CollegeBoard

AP® Chemistry
Practice Exam and Notes

Important note:

Starting with the 2015 exam, Section 2 of the AP Chemistry exam will be 105 minutes long, instead of 90 minutes long. The exam will last 3 hours and 15 minutes, instead of 3 hours.

Exam time per section, as of 2015:

Section	Question type	Number of questions	Timing
I	Multiple choice	60	90 minutes
II	Long free response Short free response	3 4	105 minutes or one hour and 45 minutes

Effective Fall 2013

About the College Board®

The College Board is a mission-driven not-for-profit organization that connects students to college success and opportunity. Founded in 1900, the College Board was created to expand access to higher education. Today, the membership association is made up of over 6,000 of the world's leading educational institutions and is dedicated to promoting excellence and equity in education. Each year, the College Board helps more than seven million students prepare for a successful transition to college through programs and services in college readiness and college success — including the SAT® and the Advanced Placement Program®. The organization also serves the education community through research and advocacy on behalf of students, educators, and schools.

For further information visit **www.collegeboard.org**.

AP Equity and Access Policy

The College Board strongly encourages educators to make equitable access a guiding principle for their AP programs by giving all willing and academically prepared students the opportunity to participate in AP. We encourage the elimination of barriers that restrict access to AP for students from ethnic, racial and socioeconomic groups that have been traditionally underserved. Schools should make every effort to ensure their AP classes reflect the diversity of their student population. The College Board also believes that all students should have access to academically challenging course work before they enroll in AP classes, which can prepare them for AP success. It is only through a commitment to equitable preparation and access that true equity and excellence can be achieved.

Important Note

This Practice Exam is provided by the College Board for AP Exam preparation. Teachers are permitted to download the materials and make copies to use with their students in a classroom setting only. To maintain the security of this exam, teachers should collect all materials after their administration and keep them in a secure location.

Exams may **not** be posted on school or personal websites, nor electronically redistributed for any reason. Further distribution of these materials outside of the secure College Board site disadvantages teachers who rely on uncirculated questions for classroom testing. Any additional distribution is in violation of the College Board's copyright policies and may result in the termination of Practice Exam access for your school as well as the removal of access to other online services such as the AP Teacher Community and Online Score Reports.

Contents

Introduction

Beginning in May 2014, the AP Chemistry Exam will assess understanding of chemistry principles, content, and concepts in combination with science practices. The revised exam will continue to feature multiple-choice and free-response questions. Section I will have 60 multiple-choice questions, with up to 50 percent of the questions falling within sets of multiple-choice questions. Question sets provide a single stimulus or set of data and 2 to 6 related questions. Section II will consist of 7 free-response questions, with 3 long questions and 4 short questions.

Part I of this publication is the Practice Exam. This will mirror the look and feel of an actual AP Exam, including instructions and sample questions. However, these exam items have never been administered in an operational exam, and, therefore, statistical analysis is not available. The purpose of this section is to provide educators with sample exam questions that accurately reflect the composition/design of the revised exam and to offer these questions in a way that gives teachers the opportunity to test their students in an exam situation that closely resembles the actual exam administration.

Part II is the Notes on the Practice Exam. This section offers detailed explanations of how each question in the practice exam links back to the *AP Chemistry Curriculum Framework* (Notes) in order to provide a clear link between curriculum and assessment. It also explains why the correct answer is the correct choice and why the other answers are incorrect (Rationales).

How AP Courses and Exams Are Developed

AP courses and exams are designed by committees of college faculty and AP teachers who ensure that each AP course and exam reflects and assesses college-level expectations. These committees define the scope and expectations of the course, articulating through a curriculum framework what students should know and be able to do upon completion of the AP course. Their work is informed by data collected from a range of colleges and universities to ensure that AP course work reflects current scholarship and advances in the discipline.

These same committees are also responsible for designing and approving exam specifications and exam questions that clearly connect to the curriculum framework. The AP Exam development process is a multi-year endeavor; all AP Exams undergo extensive review, revision, piloting, and analysis to ensure that questions are high quality and fair and that the questions comprise an appropriate range of difficulty.

Throughout AP course and exam development, the College Board gathers feedback from secondary and post-secondary educators. This feedback is carefully considered to ensure that AP courses and exams provide students with a college-level learning experience and the opportunity to demonstrate their qualifications for advanced placement and college credit upon college entrance.

Course Development

Each committee first articulates its discipline's high-level goals and then identifies the course's specific learning objectives. This approach is consistent with "backward design," the practice of developing curricula, instruction, and assessments with the end goal in mind. The learning objectives describe what students should know and be able to do, thereby providing clear instructional goals as well as targets of measurement for the exam.

Exam Development

Exam development begins with the committee making decisions about the overall nature of the exam. How long will it be? How many multiple-choice questions? How many free-response questions? How much time will be devoted to each section? How will the course content and skills be distributed across each section of the exam? Answers to these questions become part of the exam specifications.

With the exam specifications set, test developers design questions that conform to these specifications. The committee reviews every exam question for alignment with the curriculum framework, content accuracy, and a number of other criteria that ensure the integrity of the exam.

Exam questions are then piloted in AP classrooms to determine their statistical properties. Questions that have been approved by the committee and piloted successfully are included in an exam. When an exam is assembled, the committee conducts a final review of the exam to ensure overall conformity with the specifications.

How AP Exams Are Scored

The exam scoring process, like the course and exam development process, relies on the expertise of both AP teachers and college faculty. While multiple-choice questions are scored by machine, the free-response questions are scored by thousands of college faculty and expert AP teachers at the annual AP Reading. AP Exam Readers are thoroughly trained, and their work is monitored throughout the Reading for fairness and consistency. In each subject, a highly respected college faculty member fills the role of Chief Reader, who, with the help of AP Readers in leadership positions, maintains the accuracy of the scoring standards. Scores on the free-response questions are weighted and combined with the results of the computer-scored multiple-choice questions, and this raw score is summed to give a composite AP score of 5, 4, 3, 2, or 1.

The score-setting process is both precise and labor intensive, involving numerous psychometric analyses of the results of a specific AP Exam in a specific year and of the particular group of students who took that exam. Additionally, to ensure alignment with college-level standards, part of the score-setting process involves comparing the performance of AP students with the performance of students enrolled in comparable courses in colleges throughout the United States. In general, the AP composite score points are set so that the lowest raw score needed to earn an AP score of 5 is equivalent to the average score among college students earning grades of A in the college course. Similarly, AP Exam scores of 4 are equivalent to college grades of A–, B+, and B. AP Exam scores of 3 are equivalent to college grades of B–, C+, and C.

Using and Interpreting AP Scores

The extensive work done by college faculty and AP teachers in the development of the course and the exam and throughout the scoring process ensures that AP Exam scores accurately represent students' achievement in the equivalent college course. While colleges and universities are responsible for setting their own credit and placement policies, AP scores signify how qualified students are to receive college credit and placement:

AP Score	Qualification
5	Extremely well qualified
4	Well qualified
3	Qualified
2	Possibly qualified
1	No recommendation

Additional Resources

Visit apcentral.collegeboard.org for more information about the AP Program.

Practice Exam

Exam Content and Format

The AP Chemistry Exam is approximately 3 hours in length. There are two sections:

- Section I is 90 minutes in length and consists of 60 multiple-choice questions accounting for 50 percent of the final score.
- Section II is 90 minutes in length and consists of 3 long free-response questions and 4 short free-response questions accounting for 50 percent of the final score. Students can budget the full 90 minutes however they wish, but the 3 long questions should take about 15–20 minutes each to answer, and the 4 short questions should take about 7–10 minutes each to answer.

Administering the Practice Exam

This section contains instructions for administering the AP Chemistry Practice Exam. You may wish to use these instructions to create an exam situation that resembles an actual administration. If so, read the indented, boldface directions to the students; all other instructions are for administering the exam and need not be read aloud. Before beginning testing, have all exam materials ready for distribution. These include test booklets, answer sheets, the AP Chemistry Periodic Table, the AP Chemistry Equations and Constants list, and calculators.

SECTION I: Multiple-Choice Questions

When you are ready to begin Section I, say:

> **Section I is the multiple-choice portion of the exam. Mark all of your responses on your answer sheet, one response per question. If you need to erase, do so carefully and completely. Your score on the multiple-choice section will be based solely on the number of questions answered correctly. You may NOT use a calculator. However, you may use the Periodic Table and the Equations and Constants list. Are there any questions?**
>
> **You have 1 hour and 30 minutes for this section. Open your Section I booklet and begin.**

Note Start Time here______. Note Stop Time here______. Check that students are marking their answers in pencil on their answer sheets, and that they are not looking at their Section II booklets. After 1 hour and 30 minutes, say:

> **Stop working. I will now collect your Section I booklet.**

There is a 10-minute break between Sections I and II. When all Section I materials have been collected and accounted for and you are ready for the break, say:

> **Please listen carefully to these instructions before we take a 10-minute break. Everything you placed under your chair at the beginning of the exam must stay there. Leave your Section II packet on your desk during the break. Are there any questions?**

You may begin your break. Testing will resume at _______.

SECTION II: Free-Response Questions

After the break, say:

> **You have 90 minutes to answer the questions in this section. You are responsible for pacing yourself, and may proceed freely from one question to the next. Write your answers on the lined pages provided for each question. If you need more paper during the exam, raise your hand. At the top of each extra piece of paper you use, be sure to write your name and the number of the question you are working on. You may use a scientific/graphing calculator, the Periodic Table, and the Equations and Constants list during this ENTIRE section. Are there any questions?**
>
> **You have 1 hour and 30 minutes for this section. Open your Section II booklet and begin.**

Note Start Time here______. Note Stop Time here______. Check that students are writing their answers in their exam booklets. After 1 hour and 20 minutes, say:

> **There are 10 minutes remaining.**

After 10 minutes, say:

> **Stop working and close your exam booklet. Put your exam booklet on your desk, face up. Remain in your seat, without talking, while the exam materials are collected.**

If any students used extra paper for the free-response section, have those students staple the extra sheet/s to the first page corresponding to that question in their exam booklets. Collect a Section II booklet from each student and check that each student wrote answers on the lined pages corresponding to each question.

Then say:

> **You are now dismissed.**

Name: ______________________________

AP® Chemistry Student Answer Sheet for Multiple-Choice Section

No.	Answer
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No.	Answer
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AP® Chemistry Practice Exam

SECTION I: Multiple-Choice Questions

DO NOT OPEN THIS BOOKLET UNTIL YOU ARE TOLD TO DO SO.

At a Glance

Total Time
1 hour, 30 minutes
Number of Questions
60
Percent of Total Score
50%
Writing Instrument
Pencil required
Electronic Device
None allowed

Instructions

Section I of this exam contains 60 multiple-choice questions. Indicate all of your answers to the multiple-choice questions on the answer sheet. No credit will be given for anything written in this exam booklet, but you may use the booklet for notes or scratch work. After you have decided which of the suggested answers is best, mark your response on your answer sheet. Give only one answer to each question. If you change an answer, be sure that the previous mark is erased completely. Here is a sample question and answer.

Sample Question	Sample Answer
Chicago is a (A) state (B) city (C) country (D) continent	Ⓐ ● Ⓒ Ⓓ

Use your time effectively, working as quickly as you can without losing accuracy. Do not spend too much time on any one question. Go on to other questions and come back to the ones you have not answered if you have time. It is not expected that everyone will know the answers to all of the multiple-choice questions.

Your total score on the multiple-choice section is based only on the number of questions answered correctly. Points are not deducted for incorrect answers or unanswered questions.

INFORMATION IN THE TABLE BELOW AND ON THE FOLLOWING PAGES MAY BE USEFUL IN ANSWERING THE QUESTIONS IN THIS SECTION OF THE EXAMINATION.

DO NOT DETACH FROM BOOK.

