AP® Chemistry
Multiple-Choice Answer Key

No	Correct Answer	No.	Correct Answer	No.	Correct Answer
1	D	31	A	61	D
2	B	32	C	62	B
3	A	33	B	63	B
4	E	34	B	64	D
5	A	35	B	65	E
6	C	36	C	66	D
7	D	37	E	67	E
8	B	38	D	68	C
9	C	39	C	69	A
10	A	40	E	70	E
11	E	41	C	71	C
12	D	42	B	72	D
13	B	43	A	73	C
14	C	44	C	74	B
15	C	45	D	75	C
16	E	46	C		
17	C	47	E		
18	E	48	D		
19	D	49	A		
20	B	50	C		
21	E	51	B		
22	D	52	E		
23	C	53	B		
24	C	54	D		
25	C	55	D		
26	A	56	C		
27	D	57	E		
28	E	58	D		
29	B	59	B		
30	D	60	C		

AP® Chemistry
Free-Response Scoring Guidelines

General Scoring Principles

In regard to mathematical errors, a 1-point deduction is made; this deduction may be applied only once per question. In regard to errors in reporting significant figures, a 1-point deduction is made; this deduction may be applied only once per question. A leeway of plus or minus one significant figure different from the correct number of significant figures is allowed before a 1-point deduction is made.

For questions including parts that refer back to previous parts of the same question, a wrong answer that derives from the correct use of a previously calculated incorrect answer should not be counted as wrong. The emphasis of scoring is on *process*, and an error made early on in a multipart calculation should not jeopardize the earning of full credit for the correct use of that incorrect value later in the same question.

Question 1

Answer the following questions about the solubility of the salts Li_3PO_4 and $PbCl_2$. Assume that hydrolysis effects are negligible.

The equation for the dissolution of $Li_3PO_4(s)$ is shown below.

$$Li_3PO_4(s) \rightleftarrows 3\,Li^+(aq) + PO_4^{3-}(aq) \qquad K_{sp} = 3.2 \times 10^{-9} \text{ at } 25°C$$

(a) Write the equilibrium-constant expression for the dissolution of $Li_3PO_4(s)$.

$K_{sp} = [Li^+]^3[PO_4^{3-}]$	One point is earned for the correct expression.

(b) Assuming that volume changes are negligible, calculate the maximum number of moles of $Li_3PO_4(s)$ that can dissolve in

(i) 0.50 L of water at 25°C

Let x represent the molar concentration of Li_3PO_4 present in a saturated solution of Li_3PO_4. Then $K_{sp} = 3.2 \times 10^{-9} = (3x)^3(x) = 27x^4$, thus $x = \sqrt[4]{\dfrac{3.2 \times 10^{-9}}{27}} = 3.3 \times 10^{-3}\,M$. Therefore the number of moles of $Li_3PO_4(s)$ that can dissolve in 0.50 L of water is $0.50\text{ L} \times \dfrac{3.3 \times 10^{-3}\text{mol } Li_3PO_4}{1.0\text{ L}} = \mathbf{1.7 \times 10^{-3}\ mol}$	One point is earned for a correct setup using the K_{sp} expression from part (a). One point is earned for a correct calculation of moles of Li_3PO_4.

(ii) 0.50 L of 0.20 M $LiNO_3$ at 25°C (a "common-ion" problem)

