Q(s) + X^{2+}(aq) \rightarrow$ no reaction
Observation 3: $Pb(s) + Q^{2+}(aq) \rightarrow Pb^{2+}(aq) + Q(s)$

(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 on the lines provided below.

__________ , __________ , __________

least reactive metal   most reactive metal

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 to 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.

(i) 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 or is V equal to 0 ? Justify your choice.

(ii) A student spills a small amount of 0.5 *M* $Na_2SO_4(aq)$ 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 ? Justify your choice.

(iii) 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 ? Justify your choice.

STOP

END OF EXAM

Name: ______________________________ Period: ____________

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 observations.

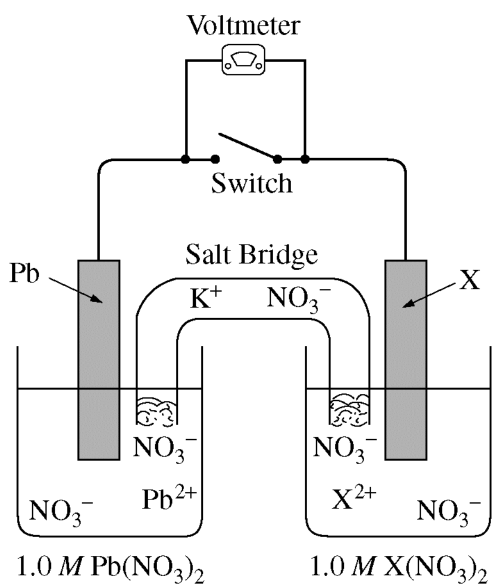
Observation 1: $Pb(s) + X^{2+}(aq) \rightarrow Pb^{2+}(aq) + X(s)$
Observation 2: $Q(s) + X^{2+}(aq) \rightarrow$ no reaction
Observation 3: $Pb(s) + Q^{2+}(aq) \rightarrow Pb^{2+}(aq) + Q(s)$

(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 on the lines provided below.

________________ , ________________ , ________________

least reactive metal   most reactive metal

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 to 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.

(i) 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 or is V equal to 0 ? Justify your choice.

(ii) A student spills a small amount of 0.5 M $Na_2SO_4(aq)$ 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 ? Justify your choice.

(iii) 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 ? Justify your choice.

Mean = 3.97
out of 9 points

AP® CHEMISTRY
SCORING GUIDELINES

(9 points)

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 observations.

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Observation 2: $Q(s) + X^{2+}(aq) \rightarrow$ no reaction
Observation 3: $Pb(s) + Q^{2+}(aq) \rightarrow Pb^{2+}(aq) + Q(s)$

(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 on the lines provided below.

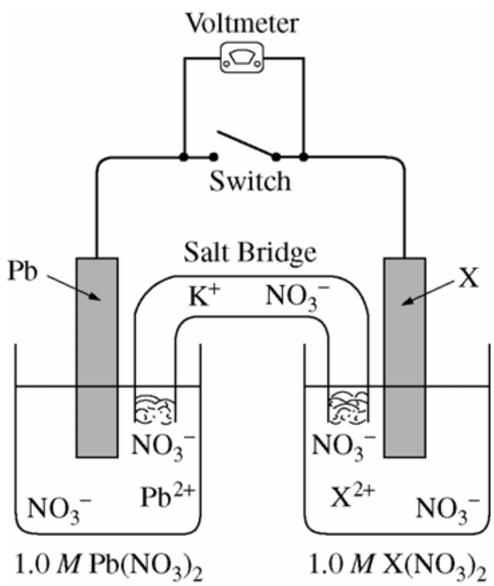
_______Q__________ , _______X__________ , _______Pb__________

least reactive metal — most reactive metal

Q, X, Pb	2 points are earned for the correctly ordered relationship. (1 point earned for Q, Pb, X or X, Q, Pb)

Continued on next page

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 to 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.

$Pb(s) \rightarrow Pb^{2+}(aq) + 2\,e^{-}$	1 point is earned for the correct equation.

(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.