PERIODIC TABLE OF THE ELEMENTS

1 **H** 1.008																	2 **He** 4.00
3 **Li** 6.94	4 **Be** 9.01											5 **B** 10.81	6 **C** 12.01	7 **N** 14.01	8 **O** 16.00	9 **F** 19.00	10 **Ne** 20.18
11 **Na** 22.99	12 **Mg** 24.30											13 **Al** 26.98	14 **Si** 28.09	15 **P** 30.97	16 **S** 32.06	17 **Cl** 35.45	18 **Ar** 39.95
19 **K** 39.10	20 **Ca** 40.08	21 **Sc** 44.96	22 **Ti** 47.90	23 **V** 50.94	24 **Cr** 52.00	25 **Mn** 54.94	26 **Fe** 55.85	27 **Co** 58.93	28 **Ni** 58.69	29 **Cu** 63.55	30 **Zn** 65.39	31 **Ga** 69.72	32 **Ge** 72.59	33 **As** 74.92	34 **Se** 78.96	35 **Br** 79.90	36 **Kr** 83.80
37 **Rb** 85.47	38 **Sr** 87.62	39 **Y** 88.91	40 **Zr** 91.22	41 **Nb** 92.91	42 **Mo** 95.94	43 **Tc** (98)	44 **Ru** 101.1	45 **Rh** 102.91	46 **Pd** 106.42	47 **Ag** 107.87	48 **Cd** 112.41	49 **In** 114.82	50 **Sn** 118.71	51 **Sb** 121.75	52 **Te** 127.60	53 **I** 126.91	54 **Xe** 131.29
55 **Cs** 132.91	56 **Ba** 137.33	57 ***La** 138.91	72 **Hf** 178.49	73 **Ta** 180.95	74 **W** 183.85	75 **Re** 186.21	76 **Os** 190.2	77 **Ir** 192.2	78 **Pt** 195.08	79 **Au** 196.97	80 **Hg** 200.59	81 **Tl** 204.38	82 **Pb** 207.2	83 **Bi** 208.98	84 **Po** (209)	85 **At** (210)	86 **Rn** (222)
87 **Fr** (223)	88 **Ra** 226.02	89 **†Ac** 227.03	104 **Rf** (261)	105 **Db** (262)	106 **Sg** (266)	107 **Bh** (264)	108 **Hs** (277)	109 **Mt** (268)	110 **Ds** (271)	111 **Rg** (272)							

*Lanthanide Series	58 **Ce** 140.12	59 **Pr** 140.91	60 **Nd** 144.24	61 **Pm** (145)	62 **Sm** 150.4	63 **Eu** 151.97	64 **Gd** 157.25	65 **Tb** 158.93	66 **Dy** 162.50	67 **Ho** 164.93	68 **Er** 167.26	69 **Tm** 168.93	70 **Yb** 173.04	71 **Lu** 174.97
†Actinide Series	90 **Th** 232.04	91 **Pa** 231.04	92 **U** 238.03	93 **Np** (237)	94 **Pu** (244)	95 **Am** (243)	96 **Cm** (247)	97 **Bk** (247)	98 **Cf** (251)	99 **Es** (252)	100 **Fm** (257)	101 **Md** (258)	102 **No** (259)	103 **Lr** (262)

ADVANCED PLACEMENT CHEMISTRY EQUATIONS AND CONSTANTS

Throughout the test the following symbols have the definitions specified unless otherwise noted.

L, mL = liter(s), milliliter(s)
g = gram(s)
nm = nanometer(s)
atm = atmosphere(s)
mm Hg = millimeters of mercury
J, kJ = joule(s), kilojoule(s)
V = volt(s)
mol = mole(s)

ATOMIC STRUCTURE

$$E = h\nu$$
$$c = \lambda\nu$$

E = energy
ν = frequency
λ = wavelength

Planck's constant, $h = 6.626 \times 10^{-34}$ J s
Speed of light, $c = 2.998 \times 10^{8}$ m s^{-1}
Avogadro's number $= 6.022 \times 10^{23}$ mol^{-1}
Electron charge, $e = -1.602 \times 10^{-19}$ coulomb

EQUILIBRIUM

$$K_c = \frac{[\mathrm{C}]^c[\mathrm{D}]^d}{[\mathrm{A}]^a[\mathrm{B}]^b}, \text{ where } a\,\mathrm{A} + b\,\mathrm{B} \rightleftarrows c\,\mathrm{C} + d\,\mathrm{D}$$

$$K_p = \frac{(P_{\mathrm{C}})^c(P_D)^d}{(P_{\mathrm{A}})^a(P_{\mathrm{B}})^b}$$

$$K_a = \frac{[\mathrm{H}^+][\mathrm{A}^-]}{[\mathrm{HA}]}$$

$$K_b = \frac{[\mathrm{OH}^-][\mathrm{HB}^+]}{[\mathrm{B}]}$$

$$K_w = [\mathrm{H}^+][\mathrm{OH}^-] = 1.0 \times 10^{-14} \text{ at } 25^\circ\mathrm{C}$$
$$= K_a \times K_b$$

$$\mathrm{pH} = -\log[\mathrm{H}^+]\,,\ \mathrm{pOH} = -\log[\mathrm{OH}^-]$$

$$14 = \mathrm{pH} + \mathrm{pOH}$$

$$\mathrm{pH} = \mathrm{p}K_a + \log\frac{[\mathrm{A}^-]}{[\mathrm{HA}]}$$

$$\mathrm{p}K_a = -\log K_a,\ \mathrm{p}K_b = -\log K_b$$

Equilibrium Constants

K_c (molar concentrations)
K_p (gas pressures)
K_a (weak acid)
K_b (weak base)
K_w (water)

KINETICS

$$\ln[\mathrm{A}]_t - \ln[\mathrm{A}]_0 = -kt$$

$$\frac{1}{[\mathrm{A}]_t} - \frac{1}{[\mathrm{A}]_0} = kt$$

$$t_{1/2} = \frac{0.693}{k}$$

k = rate constant
t = time
$t_{1/2}$ = half-life

GASES, LIQUIDS, AND SOLUTIONS

$$PV = nRT$$

$$P_A = P_{\text{total}} \times X_{\text{A}}, \text{ where } X_{\text{A}} = \frac{\text{moles A}}{\text{total moles}}$$

$$P_{total} = P_{\text{A}} + P_{\text{B}} + P_{\text{C}} + \ldots$$

$$n = \frac{m}{\boldsymbol{M}}$$

$$\text{K} = {}^\circ\text{C} + 273$$

$$D = \frac{m}{V}$$

$$KE \text{ per molecule} = \frac{1}{2} mv^2$$

$$\text{Molarity}, M = \text{moles of solute per liter of solution}$$

$$A = abc$$

P = pressure
V = volume
T = temperature
n = number of moles
m = mass
$\boldsymbol{M}$ = molar mass
D = density
KE = kinetic energy
v = velocity
A = absorbance
a = molar absorptivity
b = path length
c = concentration

Gas constant, $R = 8.314 \text{ J mol}^{-1}\text{ K}^{-1}$
$= 0.08206 \text{ L atm mol}^{-1}\text{ K}^{-1}$
$= 62.36 \text{ L torr mol}^{-1}\text{ K}^{-1}$
1 atm = 760 mm Hg
= 760 torr
STP = 0.00 °C and 1.000 atm

THERMOCHEMISTRY/ ELECTROCHEMISTRY

$$q = mc\Delta T$$

$$\Delta S^\circ = \sum S^\circ \text{ products} - \sum S^\circ \text{ reactants}$$

$$\Delta H^\circ = \sum \Delta H_f^\circ \text{ products} - \sum \Delta H_f^\circ \text{ reactants}$$

$$\Delta G^\circ = \sum \Delta G_f^\circ \text{ products} - \sum \Delta G_f^\circ \text{ reactants}$$

$$\begin{aligned} \Delta G^\circ &= \Delta H^\circ - T\Delta S^\circ \\ &= -RT \ln K \\ &= -nFE^\circ \end{aligned}$$

$$I = \frac{q}{t}$$

q = heat
m = mass
c = specific heat capacity
T = temperature
S° = standard entropy
H° = standard enthalpy
G° = standard free energy
n = number of moles
E° = standard reduction potential
I = current (amperes)
q = charge (coulombs)
t = time (seconds)

Faraday's constant, F = 96,485 coulombs per mole of electrons

$$1 \text{ volt} = \frac{1 \text{ joule}}{1 \text{ coulomb}}$$

CHEMISTRY

Section I

60 Multiple-Choice Questions

(Time—90 minutes)

YOU MAY NOT USE YOUR CALCULATOR FOR SECTION I

Note: For all questions, assume that the temperature is 298 K, the pressure is 1.00 atmosphere, and solutions are aqueous unless otherwise specified.

Directions: Each of the questions or incomplete statements below is followed by four suggested answers or completions. Select the answer that is best in each case and then fill in the corresponding circle on the answer sheet.

1. Complete combustion of a sample of a hydrocarbon in excess oxygen produces equimolar quantities of carbon dioxide and water. Which of the following could be the molecular formula of the compound?

(A) C_2H_2
(B) C_2H_6
(C) C_4H_8
(D) C_6H_6

Substance	Equilibrium Vapor Pressure at 20°C (torr)
$C_6H_6(l)$	75
$C_2H_5OH(l)$	44
$CH_3OH(l)$	92
$C_2H_6O_2(l)$	0.06

2. Based on the data in the table above, which of the following liquid substances has the weakest intermolecular forces?

(A) $C_6H_6(l)$
(B) $C_2H_5OH(l)$
(C) $CH_3OH(l)$
(D) $C_2H_6O_2(l)$

Ion	Ionic Radius (pm)
Zn^{2+}	74
Ca^{2+}	100
Ba^{2+}	135

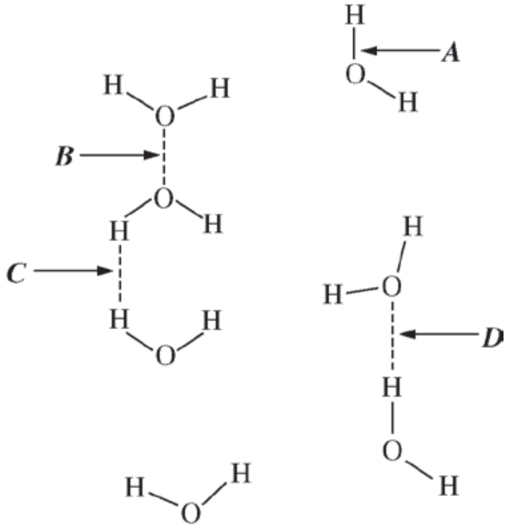
3. Based on the data in the table above, which of the following correctly predicts the relative strength of the attraction of Zn^{2+}, Ca^{2+}, and Ba^{2+} ions to water molecules in a solution, from strongest to weakest, and provides the correct reason?

(A) $Zn^{2+} > Ca^{2+} > Ba^{2+}$ because the smaller ions have a stronger coulombic attraction to water
(B) $Zn^{2+} > Ca^{2+} > Ba^{2+}$ because the smaller ions are more electronegative
(C) $Ba^{2+} > Ca^{2+} > Zn^{2+}$ because the larger ions are more polarizable
(D) $Ba^{2+} > Ca^{2+} > Zn^{2+}$ because the larger ions are less electronegative

4. $Zn(s)$ is used to reduce other compounds in chemical reactions. If a chemist needs a substance that is more effective in its reducing ability, which of the following species would be the best choice?

(A) Na
(B) H^+
(C) K^+
(D) Cl^-

GO ON TO THE NEXT PAGE.



5. In the diagram above, which of the labeled arrows identifies hydrogen bonding in water?

   (A) ***A***
   (B) ***B***
   (C) ***C***
   (D) ***D***

6. A kinetics experiment is set up to collect the gas that is generated when a sample of chalk, consisting primarily of solid $CaCO_3$, is added to a solution of ethanoic acid, CH_3COOH. The rate of reaction between $CaCO_3$ and CH_3COOH is determined by measuring the volume of gas generated at 25°C and 1 atm as a function of time. Which of the following experimental conditions is most likely to increase the rate of gas production?

   (A) Decreasing the volume of ethanoic acid solution used in the experiment
   (B) Decreasing the concentration of the ethanoic acid solution used in the experiment
   (C) Decreasing the temperature at which the experiment is performed
   (D) Decreasing the particle size of the $CaCO_3$ by grinding it into a fine powder

$$H_2(g) + I_2(g) \rightleftarrows 2\,HI(g)$$

7. At 450°C, 2.0 moles each of $H_2(g)$, $I_2(g)$, and $HI(g)$ are combined in a 1.0 L rigid container. The value of K_c at 450°C is 50. Which of the following will occur as the system moves toward equilibrium?

   (A) More $H_2(g)$ and $I_2(g)$ will form.
   (B) More $HI(g)$ will form.
   (C) The total pressure will decrease.
   (D) No net reaction will occur, because the number of molecules is the same on both sides of the equation.

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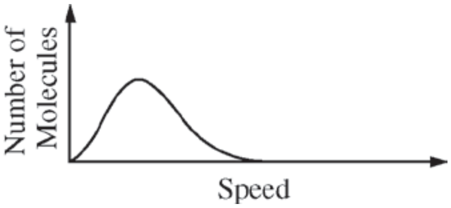
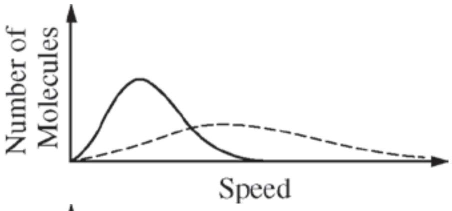
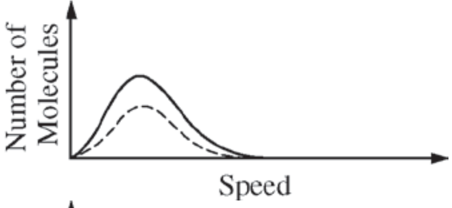


8. The graph above shows the speed distribution of molecules in a sample of a gas at a certain temperature. Which of the following graphs shows the speed distribution of the same molecules at a lower temperature (as a dashed curve) ?