In 0.20 M $LiNO_3$, $[Li^+] = 0.20\,M$. Assume that the amount of $Li^+(aq)$ contributed to the solution by the $Li_3PO_4(s)$ that dissolves is negligibly small compared to 0.20 M. Then let y represent the molar concentration of $PO_4^{3-}(aq)$ present in the solution due to the $Li_3PO_4(s)$ that dissolves in the 0.20 M $LiNO_3$. Then $K_{sp} = 3.2 \times 10^{-9} = (0.20)^3(y) \Rightarrow y = \dfrac{3.2 \times 10^{-9}}{(0.20)^3} = 4.0 \times 10^{-7}\,M.$ So $[PO_4^{3-}(aq)] = [Li_3PO_4(aq)] = 4.0 \times 10^{-7}\,M$ in 0.20 M $LiNO_3(aq)$. Therefore, the number of moles of $Li_3PO_4(s)$ that can dissolve in 0.50 L of water is $0.50\text{ L} \times \dfrac{4.0 \times 10^{-7}\text{mol } Li_3PO_4}{1.0\text{ L}} = \mathbf{2.0 \times 10^{-7}\ mol}$	One point is earned for recognizing that $[Li^+]$ is approximately equal to 0.20 M in the solution to which the $Li_3PO_4(s)$ was added. One point is earned for a correct calculation of moles of Li_3PO_4.

Question 1 (continued)

The equation for the dissolution of $PbCl_2$ is shown below.

$$PbCl_2(s) \rightleftarrows Pb^{2+}(aq) + 2\,Cl^-(aq) \qquad K_{sp} = 1.6 \times 10^{-5} \text{ at } 25°C$$

(c) Calculate the concentration of $Cl^-(aq)$ in a saturated solution of $PbCl_2$ at 25°C.

Let $z = [Pb^{2+}]$ in a saturated solution of $PbCl_2$. Then $K_{sp} = [Pb^{2+}][Cl^-]^2 = (z)(2z)^2 = 4z^3$. Thus $1.6 \times 10^{-5} = 4z^3 \Rightarrow z = \sqrt[3]{\frac{1.6 \times 10^{-5}}{4}}$ $\Rightarrow z = [Pb^{2+}] = 1.6 \times 10^{-2}\,M$ $\Rightarrow [Cl^-] = 2[Pb^{2+}] = 2(1.6 \times 10^{-2}\,M) = \mathbf{3.2 \times 10^{-2}\,M}$	One point is earned for a correct setup. One point is earned for a correct calculation of the value of $[Cl^-]$.

(d) An open container holds 1.000 L of 0.00400 M $PbCl_2$, which is unsaturated at 25°C. Calculate the minimum volume of water, in mL, that must evaporate from the container before solid $PbCl_2$ can precipitate.

1.000 L of 0.00400 M $PbCl_2(aq)$ contains 0.00400 mol of $PbCl_2(aq)$, thus it contains 0.00400 mol $Pb^{2+}(aq)$ and 0.00800 mol $Cl^-(aq)$. Let V = volume of the solution at saturation, then $K_{sp} = 1.6 \times 10^{-5} = \left(\frac{0.00400 \text{ mol}}{V}\right)\left(\frac{0.00800}{V}\right)^2 = \frac{2.6 \times 10^{-7}}{V^3}$ $\Rightarrow V = \sqrt[3]{\frac{2.6 \times 10^{-7}}{1.6 \times 10^{-5}}} = 0.25 \text{ L} = 250 \text{ mL at saturation}$ Thus the volume of water that must evaporate = 1,000. – 250 = **750 mL** **OR** From part (c), the amount of $PbCl_2$ dissolved in 1 L of saturated $PbCl_2(aq)$ is $1.6 \times 10^{-2}\,M$. Let V = volume of the solution at saturation, then $\frac{0.016 \text{ mol } PbCl_2}{1{,}000 \text{ mL}} = \frac{0.00400 \text{ mol } PbCl_2}{V} \Rightarrow V = 250 \text{ mL}$ Thus the volume of water that must evaporate = 1,000. – 250 = **750 mL**	One point is earned for the calculation of the saturation volume. One point is earned for subtracting the saturation volume from 1,000 mL.

Molarity = $\frac{\text{moles}}{\text{volume}}$ $\quad 1.6 \times 10^{-2} = \frac{0.004}{V}$ $\quad V = 250$ mL

If solution volume is less than 250 mL, $[Pb^{2+}]$ and $[Cl^-]$ will exceed Ksp

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Question 2

Answer the following using chemical concepts and principles of the behavior of gases.