$E^{\circ}_{cell} = E^{\circ}_{cathode} - E^{\circ}_{anode}$ $E^{\circ}_{cathode} = E^{\circ}_{cell} + E^{\circ}_{anode}$ $E^{\circ}_{cathode} = 0.47 + (-0.13) = 0.34\text{ V}$	1 point is earned for the calculated reduction potential with mathematical justification.

(ii) Determine the identity of metal X.

The metal is copper.	1 point is earned for identification of the metal.

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

The mass of the Pb electrode decreases and the mass of the Cu electrode increases.	1 point is earned for <u>both</u> descriptions.

(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.

(i) 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 or is V equal to 0? Justify your choice.

V = 0 V. The transfer of ions through the salt bridge will stop. A charge imbalance between the half-cells will prevent electrons from flowing through the wire.	1 point is earned for the correct choice with an appropriate explanation.

(ii) A student spills a small amount of 0.5 *M* $Na_2SO_4(aq)$ 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 ? Justify your choice.

V > 0.47 V. The sulfate ion will react with the Pb^{2+} ion to form a precipitate. This results in a thermodynamically favored anode half-cell reaction and hence a larger potential difference. The choice may also be justified using the Nernst equation. $E_{cell} = E^{\circ}_{cell} - \left(\frac{RT}{nF}\right)\ln\frac{[Pb^{2+}]}{[Cu^{2+}]}$ Decreasing the $[Pb^{2+}]$ will increase the cell voltage.	1 point is earned for the correct choice with an appropriate explanation.

(iii) 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? Justify your choice.

V < 0.47 V. Over time, $[Pb^{2+}]$ increases and $[Cu^{2+}]$ decreases, making both half-cell reactions less thermodynamically favorable. The choice may also be justified using the Nernst equation. Increasing $[Pb^{2+}]$ and decreasing $[Cu^{2+}]$ decreases the cell voltage. The choice may also be justified by stating that the voltage is zero as a result of the establishment of equilibrium.	1 point is earned for the correct choice with an appropriate explanation.

Student Sample

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 observations.

Observation 1: $Pb(s) + X^{2+}(aq) \rightarrow Pb^{2+}(aq) + X(s)$
Observation 2: $Q(s) + X^{2+}(aq) \rightarrow$ no reaction
Observation 3: $Pb(s) + Q^{2+}(aq) \rightarrow Pb^{2+}(aq) + Q(s)$

(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 on the lines provided below.

Q , X , Pb

least reactive metal — most reactive metal

(b) $Pb \rightarrow Pb^{2+} + 2e^-$

(c) i. $\mathcal{E}^\circ_{cell} = \mathcal{E}^\circ_{red} + \mathcal{E}^\circ_{ox}$ $\quad \mathcal{E}^\circ_{ox} = .13\ V$

$\mathcal{E}^\circ_{red} = .47\ V - .13\ V = \boxed{.34\ V}$

ii. Cu

(d) The mass of Pb (the anode) decreases because Pb is oxidized and forms Pb^{2+} ions in solution, while the mass of Cu (at the cathode) increases because Cu^{2+} is reduced to form more Cu metal.

(e) i. V = 0 because the salt bridge is necessary to balance the charge. without the salt bridge, e^- can't flow through the circuit, and therefore, the voltage is zero.

ii. $Pb^{2+} + SO_4^{2-} \rightarrow PbSO_4$ V is greater than .47 because $[Pb^{2+}]$ is reduced by the formation of the precipitate, so to form more Pb^{2+}, more oxidation occurs at the anode, and more electrons are sent to the cathode, increasing the voltage.

iii. V is less than .47 because the reaction has been going for a long time and the cell is getting closer to equilibrium, at which point, no voltage will be detected and the cell will be dead.

Question 6

Overview

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.

Sample: 6A
Score: 9

The response earned all available points. In part (a) 2 points were earned for the list Q, X, Pb. All the points were earned in parts (b), (c)(i), (c)(ii), and (d). In part (e)(i) 1 point was earned for stating that $V = 0$ V and giving an explanation. In part (e)(ii) 1 point was earned for stating that $V > 0.47$ and giving an explanation. In part (e)(iii) 1 point was earned for stating that $V < 0.47$ V and giving an explanation.

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 $Pb^{2+} + 2e^- \rightarrow Pb$, 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.