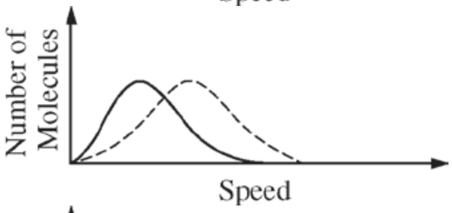
(A)



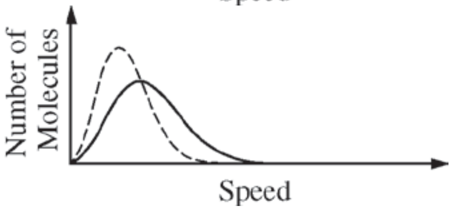
(B)



(C)



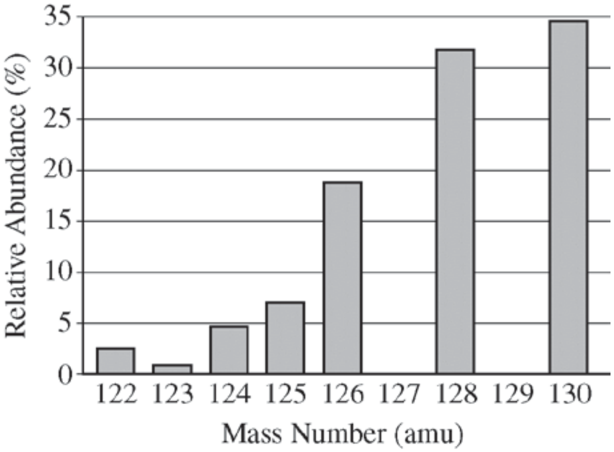
(D)



9. A 100 g sample of a metal was heated to 100°C and then quickly transferred to an insulated container holding 100 g of water at 22°C. The temperature of the water rose to reach a final temperature of 35°C. Which of the following can be concluded?

(A) The metal temperature changed more than the water temperature did; therefore the metal lost more thermal energy than the water gained.
(B) The metal temperature changed more than the water temperature did, but the metal lost the same amount of thermal energy as the water gained.
(C) The metal temperature changed more than the water temperature did; therefore the heat capacity of the metal must be greater than the heat capacity of the water.
(D) The final temperature is less than the average starting temperature of the metal and the water; therefore the total energy of the metal and water decreased.

GO ON TO THE NEXT PAGE.



10. The elements I and Te have similar average atomic masses. A sample that was believed to be a mixture of I and Te was run through a mass spectrometer, resulting in the data above. All of the following statements are true. Which one would be the best basis for concluding that the sample was pure Te?

(A) Te forms ions with a –2 charge, whereas I forms ions with a –1 charge.
(B) Te is more abundant than I in the universe.
(C) I consists of only one naturally occurring isotope with 74 neutrons, whereas Te has more than one isotope.
(D) I has a higher first ionization energy than Te does.

$$H_2C_2O_4(aq) + H_2O(l) \rightleftarrows H_3O^+(aq) + HC_2O_4^-(aq)$$
$$HC_2O_4^-(aq) + H_2O(l) \rightleftarrows H_3O^+(aq) + C_2O_4^{2-}(aq)$$
$$H_2O(l) + H_2O(l) \rightleftarrows H_3O^+(aq) + OH^-(aq)$$

11. All the reactions represented above occur in an aqueous solution of oxalic acid. Which of the following represent a Brønsted-Lowry conjugate acid-base pair?

(A) $H_2C_2O_4(aq)$ and $C_2O_4^{2-}(aq)$
(B) $HC_2O_4^-(aq)$ and $C_2O_4^{2-}(aq)$
(C) $HC_2O_4^-(aq)$ and $H_2O(aq)$
(D) $H_3O^+(aq)$ and $OH^-(aq)$

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12. Which of the following reactions is not thermodynamically favored at low temperatures but becomes favored as the temperature increases?

	Reaction	$\Delta H°$ (kJ/mol$_{rxn}$)	$\Delta S°$ (J/(mol$_{rxn}$·K))
(A)	$2\ CO(g) + O_2(g) \rightarrow 2\ CO_2(g)$	−566	−173
(B)	$2\ H_2O(g) \rightarrow 2\ H_2(g) + O_2(g)$	484	90.0
(C)	$2\ N_2O(g) \rightarrow 2\ N_2(g) + O_2(g)$	−164	149
(D)	$PbCl_2(s) \rightarrow Pb^{2+}(aq) + 2\ Cl^-(aq)$	23.4	−12.5

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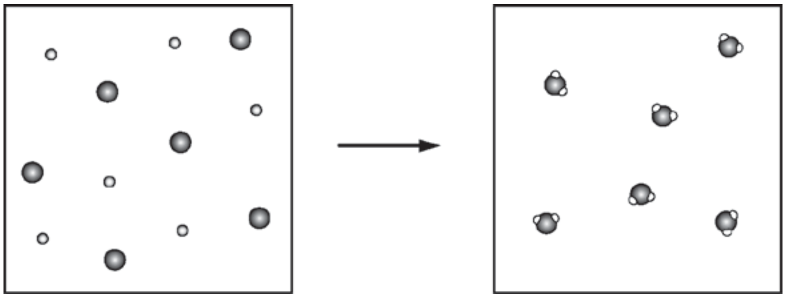
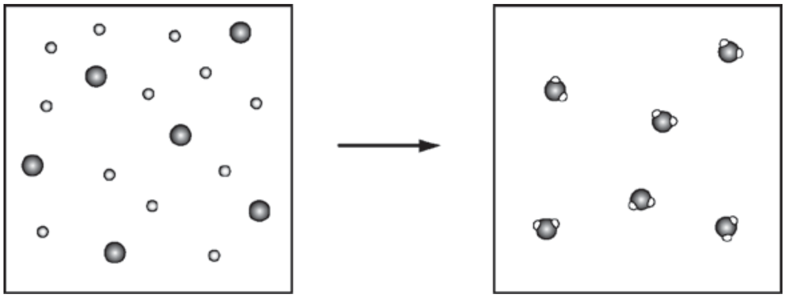
13. Which of the following particulate diagrams best shows the formation of water vapor from hydrogen gas and oxygen gas in a rigid container at 125°C ?

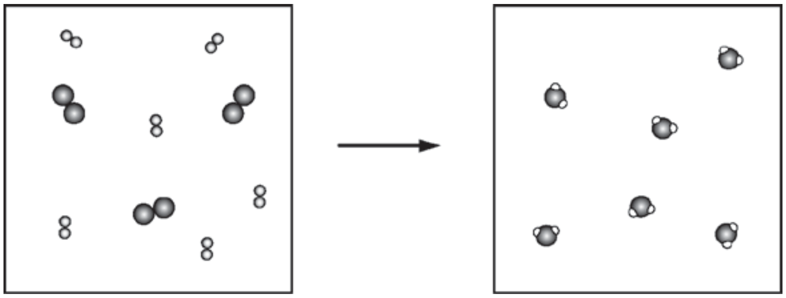
(A)



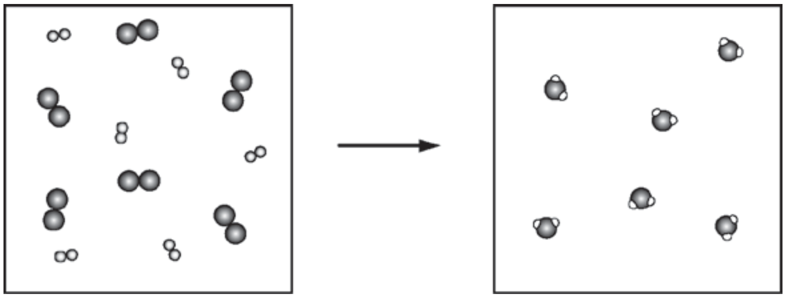
(B)



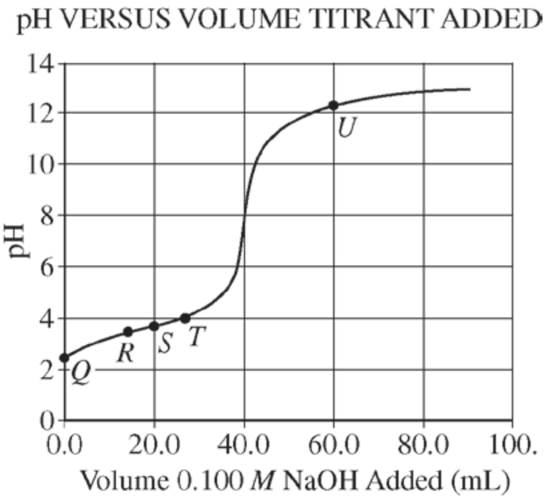
(C)



(D)



Questions 14-17 refer to the following.

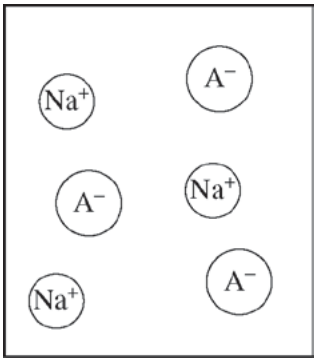


A 50.0 mL sample of an acid, HA, of unknown molarity is titrated, and the pH of the resulting solution is measured with a pH meter and graphed as a function of the volume of 0.100 M NaOH added.

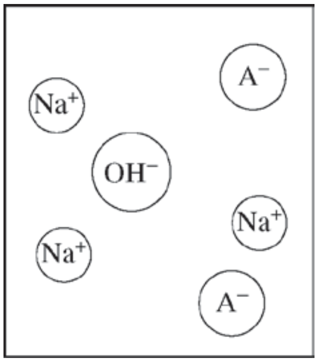
14. At point R in the titration, which of the following species has the highest concentration?
    (A) HA
    (B) A^-
    (C) H_3O^+
    (D) OH^-

15. Which of the following is the best particulate representation of the species (other than H_2O) that are present in significant concentrations in the solution at point U in the titration?

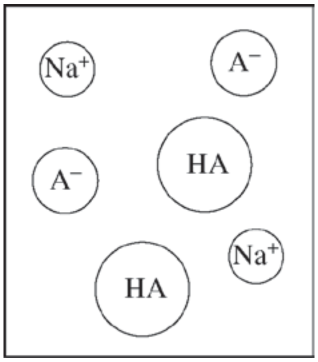
(A)



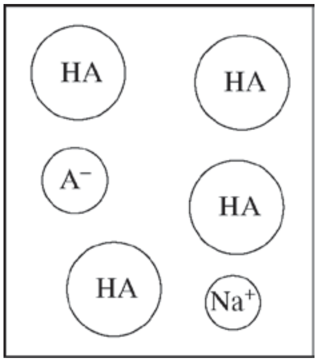
(B)



(C)



(D)



16. At which point on the titration curve is $[A^-]$ closest to twice that of $[HA]$?

(A) *R*
(B) *S*
(C) *T*
(D) *U*

17. A student carries out the same titration, but uses an indicator instead of a pH meter. If the indicator changes color slightly past the equivalence point, what will the student obtain for the calculated concentration of the acid?

(A) Slightly less than 0.0800 *M*
(B) Slightly more than 0.0800 *M*
(C) Slightly less than 0.125 *M*
(D) Slightly more than 0.125 *M*

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Questions 18-20 refer to three gases in identical rigid containers under the conditions given in the table below.

Container	A	B	C
Gas	Methane	Ethane	Butane
Formula	CH_4	C_2H_6	C_4H_{10}
Molar mass (g/mol)	16	30.	58
Temperature (°C)	27	27	27
Pressure (atm)	2.0	4.0	2.0

18. The average kinetic energy of the gas molecules is

(A) greatest in container A
(B) greatest in container B
(C) greatest in container C
(D) the same in all three containers

19. The density of the gas, in g/L, is

(A) greatest in container A
(B) greatest in container B
(C) greatest in container C
(D) the same in all three containers

20. If the pressure of each gas is increased at constant temperature until condensation occurs, which gas will condense at the lowest pressure?

(A) Methane
(B) Ethane
(C) Butane
(D) All the gases will condense at the same pressure.

---

21. The mass percent of carbon in pure glucose, $C_6H_{12}O_6$, is 40.0 percent. A chemist analyzes an impure sample of glucose and determines that the mass percent of carbon is 38.2 percent. Which of the following impurities could account for the low mass percent of carbon in the sample?

(A) Water, H_2O
(B) Ribose, $C_5H_{10}O_5$
(C) Fructose, $C_6H_{12}O_6$, an isomer of glucose
(D) Sucrose, $C_{12}H_{22}O_{11}$

22. Caffeine ($C_8H_{10}N_4O_2$) is a weak base with a K_b value of 4×10^{-4}. The pH of a 0.01 M solution of caffeine is in the range of

(A) 2–3
(B) 5–6
(C) 7–8
(D) 11–12

23. Lewis electron-dot diagrams for CO_2 and SO_2 are given above. The molecular geometry and polarity of the two substances are

(A) the same because the molecular formulas are similar
(B) the same because C and S have similar electronegativity values
(C) different because the lone pair of electrons on the S atom make it the negative end of a dipole
(D) different because S has a greater number of electron domains (regions of electron density) surrounding it than C has

$$2\,NO(g) + O_2(g) \rightarrow 2\,NO_2(g)$$

24. Consider the following mechanism for the reaction represented above.

Step 1: $2\,NO \rightleftarrows N_2O_2$ (*fast reversible*)

Step 2: $N_2O_2 + O_2 \rightarrow 2\,NO_2$ (*slow*)

Which of the following statements is true?