(a) A metal cylinder with a volume of 5.25 L contains 3.22 g of He(*g*) and 11.56 g of $N_2(g)$ at 15.0°C.

(i) Calculate the total pressure in the cylinder.

$3.22\text{ g He} \times \frac{1.00\text{ mol He}}{4.00\text{ g He}} = 0.805\text{ mol He}$ $11.56\text{ g N}_2 \times \frac{1.00\text{ mol N}_2}{28.02\text{ g N}_2} = 0.4126\text{ mol N}_2$ total moles of gas = (0.805 + 0.4126) = 1.218 mol $P = \frac{nRT}{V} = \frac{(1.218\text{ mol})(0.0821\text{ L atm mol}^{-1}\text{K}^{-1})(15+273)\text{ K}}{5.25\text{ L}}$ P = **5.49 atm**	One point is earned for the calculations of moles and adding them together. One point is earned for the correct substitution into the gas law equation. One point is earned for the correct answer.

(ii) Calculate the partial pressure of $N_2(g)$ in the cylinder.

$\text{pressure N}_2 = \frac{\text{moles N}_2\text{ gas}}{\text{total moles of gas}} \times \text{total pressure in flask}$ $= \frac{0.4126\text{ mol}}{1.218\text{ mol}} \times 5.49\text{ atm} = $ **1.86 atm**	One point is earned for the calculation of the mole fraction of N_2. One point is earned for the correct answer.

(b) A 1.50 L container holds a 9.62 g sample of an unknown gaseous saturated hydrocarbon at 30°C and 3.62 atm.

(i) Calculate the density of the gas.

$D = \frac{m}{V} = \frac{9.62\text{ g}}{1.50\text{ L}} = $ **6.41 g L^{-1}**	One point is earned for the correct answer.

Question 2 (continued)

(ii) Calculate the molar mass of the gas.

Let M = molar mass, then $PV = nRT = \left(\frac{m}{M}\right)RT \Rightarrow$ $M = \frac{mRT}{PV} = \frac{(9.62\text{ g})(0.0821\text{ L atm K}^{-1}\text{mol}^{-1})(303\text{ K})}{(3.62\text{ atm})(1.50\text{ L})} = \mathbf{44.1\text{ g mol}^{-1}}$	One point is earned for the correct answer.

(iii) Write the formula of the hydrocarbon.

OR, use trial & error

Alkanes

Saturated hydrocarbons have the generic formula C_nH_{2n+2}, therefore let $44.1\text{ g} = 12(n) + 1(2n+2) = 14n + 2 \Rightarrow$ $42.1 = 14n \Rightarrow 3 = n \Rightarrow \mathbf{C_3H_8}$	One point is earned for the correct answer.

(iv) Calculate the root-mean-square speed of the gas molecules in the container at 30°C.
(Note: $1\text{ J} = 1\text{ kg m}^2\text{ s}^{-2}$)

$v_{rms} = \sqrt{\frac{3RT}{M}} = \sqrt{\frac{3(8.31\text{ kg m}^2\text{s}^{-2}\text{ mol}^{-1}\text{ K}^{-1})(303\text{ K})}{0.0441\text{ kg mol}^{-1}}}$ $= \mathbf{414\text{ m s}^{-1}}$	One point is earned for the correct setup using the molar mass in kilograms. One point is earned for the correct answer.

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Question 3

A student performs a titration in which a 10.00 mL sample of 0.0571 *M* HCl is titrated with a solution of NaOH of unknown concentration.

(a) Describe the steps that the student should take to prepare and fill the buret for the titration given a wet 50.00 mL buret and the materials listed below.