(A) Step 1 represents a unimolecular reaction.
(B) Increasing the concentration of NO will decrease the overall rate of the reaction.
(C) Raising the temperature will have no effect on the numerical value of the rate constant.
(D) The rate law that is consistent with the mechanism is $rate = k[NO]^2[O_2]$.

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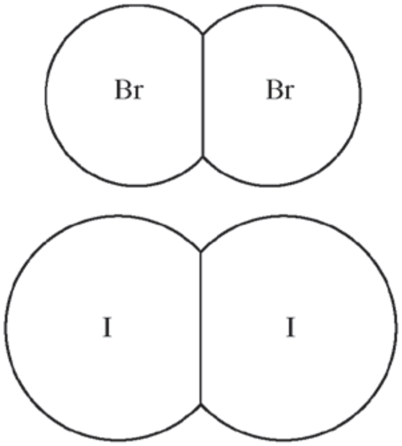

25. The diagram above shows molecules of Br_2 and I_2 drawn to the same scale. Which of the following is the best explanation for the difference in the boiling points of liquid Br_2 and I_2, which are 59°C and 184°C, respectively?

(A) Solid iodine is a network covalent solid, whereas solid bromine is a molecular solid.

(B) The covalent bonds in I_2 molecules are weaker than those in Br_2 molecules.

(C) I_2 molecules have electron clouds that are more polarizable than those of Br_2 molecules, thus London dispersion forces are stronger in liquid I_2.

(D) Bromine has a greater electronegativity than iodine, thus there are stronger dipole-dipole forces in liquid bromine than in liquid iodine.

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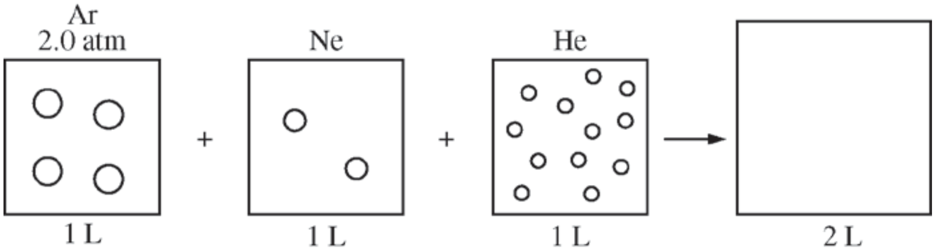
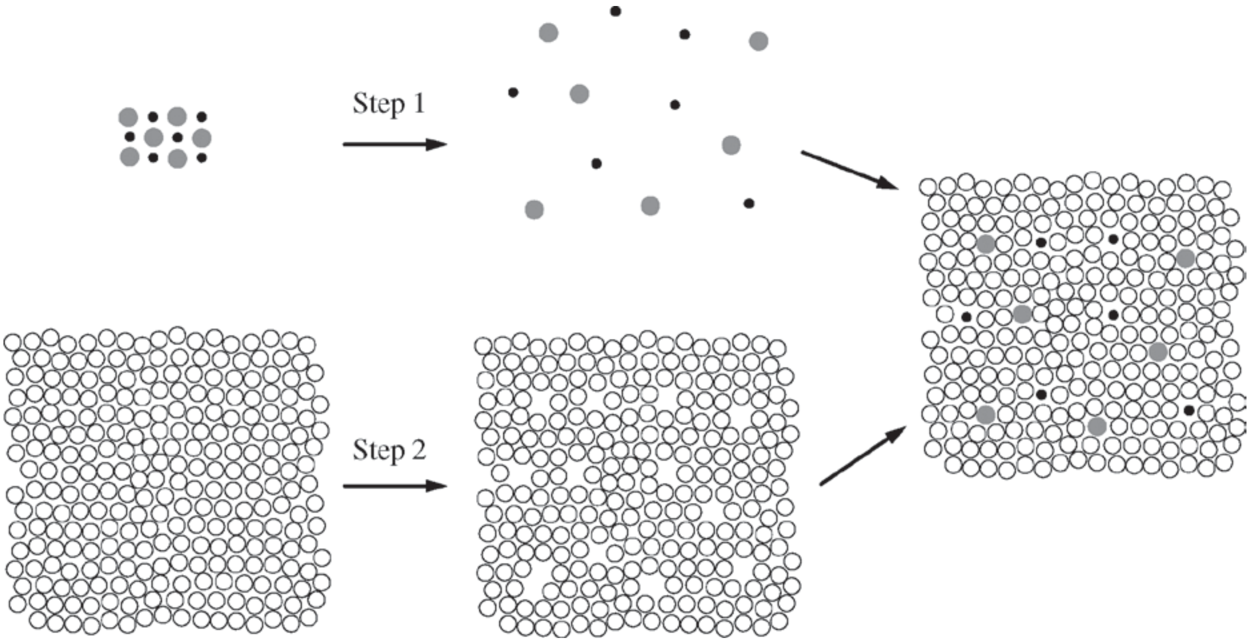


26. The figure above represents three sealed 1.0 L vessels, each containing a different inert gas at 298 K. The pressure of Ar in the first vessel is 2.0 atm. The ratio of the numbers of Ar, Ne, and He atoms in the vessels is 2 : 1 : 6, respectively. After all the gases are combined in a previously evacuated 2.0 L vessel, what is the total pressure of the gases at 298 K?

    (A) 3.0 atm
    (B) 4.5 atm
    (C) 9.0 atm
    (D) 18 atm



27. The dissolution of an ionic solute in a polar solvent can be imagined as occurring in three steps, as shown in the figure above. In step 1, the separation between ions in the solute is greatly increased, just as will occur when the solute dissolves in the polar solvent. In step 2, the polar solvent is expanded to make spaces that the ions will occupy. In the last step, the ions are inserted into the spaces in the polar solvent. Which of the following best describes the enthalpy change, ΔH, for each step?

    (A) All three steps are exothermic.
    (B) All three steps are endothermic.
    (C) Steps 1 and 2 are exothermic, and the final step is endothermic.
    (D) Steps 1 and 2 are endothermic, and the final step is exothermic.

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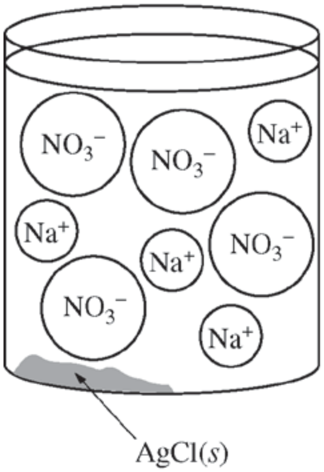
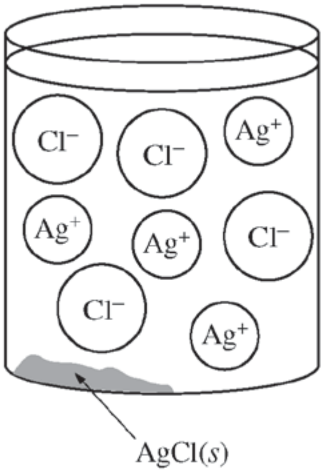
$$Ag^+(aq) + Cl^-(aq) \rightleftarrows AgCl(s)$$

28. A student mixes dilute $AgNO_3(aq)$ with <u>excess</u> $NaCl(aq)$ to form $AgCl(s)$, as represented by the net ionic equation above. Which of the diagrams below best represents the ions that are present in significant concentrations in the solution? (K_{sp} for AgCl is 1.8×10^{-10}.)

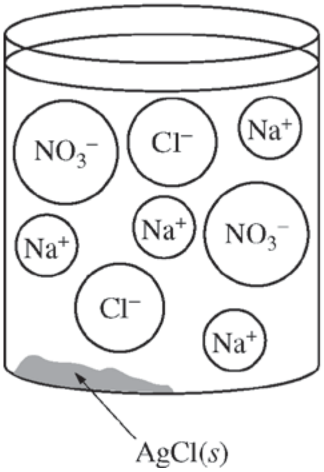
(A)



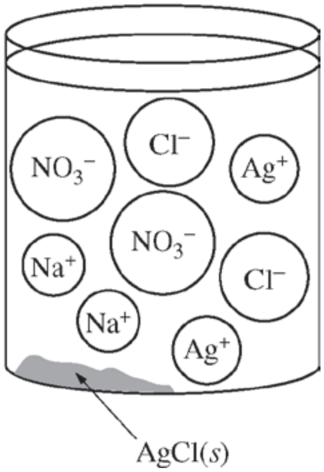
(B)



(C)



(D)



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Questions 29-33 refer to the following.

$$PCl_5(g) \rightleftarrows PCl_3(g) + Cl_2(g)$$

$PCl_5(g)$ decomposes into $PCl_3(g)$ and $Cl_2(g)$ according to the equation above. A pure sample of $PCl_5(g)$ is placed in a rigid, evacuated 1.00 L container. The initial pressure of the $PCl_5(g)$ is 1.00 atm. The temperature is held constant until the $PCl_5(g)$ reaches equilibrium with its decomposition products. The figures below show the initial and equilibrium conditions of the system.

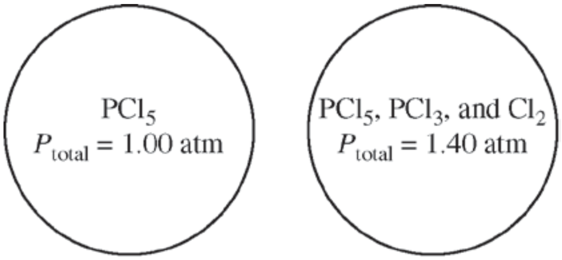

Figure 1: Initial　　Figure 2: Equilibrium

29. Which of the following is the most likely cause for the increase in pressure observed in the container as the reaction reaches equilibrium?

(A) A decrease in the strength of intermolecular attractions among molecules in the flask
(B) An increase in the strength of intermolecular attractions among molecules in the flask
(C) An increase in the number of molecules, which increases the frequency of collisions with the walls of the container
(D) An increase in the speed of the molecules that then collide with the walls of the container with greater force

30. As the reaction progresses toward equilibrium, the rate of the forward reaction

(A) increases until it becomes the same as the reverse reaction rate at equilibrium
(B) stays constant before and after equilibrium is reached
(C) decreases to become a constant nonzero rate at equilibrium
(D) decreases to become zero at equilibrium

31. If the decomposition reaction were to go to completion, the total pressure in the container would be

(A) 1.4 atm
(B) 2.0 atm
(C) 2.8 atm
(D) 3.0 atm

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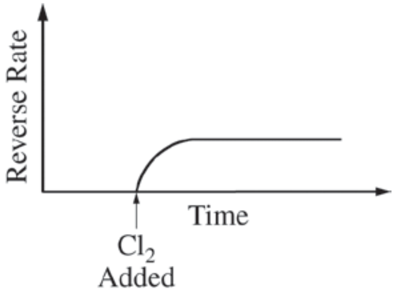
32. Which of the following statements about K_p, the equilibrium constant for the reaction, is correct?

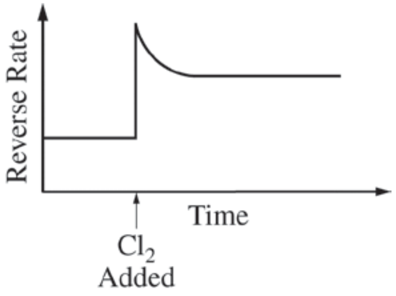
(A) $K_p > 1$
(B) $K_p < 1$
(C) $K_p = 1$
(D) It cannot be determined whether $K_p > 1$, $K_p < 1$, or $K_p = 1$ without additional information.

33. Additional $Cl_2(g)$ is injected into the system at equilibrium. Which of the following graphs best shows the rate of the reverse reaction as a function of time? (Assume that the time for injection and mixing of the additional $Cl_2(g)$ is negligible.)

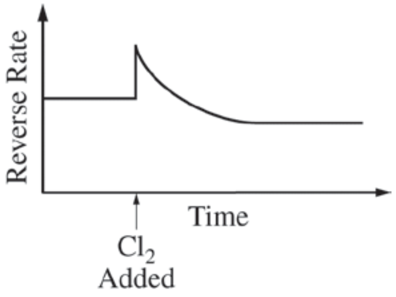
(A)



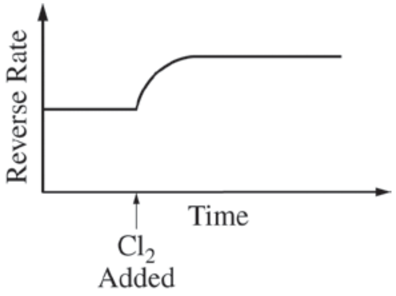
(B)



(C)



(D)



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Questions 34-38

$$K(s) + \frac{1}{2}Cl_2(g) \rightarrow KCl(s) \qquad \Delta H° = -437 \text{ kJ/mol}_{rxn}$$

The elements K and Cl react directly to form the compound KCl according to the equation above. Refer to the information above and the table below to answer the questions that follow.

Process	$\Delta H°$ (kJ/mol$_{rxn}$)
$K(s) \rightarrow K(g)$	v
$K(g) \rightarrow K^+(g) + e^-$	w
$Cl_2(g) \rightarrow 2\,Cl(g)$	x
$Cl(g) + e^- \rightarrow Cl^-(g)$	y
$K^+(g) + Cl^-(g) \rightarrow KCl(s)$	z

34. How much heat is released or absorbed when 0.050 mol of $Cl_2(g)$ is formed from $KCl(s)$?

(A) 87.4 kJ is released
(B) 43.7 kJ is released
(C) 43.7 kJ is absorbed
(D) 87.4 kJ is absorbed

35. What remains in the reaction vessel after equal masses of $K(s)$ and $Cl_2(g)$ have reacted until either one or both of the reactants have been completely consumed?

(A) KCl only
(B) KCl and K only
(C) KCl and Cl_2 only
(D) KCl, K, and Cl_2

36. Which of the values of $\Delta H°$ for a process in the table is (are) less than zero (i.e., indicate(s) an exothermic process) ?

(A) z only
(B) y and z only
(C) x, y, and z only
(D) w, x, y, and z

37. It is observed that the reaction producing KCl from its elements goes essentially to completion. Which of the following is a true statement about the thermodynamic favorability of the reaction?

(A) The reaction is favorable and driven by an enthalpy change only.
(B) The reaction is unfavorable and driven by an entropy change only.
(C) The reaction is favorable and driven by both enthalpy and entropy changes.
(D) The reaction is unfavorable due to both enthalpy and entropy changes.

$$Cl_2(g) + 2\,e^- \rightarrow 2\,Cl^-(g)$$

38. Which of the following expressions is equivalent to $\Delta H°$ for the reaction represented above?

(A) $x + y$

(B) $x - y$

(C) $x + 2y$

(D) $\frac{x}{2} - y$

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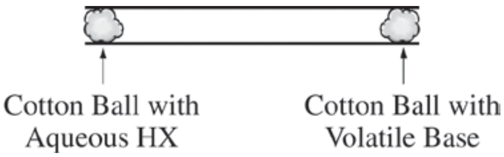

39. The experimental apparatus represented above is used to demonstrate the rates at which gases diffuse. When the cotton balls are placed in the ends of a tube at the same time, the gases diffuse from each end and meet somewhere in between, where they react to form a white solid. Which of the following combinations will produce a solid closest to the center of the tube?

(A) HCl and CH_3NH_2

(B) HCl and NH_3

(C) HBr and CH_3NH_2

(D) HBr and NH_3

40. Silicon crystals are semiconductors. Which of the following is a correct reason for the increase in the conductivity of Si crystals when a small fraction of Si atoms are replaced with those of a different element?

(A) P atoms introduce additional mobile negative charges.
(B) P atoms introduce additional mobile positive charges.
(C) Ge atoms have more electrons than Si atoms have.
(D) Ge atoms are much smaller than Si atoms.

41. N_2 molecules absorb ultraviolet light but not visible light. I_2 molecules absorb both visible and ultraviolet light. Which of the following statements explains the observations?

(A) More energy is required to make N_2 molecules vibrate than is required to make I_2 molecules vibrate.
(B) More energy is required to remove an electron from an I_2 molecule than is required to remove an electron from a N_2 molecule.
(C) Visible light does not produce transitions between electronic energy levels in the N_2 molecule but does produce transitions in the I_2 molecule.
(D) The molecular mass of I_2 is greater than the molecular mass of N_2.

Element	Metallic Radius (pm)	Melting Point (°C)	Common Oxidation State
Au	144	1064	1+, 3+
Cu	128	1085	1+, 2+
Ag	144	961	1+

42. To make Au stronger and harder, it is often alloyed with other metals, such as Cu and Ag. Consider two alloys, one of Au and Cu and one of Au and Ag, each with the same mole fraction of Au. If the Au/Cu alloy is harder than the Au/Ag alloy, then which of the following is the best explanation based on the information in the table above?

(A) Cu has two common oxidation states, but Ag has only one.
(B) Cu has a higher melting point than Au has, but Ag has a lower melting point than Au has.
(C) Cu atoms are smaller than Ag atoms, thus they interfere more with the displacement of atoms in the alloy.
(D) Cu atoms are less polarizable than are Au or Ag atoms, thus Cu has weaker interparticle forces.

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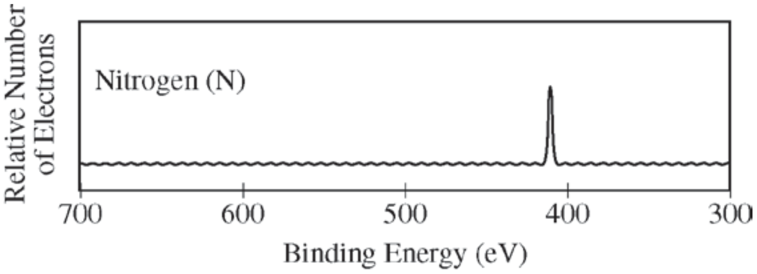
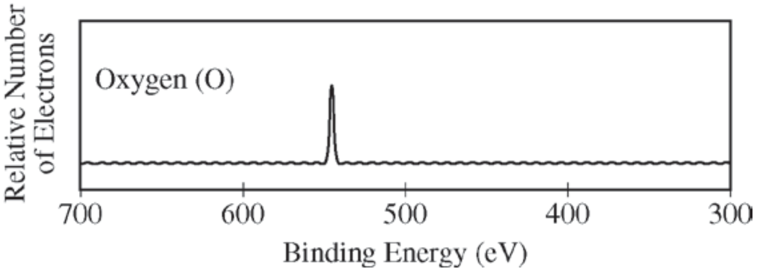
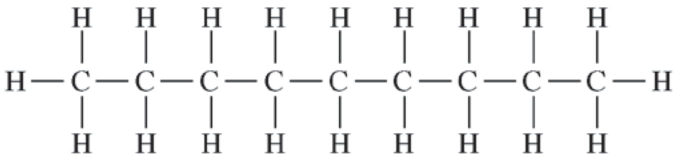


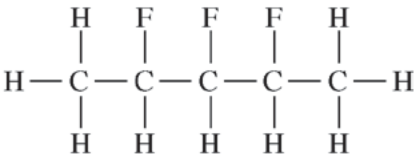


43. The photoelectron spectra above show the energy required to remove a 1*s* electron from a nitrogen atom and from an oxygen atom. Which of the following statements best accounts for the peak in the upper spectrum being to the right of the peak in the lower spectrum?

(A) Nitrogen atoms have a half-filled *p* subshell.
(B) There are more electron-electron repulsions in oxygen atoms than in nitrogen atoms.
(C) Electrons in the *p* subshell of oxygen atoms provide more shielding than electrons in the *p* subshell of nitrogen atoms.
(D) Nitrogen atoms have a smaller nuclear charge than oxygen atoms.



Nonane



2,3,4-trifluoropentane

44. Consider the molecules represented above and the data in the table below.

Compound	Molecular Formula	Molar Mass (g/mol)	Boiling Point (°C)
Nonane	C_9H_{20}	128	151
2,3,4-trifluoropentane	$C_5H_9F_3$	126	89

Nonane and 2,3,4-trifluoropentane have almost identical molar masses, but nonane has a significantly higher boiling point. Which of the following statements best helps explain this observation?

(A) The C−F bond is easier to break than the C−H bond.
(B) The C−F bond is more polar than the C−H bond.
(C) The carbon chains are longer in nonane than they are in 2,3,4-trifluoropentane.
(D) The carbon chains are farther apart in a sample of nonane than they are in 2,3,4-trifluoropentane.

Questions 45-47 refer to galvanic cells made from different combinations of the three half-cells described below.

Half-cell 1: strip of Al(s) in 1.00 M $Al(NO_3)_3(aq)$
Half-cell 2: strip of Cu(s) in 1.00 M $Cu(NO_3)_2(aq)$
Half-cell 3: strip of Fe(s) in 1.00 M $Fe(NO_3)_2(aq)$

Galvanic Cell	Half-cells	Cell Reaction	E°_{cell} (V)
X	1 and 2	$2\ Al(s) + 3\ Cu^{2+}(aq) \rightarrow 2\ Al^{3+}(aq) + 3\ Cu(s)$	2.00
Y	1 and 3	$2\ Al(s) + 3\ Fe^{2+}(aq) \rightarrow 2\ Al^{3+}(aq) + 3\ Fe(s)$	1.22
Z	2 and 3	$Fe(s) + Cu^{2+}(aq) \rightarrow Fe^{2+}(aq) + Cu(s)$	?

45. What is the standard cell potential of galvanic cell Z?

(A) 0.26 V
(B) 0.78 V
(C) 2.34 V
(D) 3.22 V

46. In galvanic cells Y and Z, which of the following takes place in half-cell 3 ?

(A) Reduction occurs in both cell Y and cell Z.
(B) Oxidation occurs in both cell Y and cell Z.
(C) Reduction occurs in cell Y, and oxidation occurs in cell Z.
(D) Oxidation occurs in cell Y, and reduction occurs in cell Z.

47. If the half-cell containing 1.00 M $Fe(NO_3)_2(aq)$ in galvanic cells Y and Z is replaced with a half-cell containing 5.00 M $Fe(NO_3)_2(aq)$, what will be the effect on the cell voltage of the two galvanic cells?

(A) The voltage will increase in both cells.
(B) The voltage will decrease in both cells.
(C) The voltage will increase in cell Y and decrease in cell Z.
(D) The voltage will decrease in cell Y and increase in cell Z.

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Questions 48-52 refer to the following.

Concentration (M)	pH of Acid 1	pH of Acid 2	pH of Acid 3	pH of Acid 4
0.010	3.44	2.00	2.92	2.20
0.050	3.09	1.30	2.58	1.73
0.10	2.94	1.00	2.42	1.55
0.50	2.69	0.30	2.08	1.16
1.00	2.44	0.00	1.92	0.98

The pH of solutions of four acids prepared at various concentrations were measured and recorded in the table above. The four acids are, in no particular order, chlorous, hydrochloric, lactic, and propanoic.

48. For which acid is the value of the acid-dissociation constant, K_a, the smallest?

(A) Acid 1
(B) Acid 2
(C) Acid 3
(D) Acid 4

49. Which of the four acids listed in the table is hydrochloric acid?

(A) Acid 1
(B) Acid 2
(C) Acid 3
(D) Acid 4

50. Of the following species, which has the greatest concentration in a 1.0 M solution of acid 1 at equilibrium?

(A) OH^-
(B) H_3O^+
(C) Acid 1
(D) The conjugate base of acid 1

51. If equal volumes of the four acids at a concentration of 0.50 M are each titrated with a strong base, which will require the greatest volume of base to reach the equivalence point?

(A) Acid 1
(B) Acid 2
(C) Acid 3
(D) All the acids will require the same volume of base to reach the equivalence point.

52. A 25 mL sample of a 1.0 M solution of acid 1 is mixed with 25 mL of 0.50 M NaOH. Which of the following best explains what happens to the pH of the mixture when a few drops of 1.0 M HNO_3 are added?

(A) The pH of the mixture increases sharply, because HNO_3 is a strong acid.
(B) The pH of the mixture decreases sharply, because H_3O^+ ions were added.
(C) The pH of the mixture stays about the same, because the conjugate base of acid 1 reacts with the added H_3O^+ ions.
(D) The pH of the mixture stays about the same, because the OH^- ions in the solution react with the added H_3O^+ ions.

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Step 1: $Cl(g) + O_3(g) \rightarrow ClO(g) + O_2(g)$

Step 2: $ClO(g) + O(g) \rightarrow Cl(g) + O_2(g)$

53. A proposed mechanism for destruction of ozone gas in the stratosphere is represented above. Which of the following is evidence that the mechanism is occurring?

(A) The presence of $Cl(g)$ increases the rate of the overall reaction.

(B) The presence of $Cl(g)$ decreases the rate of the overall reaction.

(C) The presence of $Cl(g)$ increases the equilibrium constant of the overall reaction.

(D) The presence of $Cl(g)$ decreases the equilibrium constant of the overall reaction.

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	NaF	MgO
Boiling Point (°C)	1695	3600

	Na^+	Mg^{2+}	F^-	Cl^-	O^{2-}
Ionic Radius (pm)	76	72	133	181	140

54. Based on the data in the tables above, which of the following statements provides the best prediction for the boiling point of $NaCl$?

    (A) $NaCl$ will have a lower boiling point than NaF because the coulombic attractions are weaker in $NaCl$ than in NaF.

    (B) $NaCl$ will have a boiling point between that of NaF and MgO because the covalent character of the bonds in $NaCl$ is intermediate between that of MgO and NaF.

    (C) $NaCl$ will have a higher boiling point than MgO because the ions are spaced farther apart in $NaCl$.

    (D) $NaCl$ will have a higher boiling point than MgO because the energy required to transfer electrons from the anion to the cation is larger in $NaCl$ than in MgO.