0.0571 *M* HCl solution	Indicator solution
NaOH(*aq*) (unknown concentration)	Distilled water
10.5 *M* NaOH solution	100 mL beaker

Rinse the buret with some distilled water and then pour some of the NaOH solution of unknown concentration into the beaker and use it to rinse the buret two times. Use the beaker to carefully fill the buret with the NaOH solution of unknown concentration. Put the beaker under the buret and drain enough solution to remove any air bubbles in the neck and tip of the buret.	One point is earned for rinsing the buret with the titrant solution. One point is earned for removing air bubbles from the neck and tip of the buret.

(b) Calculate the pH of the 0.0571 *M* HCl

HCl is a strong acid $\Rightarrow$ $[H^+]$ in 0.0571 *M* HCl = 0.0571 *M* pH = $-\log[H^+] = -\log(0.0571) = \mathbf{1.243}$	One point is earned for the correct answer.

(c) A volume of 7.62 mL of the NaOH solution was needed to reach the end point of the titration. Calculate the molarity of the NaOH solution used in the titration.

mol HCl titrated = $10.00 \text{ mL} \times \frac{0.0571 \text{ mol HCl}}{1{,}000 \text{ mL}} = 0.000571$ mol; ratio HCl:NaOH in neutralization is 1:1, so 0.000571 mol NaOH reacted; $\frac{0.000571 \text{ mol NaOH}}{0.00762 \text{ L}} = \mathbf{0.0749\ \mathit{M}\ NaOH}$	One point is earned for calculating the moles of HCl in the sample that was titrated. One point is earned for calculating the molarity of the NaOH solution.

Question 3 (continued)

In a different titration using a different NaOH solution, the concentration of NaOH was determined by the student to be 0.0614 *M*.

(d) Given that the actual concentration of the NaOH solution was 0.0627 *M*, calculate the percent error of the student's result.

percent error $= \frac{\lvert 0.0614 - 0.0627 \rvert}{0.0627} \times 100 = \mathbf{2.1\ \%}$	One point is earned for the correct answer.

(e) Calculate the volume of 10.5 *M* NaOH that is needed to prepare 250.0 mL of 0.0627 *M* NaOH. $M_1V_1 = M_2V_2$

$250.0\text{ mL} \times \frac{0.0627\text{ mol}}{1{,}000.\text{ mL}} = 0.0157\text{ mol NaOH needed}$	One point is earned for calculating the moles of NaOH needed.
$0.0157\text{ mol NaOH} \times \frac{1{,}000.\text{ mL}}{10.5\text{ mol NaOH}} = \mathbf{1.49\text{ mL}}$	One point is earned for the correct answer.

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Question 4

For each of the following three reactions, in part (i) write a balanced equation and in part (ii) answer the question about the reaction. In part (i), coefficients should be in terms of lowest whole numbers. Assume that solutions are aqueous unless otherwise indicated. Represent substances in solutions as ions if the substances are extensively ionized. Omit formulas for any ions or molecules that are unchanged by the reaction. You may use the empty space at the bottom of the next page for scratch work, but only equations that are written in the answer boxes provided will be graded.

EXAMPLE:

A strip of magnesium metal is added to a solution of silver(I) nitrate.

(i) Balanced equation:

$Mg + 2 Ag^+ \longrightarrow Mg^{2+} + 2 Ag$

(ii) Which substance is oxidized in the reaction?

Mg is oxidized.

(a) Equal volumes of 0.1 M hydrofluoric acid and 0.1 M potassium hydroxide are combined.

(i) Balanced equation: $\mathbf{HF + OH^- \rightarrow F^- + H_2O}$

(ii) Draw the complete Lewis electron-dot diagram for the reactant that is the Brønsted-Lowry base in the forward reaction.

(b) Solid calcium metal burns in air

(i) Balanced equation: $\mathbf{2\ Ca + O_2 \rightarrow 2\ CaO}$

(ii) Predict the algebraic sign of $\Delta H°$ for the reaction. Explain your prediction.