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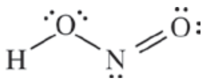
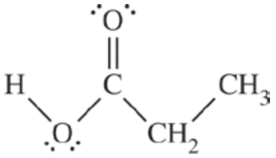
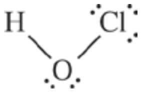
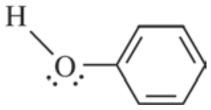
Acid	Structure	K_a
HNO_2		4.0×10^{-4}
$HC_3H_5O_2$		1.3×10^{-5}
HClO		3.0×10^{-8}
HOC_6H_5		1.6×10^{-10}

55. The table above shows the values of K_a for four weak acids. Which of the following pairs of chemical species, when combined in equimolar amounts, results in a buffer with a pH closest to 7.5 ?

(A) HNO_2 and OH^-
(B) $HC_3H_5O_2$ and $C_3H_5O_2^-$
(C) HClO and ClO^-
(D) C_6H_5OH and $C_6H_5O^-$

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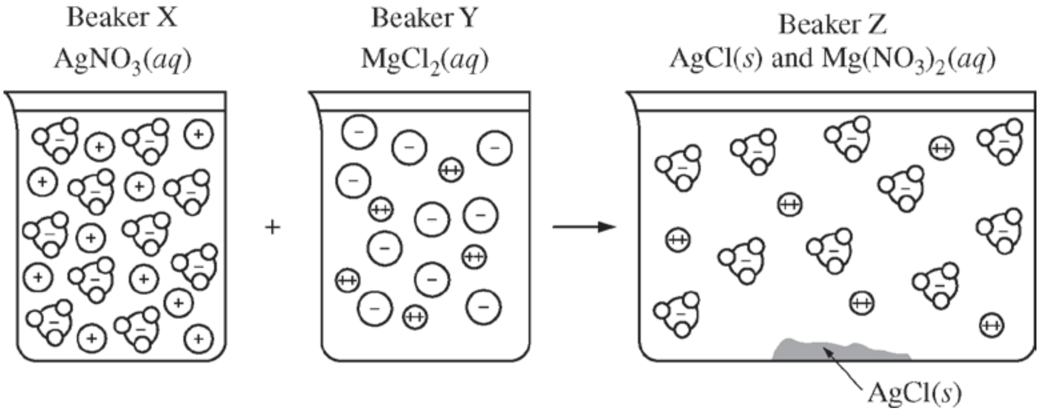

56. Beaker X and beaker Y each contain 1.0 L of solution, as shown above. A student combines the solutions by pouring them into a larger, previously empty beaker Z and observes the formation of a white precipitate. Assuming that volumes are additive, which of the following sets of solutions could be represented by the diagram above?

	Beaker X	Beaker Y	Beaker Z
(A)	2.0 M $AgNO_3$	2.0 M $MgCl_2$	4.0 M $Mg(NO_3)_2$ and $AgCl(s)$
(B)	2.0 M $AgNO_3$	2.0 M $MgCl_2$	2.0 M $Mg(NO_3)_2$ and $AgCl(s)$
(C)	2.0 M $AgNO_3$	1.0 M $MgCl_2$	1.0 M $Mg(NO_3)_2$ and $AgCl(s)$
(D)	2.0 M $AgNO_3$	1.0 M $MgCl_2$	0.50 M $Mg(NO_3)_2$ and $AgCl(s)$

$2\ N_2O_5(g) \rightarrow 4\ NO_2(g) + O_2(g)$

57. A sample of N_2O_5 was placed in an evacuated container, and the reaction represented above occurred. The value of $P_{N_2O_5}$, the partial pressure of $N_2O_5(g)$, was measured during the reaction and recorded in the table below.

Time (min)	$P_{N_2O_5}$ (atm)	$\ln(P_{N_2O_5})$	$\frac{1}{P_{N_2O_5}}$ (atm^{-1})
0	150	5.0	0.0067
100	75	4.3	0.013
200	38	3.6	0.027
300	19	2.9	0.053

Which of the following correctly describes the reaction?

(A) The decomposition of N_2O_5 is a zero-order reaction.
(B) The decomposition of N_2O_5 is a first-order reaction.
(C) The decomposition of N_2O_5 is a second-order reaction.
(D) The overall reaction order is 3.

Element	Atomic Radius	First Ionization Energy
Calcium	194 pm	590 kJ/mol
Potassium	—	—

58. Based on periodic trends and the data in the table above, which of the following are the most probable values of the atomic radius and the first ionization energy for potassium, respectively?

(A) 242 pm, 633 kJ/mol
(B) 242 pm, 419 kJ/mol
(C) 120 pm, 633 kJ/mol
(D) 120 pm, 419 kJ/mol

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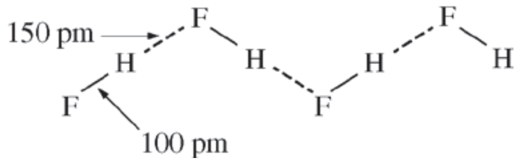


59. The figure above shows that in solid hydrogen fluoride there are two different distances between H atoms and F atoms. Which of the following best accounts for the two different distances?

(A) Accommodation of the necessary bond angles in the formation of the solid
(B) Difference in strength between covalent bonds and intermolecular attractions
(C) Different isotopes of fluorine present in the samples
(D) Uneven repulsions among nonbonding electron pairs

$$COCl_2(g) \rightleftarrows CO(g) + Cl_2(g)$$

60. $COCl_2(g)$ decomposes according to the equation above. When pure $COCl_2(g)$ is injected into a rigid, previously evacuated flask at 690 K, the pressure in the flask is initially 1.0 atm. After the reaction reaches equilibrium at 690 K, the total pressure in the flask is 1.2 atm. What is the value of K_p for the reaction at 690 K?

(A) 0.040
(B) 0.050
(C) 0.80
(D) 1.0

S T O P

IF YOU FINISH BEFORE TIME IS CALLED, YOU MAY CHECK YOUR WORK.

DO NOT TURN TO SECTION II UNTIL YOU ARE TOLD TO DO SO

AP® Chemistry Practice Exam

SECTION II: Free-Response Questions

DO NOT OPEN THIS BOOKLET UNTIL YOU ARE TOLD TO DO SO.

At a Glance

Total Time
90 minutes
Number of Questions
7
Percent of Total Score
50%
Writing Instrument
Either pencil or pen with black or dark blue ink
Electronic Device
Allowed

IMPORTANT Identification Information

PLEASE PRINT WITH PEN:

1. First two letters of your last name ☐☐

   First letter of your first name ☐

2. Date of birth

   ☐☐ ☐☐ ☐☐☐☐
   Month Day Year

3. Six-digit school code

   ☐☐☐☐☐☐

4. Unless I check the box below, I grant the College Board the unlimited right to use, reproduce, and publish my free-response materials, both written and oral, for educational research and instructional purposes. My name and the name of my school will not be used in any way in connection with my free-response materials. I understand that I am free to mark "No" with no effect on my score or its reporting.

   No, I do not grant the College Board these rights. ☐

Instructions

The questions are printed in this booklet. Pages containing a periodic table and lists containing equations and constants are also printed in this booklet.

You may use the pages that the questions are printed on to organize your answers or for scratch work, but you must write your answers in the areas designated for each response.

Write clearly and legibly. Cross out any errors you make; erased or crossed-out work will not be scored. Manage your time carefully. Do not spend too much time on any one question.

NO TEST MATERIAL ON THIS PAGE

CHEMISTRY

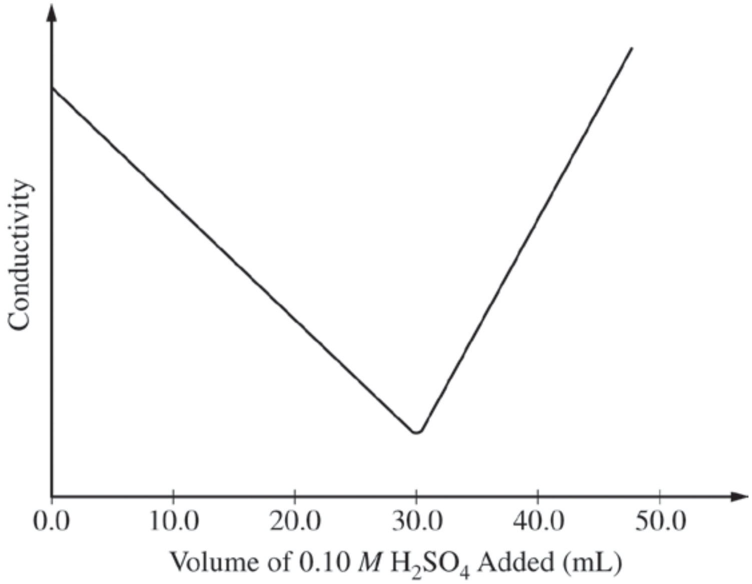
Section II

7 Constructed-Response Questions

(Time—90 minutes)

YOU MAY USE YOUR CALCULATOR FOR SECTION II

Directions: Questions 1, 2, and 3 are long constructed-response questions that should require about 20 minutes each to answer. Questions 4, 5, 6, and 7 are short constructed-response questions that should require about seven minutes each to answer. Read each question carefully and write your response in the space provided following each question. Your responses to these questions will be scored on the basis of the accuracy and relevance of the information cited. Explanations should be clear and well organized. Specific answers are preferable to broad, diffuse responses. For calculations, clearly show the method used and the steps involved in arriving at your answers. It is to your advantage to do this, since you may obtain partial credit if you do and you will receive little or no credit if you do not.



1. A student performs an experiment in which the conductivity of a solution of $Ba(OH)_2$ is monitored as the solution is titrated with 0.10 M H_2SO_4. The original volume of the $Ba(OH)_2$ solution is 25.0 mL. A precipitate of $BaSO_4$ ($K_{sp} = 1.0 \times 10^{-10}$) formed during the titration. The data collected from the experiment are plotted in the graph above.

   (a) As the first 30.0 mL of 0.10 M H_2SO_4 are added to the $Ba(OH)_2$ solution, two types of chemical reactions occur simultaneously. On the lines provided below, write the balanced net-ionic equations for (i) the neutralization reaction and (ii) the precipitation reaction.

   (i) Equation for neutralization reaction: ______________________________

   (ii) Equation for precipitation reaction: ______________________________

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(b) The conductivity of the $Ba(OH)_2$ solution decreases as the volume of added 0.10 *M* H_2SO_4 changes from 0.0 mL to 30.0 mL.

(i) Identify the chemical species that enable the solution to conduct electricity as the first 30.0 mL of 0.10 *M* H_2SO_4 are added.

(ii) On the basis of the equations you wrote in part (a), explain why the conductivity decreases.

(c) Using the information in the graph, calculate the molarity of the original $Ba(OH)_2$ solution.

(d) Calculate the concentration of $Ba^{2+}(aq)$ in the solution at the equivalence point (after exactly 30.0 mL of 0.10 *M* H_2SO_4 are added).

(e) The concentration of $Ba^{2+}(aq)$ in the solution decreases as the volume of added 0.10 *M* H_2SO_4 increases from 30.0 mL to 31.0 mL. Explain.

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ADDITIONAL PAGE FOR ANSWERING QUESTION 1

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ADDITIONAL PAGE FOR ANSWERING QUESTION 1

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2. A student is given the task of determining the enthalpy of reaction for the reaction between HCl(*aq*) and NaOH(*aq*). The following materials are available.

1.00 *M* HCl(*aq*)
2.00 *M* HCl(*aq*)
insulated cups with covers
thermometer (± 0.1°C)
1.00 *M* NaOH(*aq*)
2.00 *M* NaOH(*aq*)
gloves
stirring rod
distilled water
goggles
lab coat

The student may select from the glassware listed in the table below.

Glassware Items	Precision
250 mL Erlenmeyer flasks	± 25 mL
100 mL beakers	± 10 mL
100 mL graduated cylinders	± 0.1 mL

(a) The student selects two 100 mL beakers, uses them to measure 50 mL each of 1.00 *M* HCl(*aq*) solution and 1.00 *M* NaOH(*aq*) solution, and measures an initial temperature of 24.5°C for each solution. Then the student pours the two solutions into an insulated cup, stirs the mixture, covers the cup, and records a maximum temperature of 29.9°C.

(i) Is the experimental design sufficient to determine the enthalpy of reaction to a precision of two significant figures? Justify your answer.

(ii) List two specific changes to the experiment that will allow the student to determine the enthalpy of reaction to a precision of three significant figures. Explain.

(b) A second student is given two solutions, 75.0 mL of 1.00 *M* HCl and 75.0 mL of 1.00 *M* NaOH, each at 25.0°C. The student pours the solutions into an insulated cup, stirs the mixture, covers the cup, and records the maximum temperature of the mixture.

(i) The student calculates the amount of heat evolved in the experiment to be 4.1 kJ. Calculate the student's experimental value for the enthalpy of reaction, in kJ/mol_{rxn}.

(ii) The student assumes that the thermometer and the calorimeter do not absorb energy during the reaction. Does this assumption result in a calculated value of the enthalpy of reaction that is higher than, lower than, or the same as it would have been had the heat capacities of the thermometer and calorimeter been taken into account? Justify your answer.

(iii) One assumption in interpreting the results of the experiment is that the reaction between HCl(*aq*) and NaOH(*aq*) goes to completion. Justify the validity of this assumption in terms of the equilibrium constant for the reaction.

(c) A third student calculates a value for the enthalpy of reaction that is significantly higher than the accepted value.

(i) Identify a specific error in procedure made by the student that will result in a calculated value for the enthalpy of reaction that is higher than the accepted value. (Vague statements like "human error" or "incorrect calculations" will not earn credit.)

(ii) Explain how the error that you identified in part (c)(i) leads to a calculated value for the enthalpy of reaction that is higher than the accepted value.

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ADDITIONAL PAGE FOR ANSWERING QUESTION 2

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ADDITIONAL PAGE FOR ANSWERING QUESTION 2

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ADDITIONAL PAGE FOR ANSWERING QUESTION 2

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$$SO_2Cl_2(g) \rightleftarrows SO_2(g) + Cl_2(g)$$

3. A 4.32 g sample of liquid SO_2Cl_2 is placed in a rigid, evacuated 1.50 L reaction vessel. As the container is heated to 400. K, the sample vaporizes completely and starts to decompose according to the equation above. The decomposition reaction is endothermic.

   (a) If no decomposition occurred, what would be the pressure, in atm, of the $SO_2Cl_2(g)$ in the vessel at 400. K ?

   (b) When the system has reached equilibrium at 400. K, the total pressure in the container is 1.26 atm. Calculate the partial pressures, in atm, of $SO_2Cl_2(g)$, $SO_2(g)$, and $Cl_2(g)$ in the container at 400. K.

   (c) For the decomposition reaction at 400. K,

      (i) write the equilibrium-constant expression for K_p for the reaction, and

      (ii) calculate the value of the equilibrium constant, K_p.

   (d) The temperature of the equilibrium mixture is increased to 425 K. Will the value of K_p increase, decrease, or remain the same? Justify your prediction.

   (e) In another experiment, the original partial pressures of $SO_2Cl_2(g)$, $SO_2(g)$, and $Cl_2(g)$ are 1.0 atm each at 400. K. Predict whether the amount of $SO_2Cl_2(g)$ in the container will increase, decrease, or remain the same. Justify your prediction.

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ADDITIONAL PAGE FOR ANSWERING QUESTION 3

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ADDITIONAL PAGE FOR ANSWERING QUESTION 3

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ADDITIONAL PAGE FOR ANSWERING QUESTION 3

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$$2\ NO_2(g)\ +\ F_2(g)\ \rightarrow\ 2\ NO_2F(g)$$

4. It is proposed that the reaction represented above proceeds via the mechanism represented by the two elementary steps shown below.

Step I: $NO_2 + F_2 \rightarrow NO_2F + F$ (*slow*)

Step II: $NO_2 + F \rightleftarrows NO_2F$ (*fast reversible*)

(a) Step I of the proposed mechanism involves the collision between NO_2 and F_2 molecules. This step is slow even though such collisions occur very frequently in a mixture of $NO_2(g)$ and $F_2(g)$. Consider a specific collision between a molecule of NO_2 and a molecule of F_2.

(i) One factor that affects whether the collision will result in a reaction is the magnitude of the collision energy. Explain.

(ii) Identify and explain one other factor that affects whether the collision will result in a reaction.

(b) Consider the following potential rate laws for the reaction. Circle the rate law below that is consistent with the mechanism proposed above. Explain the reasoning behind your choice in terms of the details of the elementary steps of the mechanism.

rate = $k[NO_2]^2[F_2]$ rate = $k[NO_2][F_2]$

GO ON TO THE NEXT PAGE.

ADDITIONAL PAGE FOR ANSWERING QUESTION 4

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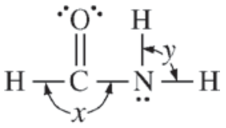
5. Methanamide, CH_3NO, is a liquid at 25°C.

(a) The complete Lewis electron-dot diagram for methanamide is shown below.



(i) In the molecule, angle x is not 180°. Estimate the observed angle. Justify your answer.

(ii) In the molecule, angle y is not 90°. Explain why in terms of electron domains (VSEPR model).

(b) Consider a molecule with the formula CH_2O_2. The structure of this molecule has a geometry around the carbon atom similar to the geometry around carbon in methanamide. In the box provided below, draw the complete Lewis electron-dot diagram for the molecule.

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ADDITIONAL PAGE FOR ANSWERING QUESTION 5

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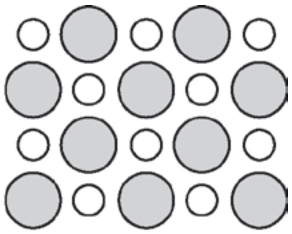
H_2O molecule

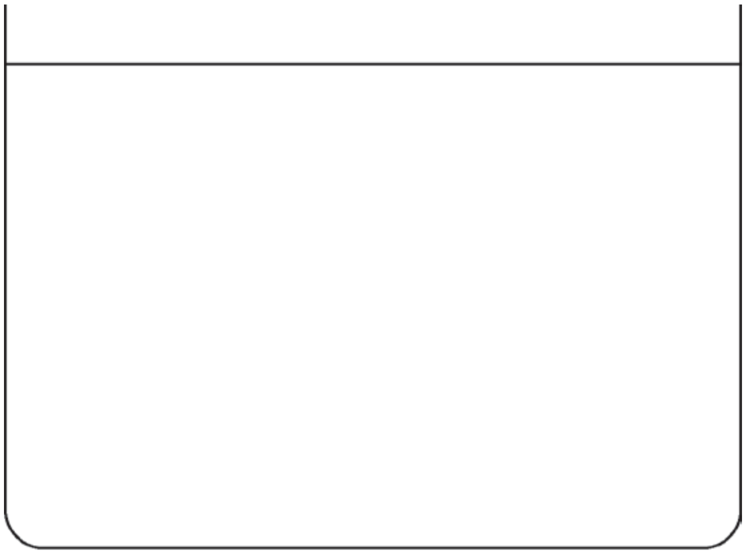


LiCl crystal

6. The structures of a water molecule and a crystal of LiCl(*s*) are represented above. A student prepares a 1.0 *M* solution by dissolving 4.2 g of LiCl(*s*) in enough water to make 100 mL of solution.

(a) In the space provided below, show the interactions of the components of LiCl(*aq*) by making a drawing that represents the different particles present in the solution. Base the particles in your drawing on the particles shown in the representations above. Include only one formula unit of LiCl and no more than ten molecules of water. Your drawing must include the following details.

- identity of ions (symbol and charge)
- the arrangement and proper orientation of the particles in the solution



LiCl (*aq*)

(b) The student passes a direct current through the solution and observes that chlorine gas is produced at the anode. Identify the chemical species produced at the cathode and justify your answer using the information given in the table below.

Half-reaction	Standard Reduction Potential at 25°C (V)
$Li^+(aq) + e^- \rightarrow Li(s)$	– 3.05
$2\,H_2O(l) + 2\,e^- \rightarrow H_2(g) + 2\,OH^-(aq)$	– 0.83

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ADDITIONAL PAGE FOR ANSWERING QUESTION 6

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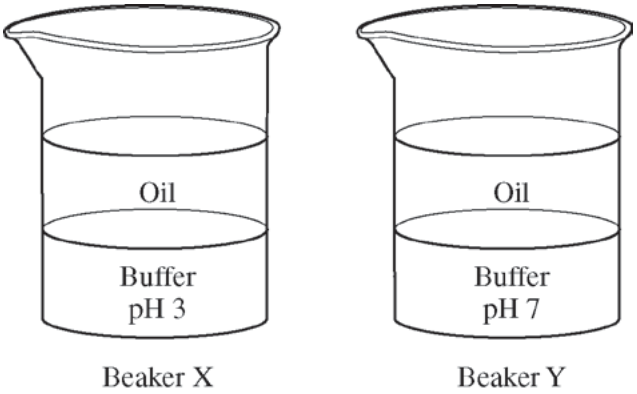
$$\underset{\text{yellow}}{\mathrm{HIn}(aq)} + \mathrm{H_2O}(l) \rightleftarrows \underset{\text{blue}}{\mathrm{In^-}(aq)} + \mathrm{H_3O^+}(aq)$$

7. The indicator HIn is a weak acid with a pK_a value of 5.0. It reacts with water as represented in the equation above. Consider the two beakers below. Each beaker has a layer of colorless oil (a nonpolar solvent) on top of a layer of aqueous buffer solution. In beaker X the pH of the buffer solution is 3, and in beaker Y the pH of the buffer solution is 7. A small amount of HIn is placed in both beakers. The mixtures are stirred well, and the oil and water layers are allowed to separate.



(a) What is the predominant form of HIn in the aqueous buffer in beaker Y, the acid form or the conjugate base form? Explain your reasoning.

(b) In beaker X the oil layer is yellow, whereas in beaker Y the oil layer is colorless. Explain these observations in terms of both acid-base equilibria and interparticle forces.

GO ON TO THE NEXT PAGE.

ADDITIONAL PAGE FOR ANSWERING QUESTION 7

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STOP

END OF EXAM

IF YOU FINISH BEFORE TIME IS CALLED, YOU MAY CHECK YOUR WORK ON SECTION II ONLY.

Notes on the Practice Exam

Introduction

This section provides a description of how the questions in the AP Practice Exam correspond to the components of the curriculum framework included in the *AP Chemistry Course and Exam Description*. For each of the questions in the AP Practice Exam, the targeted learning objectives, essential knowledge, and science practices from the curriculum framework are indicated.

In addition, the multiple-choice and free-response questions include the following features:

- For multiple-choice questions, the correct response is indicated with a justification for why it is correct. There are additional explanations that address why the other responses are incorrect.
- Free-response questions include scoring guidelines as well as descriptions of student responses that would represent "strong, good, and weak" levels. These scoring guidelines demonstrate how the essential knowledge and application of the science practices are assessed in each free-response question.

The AP Chemistry Exam is approximately 3 hours in length. There are two sections, each accounting for 50 percent of the student's exam score.

- Section I is 90 minutes in length and consists of 60 multiple-choice questions.
- Section II is 90 minutes in length and consists of three long free-response questions and four short free-response questions.

Section	Question Type	Number of Questions	Timing
I	Multiple-Choice	60	90 minutes
II	Long Free-Response	3	90 minutes
	Short Free-Response	4	

All of the questions on the exam are designed to measure the student's understanding of the big ideas, enduring understandings, and essential knowledge, and the student's application of this understanding through the science practices.

Multiple-Choice Section

In Section I, there are 60 multiple-choice questions. These questions represent the knowledge and skills students should know, understand, and be able to apply. Students will be given a periodic table and an equations and constants list to use during this section.

Information for Multiple-Choice Questions 1–60

Question 1

Essential Knowledge	1.A.3 The mole is the fundamental unit for counting numbers of particles on the macroscopic level and allows quantitative connections to be drawn between laboratory experiments, which occur at the macroscopic level, and chemical processes, which occur at the atomic level.
Science Practice	7.1 The student can connect phenomena and models across spatial and temporal scales.
Learning Objective	1.4 The student is able to connect the number of particles, moles, mass, and volume of substances to one another, both qualitatively and quantitatively.
(A)	This option is incorrect. The balanced chemical equation is $C_2H_2 + 5/2\ O_2 \rightarrow 2\ CO_2 + H_2O$, so combustion produces CO_2 and H_2O with a mole ratio of 2 to 1.
(B)	This option is incorrect. The balanced chemical equation is $C_2H_6 + 7/2\ O_2 \rightarrow 2\ CO_2 + 3\ H_2O$, so combustion produces CO_2 and H_2O with a mole ratio of 2 to 3.
(C)	**This option is correct. The balanced chemical equation is $C_4H_8 + 6\ O_2 \rightarrow 4\ CO_2 + 4\ H_2O$, so combustion produces CO_2 and H_2O with a mole ratio of 1 to 1, in agreement with the observed equimolar ratio.**
(D)	This option is incorrect. The balanced chemical equation is $C_6H_6 + 15/2\ O_2 \rightarrow 6\ CO_2 + 3\ H_2O$, so combustion produces CO_2 and H_2O with a mole ratio of 2 to 1.

Question 2

Essential Knowledge	2.B.3 Intermolecular forces play a key role in determining the properties of substances, including biological structures and interactions.
Science Practice	6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.
Learning Objective	2.16 The student is able to explain the properties (phase, vapor pressure, viscosity, etc.) of small and large molecular compounds in terms of the strengths and types of intermolecular forces.
(A)	This option is incorrect. As discussed in option C, a high vapor pressure is an indication of weak intermolecular interaction, and this substance does not have the highest vapor pressure.
(B)	This option is incorrect. As discussed in option C, a high vapor pressure is an indication of weak intermolecular interaction, and this substance does not have the highest vapor pressure.
(C)	**This option is correct. Since the transition from liquid to vapor breaks the intermolecular interactions, a high vapor pressure indicates weak interactions between molecules. Based on the data, this substance has the highest vapor pressure and thus the weakest intermolecular interactions.**
(D)	This option is incorrect. As discussed in option C, a high vapor pressure is an indication of weak intermolecular interaction, and this substance does not have the highest vapor pressure.