The sign of $\Delta H°$ will be negative because $\Delta G°$ is negative (the reaction occurs) and $\Delta S°$ is negative (a solid and a gas react to form a solid). According to the Gibbs-Helmholtz equation, $\Delta H° = \Delta G° + T\Delta S°$. Therefore $\Delta H°$ is the sum of two negative quantities and as such must be negative.

Question 4 (continued)

(c) Samples of nitrogen monoxide gas and oxygen gas are combined.

(i) Balanced equation:

$$2\,NO + O_2 \rightarrow 2\,NO_2$$

(ii) If the reaction is second order with respect to nitrogen monoxide and first order with respect to oxygen, what is the rate law for the reaction?

$rate = k[NO]^2[O_2]$

General Scoring Notes for Question 4

Five points are earned for each of parts (a), (b), and (c), distributed as follows.

Four points are earned for part (i): one point for the correct reactants, two points for the correct product(s), and one point for the correct coefficients in the balanced equation.

One point is earned for the correct answer in part (ii).

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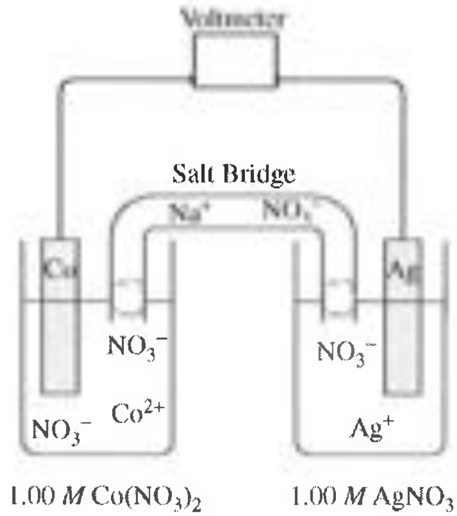
Question 5



Answer the following questions relating to the galvanic cell shown in the diagram above.

(a) Write the balanced equation for the overall cell reaction.

2 $Ag^+(aq)$ + Co(s) → 2 Ag(s) + $Co^{2+}(aq)$	One point is earned for the correct equation.

(b) Calculate the value of $E°$ for the cell.

E°_{cell} = 0.80 – (–0.28) = **1.08 V**	One point is earned for the correct value of E°_{cell} .

(c) Is the value of $\Delta G°$ for the overall cell reaction positive, negative, or 0 ? Justify your answer.

The value of $\Delta G°$ for the overall reaction must be negative because the cell reaction occurs (is spontaneous) as the cell operates. OR Since E°_{cell} is positive and $\Delta G° = -nFE°$, the value of $\Delta G°$ must be negative.	One point is earned for the correct answer, including a valid justification.

Question 5 (continued)

(d) Consider the cell as it is operating.

(i) Does E_{cell} increase, decrease, or remain the same? Explain.

As the cell operates, the concentration of Ag^+ decreases and the concentration of Co^{2+} increases $\Rightarrow$ the ratio $Q = \dfrac{[Co^{2+}]}{[Ag^+]^2}$ increases $\Rightarrow$ $\ln Q$ increases $\Rightarrow$ $E_{cell} = E^\circ_{cell} - \dfrac{RT}{nF}\ln Q$ becomes smaller (decreases).	One point is earned for the correct answer, including a valid justification

(ii) Does ΔG of the overall cell reaction increase, decrease, or remain the same? Explain.

The value of ΔG for the system increases (becomes less negative) as the cell operates and the system approaches equilibrium (when $\Delta G = 0$).	One point is earned for the correct answer, including a valid justification.

(iii) What would happen if the $NaNO_3$ solution in the salt bridge was replaced with distilled water? Explain.

The cell would not operate. The voltage of the cell is too small to overcome the electrical resistance of distilled water, which is a poor conductor due to its very low concentration of ions (about 10^{-7} M $H^+(aq)$ and 10^{-7} M $OH^-(aq)$) that could "carry" the current from one cell to the other.	One point is earned for the correct answer, including a valid justification

(e) After a certain amount of time, the mass of the Ag electrode changes by x grams. Given that the molar mass of Ag is 108 g mol^{-1} and the molar mass of Co is 59 g mol^{-1}, write the expression for the change in the mass of the Co electrode in terms of x.

No math

Δ mol Ag $= \Delta$ mass Ag $\times \dfrac{1 \text{ mol Ag}}{108 \text{ g Ag}} = x \times \dfrac{1}{108} = \dfrac{x}{108}$ Δ mol Co $= -\Delta$ mol Ag $\times \dfrac{1 \text{ mol Co}}{2 \text{ mol Ag}} = -\dfrac{x}{108} \times \dfrac{1}{2} = -\dfrac{x}{216}$ Δ mass Co $= \Delta$ mol Co $\times \dfrac{59 \text{ g Co}}{1 \text{ mol Co}} = -\dfrac{x}{216} \times 59 = -\dfrac{59}{216}x$	One point is earned for using the correct mole ratio of Co to Ag. One point is earned for the correct answer (negative sign is not required).

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Question 6

Answer each of the following using principles of atomic or molecular structure and/or intermolecular or intramolecular forces.

(a) Explain why the H–O–H bond angle in H_2O is less than the H–N–H bond angles in NH_3, as shown in the table below.

H–O–H Bond Angle in H_2O	H–N–H Bond Angles in NH_3
104.5°	107°

see pp. 177-178

Both molecules have tetrahedral electron-domain geometries and might be expected to have bond angles of 109.5°. However, electron domains for nonbonding pairs of electrons exert a greater repulsion on adjacent pairs of electrons than do electron domains for bonding pairs. Thus, in the H_2O molecule with its <u>two</u> nonbonding pairs of electrons, the electron domains of bonding pairs are compressed to a greater extent than they are in the NH_3 molecule, which has only <u>one</u> nonbonding pair of electrons.	One point is earned for citing the difference in number of nonbonding pairs of electrons. One point is earned for citing the greater repulsion from nonbonding pairs as compared with bonding pairs.

(b) Explain why the radius of the Br atom is less than the radius of the Br^- ion, as shown in the table below.

Radius of Br	Radius of Br^-
0.111 nm	0.196 nm

see p. 154

The nuclear charge (+35) is the same for both the Br and Br^- species, but the "extra" electron in Br^- causes the electron cloud to expand due to an increase in mutual repulsions among the electrons that make up the cloud.	☆ One point is earned for recognition that Br and Br^- have the same nuclear charge. One point is earned for citing increased repulsion among electrons.

same # of protons

Question 6 (continued)

(c) Explain why the dipole moment of HI is less than the dipole moment of HCl, as shown in the table below

Dipole Moment of HI	Dipole Moment of HCl
0.42 debye	1.08 debyes

debyes ?!? This is how bond polarity is measured. (You don't need to know that to answer the question)

Iodine, having a lower electronegativity than chlorine has, forms a bond with hydrogen that is less polar than the bond between chlorine and hydrogen in HCl. The lower polarity of the H–I bond means that the dipole moment of the bond is smaller than that of the H–Cl bond.	One point is earned for citing the difference in electronegativity between I and Cl. One point is earned for the comparison of the polarity of the two bonds.

(d) Explain why the normal boiling point of Ne is less than the normal boiling point of Kr, as shown in the table below.

Normal Boiling Point of Ne	Normal Boiling Point of Kr
27 K	121 K

The intermolecular forces among atoms in liquid Ne are the same type of forces as those among atoms in liquid Kr, namely London (dispersion) forces. However, the magnitudes of these forces are smaller in Ne because the electron clouds of Ne atoms are smaller and less polarizable than the electron clouds of Kr atoms. Note: An explanation that cites only periodic trends or only the relative masses of Ne and Kr does not earn credit.	One point is earned for mentioning that intermolecular forces involved are London (dispersion) forces. One point is earned for mentioning the relative polarizability of the electron clouds of the atoms.