Question 3

Essential Knowledge	2.B.2 Dipole forces result from the attraction among the positive ends and negative ends of polar molecules. Hydrogen bonding is a strong type of dipole-dipole force when very electronegative atoms (N, O, and F) are involved.
Science Practices	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	2.14 The student is able to apply Coulomb's Law qualitatively (including using representations) to describe the interactions of ions, and the attractions between ions and solvents to explain the factors that contribute to the solubility of ionic compounds.
(A)	**This option is correct. The interaction of ions with water is a Coulombic (specifically ion-dipole) interaction. Since all three ions have the same charge (+2), the strength of the interaction is related to distance, with shorter distances leading to the stronger interactions. The smaller ions therefore have stronger columbic attraction to water, as stated in this option.**
(B)	This option is incorrect. The trend in electronegativity across these ions has no bearing on the interaction between these ions and water. The electronegativity is useful for determining the ionic character and polarity of a bond, which is not of relevance to the interaction of these cations with water.
(C)	This option is incorrect. While Ba^{2+} is the largest ion and so the most polarizable, the interaction with water is dominated by ion-dipole interactions, and polarizability of the ion is not a relevant factor for such interactions.
(D)	This option is incorrect. The trend in electronegativity is not of relevance here, as discussed in option B.

Question 4

Essential Knowledge	1.C.1 Many properties of atoms exhibit periodic trends that are reflective of the periodicity of electronic structure.
Science Practice	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	1.9 The student is able to predict and/or justify trends in atomic properties based on location on the periodic table and/or the shell model.
(A)	**This option is correct. Na has a single valence electron and a low first ionization energy and so can readily lose an electron and reduce other species.**
(B)	This option is incorrect. H^+ has no electrons to transfer to, and thereby reduce, another chemical species. (If the notation H^+ is interpreted as $H_3O^+(aq)$, this option is still incorrect since the hydronium ion is a much weaker reducing agent than Na.)
(C)	This option is incorrect. K^+ has the electronic configuration of Ar, giving it a much higher ionization energy than K. (Equivalently, the second ionization energy of K is much larger in magnitude than the first ionization energy.) The high ionization energy of K^+ makes it a poor choice for reducing other chemical species.
(D)	This option is incorrect. Cl^- has the electronic configuration of Ar, giving it a high ionization energy and making it a poor choice for reducing other chemical species.

Question 5

Essential Knowledge	2.B.2 Dipole forces result from the attraction among the positive ends and negative ends of polar molecules. Hydrogen bonding is a strong type of dipole-dipole force when very electronegative atoms (N, O, and F) are involved.
Science Practice	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Learning Objective	2.13 The student is able to describe the relationships between the structural features of polar molecules and the forces of attraction between the particles.
(A)	This option is incorrect. This interaction is a covalent bond within a water molecule, not a hydrogen bond between water molecules.
(B)	This option is incorrect. This interaction is between oxygens on different water molecules, as opposed to a hydrogen bond.
(C)	This option is incorrect. This interaction is between hydrogens on different water molecules, as opposed to a hydrogen bond.
(D)	**This option is correct. This interaction correctly identifies a hydrogen bond as being between the hydrogen of one water molecule and the oxygen of an adjacent water molecule.**

Question 6

Essential Knowledge	4.A.1 The rate of a reaction is influenced by the concentration or pressure of reactants, the phase of the reactants and products, and environmental factors such as temperature and solvent.
Science Practice	4.2 The student can design a plan for collecting data to answer a particular scientific question.
Learning Objective	4.1 The student is able to design and/or interpret the results of an experiment regarding the factors (i.e., temperature, concentration, surface area) that may influence the rate of a reaction.
(A)	This option is incorrect. The rate of the reaction depends on the concentration of the ethanoic acid and the surface area of the solid $CaCO_3$. Decreasing the volume of ethanoic acid solution will not alter either of these factors and so has no effect on the rate of gas production.
(B)	This option is incorrect. Decreasing the concentration of ethanoic acid solution will decrease the rate of the reaction and thus decrease the rate of gas production.
(C)	This option is incorrect. Decreasing the temperature will decrease the rate of the reaction and thus decrease the rate of gas production.
(D)	**This option is correct. Decreasing the particle size by grinding the $CaCO_3$ into a fine powder will increase the surface area of the $CaCO_3$ and increase the rate of the reaction and the rate of gas production.**

Question 7

Essential Knowledge	6.A.3 When a system is at equilibrium, all macroscopic variables, such as concentrations, partial pressures, and temperature, do not change over time. Equilibrium results from an equality between the rates of the forward and reverse reactions, at which point $Q = K$.
Science Practice	2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objective	6.4 The student can, given a set of initial conditions (concentrations or partial pressures) and the equilibrium constant, K, use the tendency of Q to approach K to predict and justify the prediction as to whether the reaction will proceed toward products or reactants as equilibrium is approached.
(A)	This option is incorrect. As discussed in option B, $Q < K$ and the reaction will proceed in the forward direction, decreasing the amount of H_2 and I_2.
(B)	**This option is correct. Since the container is rigid and has a volume of 1.0 L, the original concentrations of the species are $[H_2] = [I_2] = [HI] = 2.0\ M$. The reaction quotient is therefore $Q = [HI]^2/([H_2][I_2]) = 1$. Since K is 50, $Q < K$ and the reaction proceeds in the forward direction, producing more HI, as stated in this option.**
(C)	This option is incorrect. As the reaction progresses in either direction, the number of moles of gas remains the same. (The reaction has two gas phase particles as both reactants and products.) The pressure will therefore not change as the reaction progresses.
(D)	This option is incorrect. The direction of the net reaction is determined by the relationship between Q and K, not the number of reactant and product molecules in the chemical equation. The system is not at equilibrium because $Q = 1$, which is not equal to 50, the given value of K.

Question 8

Essential Knowledge	5.A.1 Temperature is a measure of the average kinetic energy of atoms and molecules.
Science Practices	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain. 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.
Learning Objective	5.2 The student is able to relate temperature to the motions of particles, either via particulate representations, such as drawings of particles with arrows indicating velocities, and/or via representations of average kinetic energy and distribution of kinetic energies of the particles, such as plots of the Maxwell-Boltzmann distribution.
(A)	This option is incorrect. A decrease in temperature results in a decrease in the average speed of the molecules, as opposed to the increase shown here.
(B)	This option is incorrect. This is the distribution expected for a smaller number of particles at the same temperature as the original sample.
(C)	This option is incorrect. A decrease in temperature results in a decrease in the speed of the molecules, as opposed to the increase shown here.
(D)	**This option is correct. A decrease in temperature results in a decrease in the average speed of the molecules, as shown here.**

Question 9

Essential Knowledge	5.B.3 Chemical systems undergo three main processes that change their energy: heating/cooling, phase transitions, and chemical reactions.
Science Practice	2.3 The student can estimate numerically quantities that describe natural phenomena.
Learning Objective	5.6 The student is able to use calculations or estimations to relate energy changes associated with heating/cooling a substance to the heat capacity, relate energy changes associated with a phase transition to the enthalpy of fusion/vaporization, relate energy changes associated with a chemical reaction to the enthalpy of the reaction, and relate energy changes to $P\Delta V$ work.

(A)	This option is incorrect. The amount of energy lost by the metal equals the amount of energy gained by the water.
(B)	**This option is correct. The amount of energy lost by the metal is equal to the amount of energy gained by the water.**
(C)	This option is incorrect. The observation that the change in temperature of the metal is larger than that of water indicates that the metal has a smaller heat capacity than water.
(D)	This option is incorrect. Energy is transferred from the metal to the water, with the total energy being conserved.

Question 10

Essential Knowledge	1.D.2 An early model of the atom stated that all atoms of an element are identical. Mass spectrometry data demonstrate evidence that contradicts this early model.
Science Practice	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Learning Objective	1.14 The student is able to use data from mass spectrometry to identify the elements and the masses of individual atoms of a specific element.

(A)	This option is incorrect. The data are reported as mass number in amu, for which the charge on the ion is not relevant. (If the horizontal axis is interpreted as mass/charge, this option remains incorrect since the data provides evidence for an isotopic distribution of similarly charged species.)
(B)	This option is incorrect. The abundance in a particular sample does not necessarily reflect the abundance in the universe.
(C)	**This option is correct. The mass spectrum indicates the presence of multiple isotopes in the sample, providing evidence for Te. Furthermore, the graph shows no peak at 127, the mass number of the only stable isotope of I. This shows that there is no I in the sample, and the sample must be pure Te.**
(D)	This option is incorrect. The data provides evidence for an isotopic distribution, which is unrelated to the ionization energies of the elements.

Question 11

Essential Knowledge	3.B.2 In a neutralization reaction, protons are transferred from an acid to a base.
Science Practice	6.1 The student can justify claims with evidence.
Learning Objective	3.7 The student is able to identify compounds as Brønsted-Lowry acids, bases, and/or conjugate acid-base pairs, using proton-transfer reactions to justify the identification.

(A)	This option is incorrect. $H_2C_2O_4$ and $C_2O_4^{2-}$ is not a conjugate acid-base pair since conversion of $H_2C_2O_4$ to $C_2O_4^{2-}$ involves the loss of two hydrogen ions.
(B)	**This option is correct. Since $HC_2O_4^-$ loses one hydrogen ion to form $C_2O_4^{2-}$, these species are a conjugate acid-base pair.**
(C)	This option is incorrect. H_2O and $HC_2O_4^-$ are not related by loss or gain of a single hydrogen ion.
(D)	This option is incorrect. OH^- and H_3O^+ are not related by loss or gain of a single hydrogen ion.

Question 12

Essential Knowledge	5.E.2 Some physical or chemical processes involve both a decrease in the internal energy of the components ($\Delta H° < 0$) under consideration and an increase in the entropy of those components ($\Delta S° > 0$). These processes are necessarily "thermodynamically favored" ($\Delta G° < 0$).
Science Practice	2.3 The student can estimate numerically quantities that describe natural phenomena.
Learning Objective	5.13 The student is able to predict whether or not a physical or chemical process is thermodynamically favored by determination of (either quantitatively or qualitatively) the signs of both $\Delta H°$ and $\Delta S°$, and calculation or estimation of $\Delta G°$ when needed.

(A)	This option is incorrect. $\Delta G = \Delta H - T\,\Delta S$. At low temperature, ΔG is dominated by ΔH, and since $\Delta H < 0$, the reaction is favored. At high temperatures, ΔG is dominated by $-T\,\Delta S$, and since $\Delta S < 0$, the reaction is not favored.
(B)	**This option is correct. $\Delta G = \Delta H - T\,\Delta S$. At low temperature, ΔG is dominated by ΔH, and since $\Delta H > 0$, the reaction is not favored. At high temperatures, ΔG is dominated by $-T\,\Delta S$, and since $\Delta S > 0$, the reaction is favored.**
(C)	This option is incorrect. This reaction is favored at all temperatures, because it is driven by both enthalpy and entropy.
(D)	This option is incorrect. This reaction is not favored at any temperature, because it is not driven by either enthalpy or entropy.

Question 13

Essential Knowledge	1.E.1 Physical and chemical processes can be depicted symbolically; when this is done, the illustration must conserve all atoms of all types.
Science Practice	1.5 The student can re-express key elements of natural phenomena across multiple representations in the domain.
Learning Objective	1.17 The student is able to express the law of conservation of mass quantitatively and qualitatively using symbolic representations and particulate drawings.
(A)	This option is incorrect. Both hydrogen and oxygen are diatomic molecules, unlike the monatomic gases depicted for the reactants. In addition, the number of atoms is not conserved.
(B)	This option is incorrect. Both hydrogen and oxygen are diatomic molecules, unlike the monatomic gases depicted for the reactants.
(C)	**This option is correct. The reactants are shown as diatomic molecules and the number of atoms is conserved (6 oxygen and 12 hydrogen atoms on both the reactant and product side).**
(D)	This option is incorrect. The number of atoms is not conserved (12 oxygen atoms on the reactant side but only 6 oxygen atoms on the product side).

Question 14

Essential Knowledge	6.C.2 The pH is an important characteristic of aqueous solutions that can be controlled with buffers. Comparing pH to pK_a allows one to determine the protonation state of a molecule with a labile proton.
Science Practice	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	6.19 The student can relate the predominant form of a chemical species involving a labile proton (i.e., protonated/deprotonated form of a weak acid) to the pH of a solution and the pK_a associated with the labile proton.
(A)	**This option is correct. Point *R* is in the buffer region, where HA and A^- have the highest concentration of the four species listed as options. At the half-equivalence point, HA and A^- have equal concentrations and pH = pK_a. Point *R* is before the half-equivalence point, with a pH < pK_a, and so HA will have a higher concentration than A^-.**
(B)	This option is incorrect. As discussed for option A, since *R* is before the half-equivalence point, the concentration of A^- will be less than that of HA.
(C)	This option is incorrect. Since the pH at point *R* is about 3.5, the concentration of H_3O^+ is between 10^{-3} and 10^{-4}. Since the equivalence point is at 40 mL, the concentration of both HA and A^- are of the same order of magnitude as the titrant (0.1 *M* NaOH) and so are much larger than H_3O^+.
(D)	This option is incorrect. Since the pH is acidic, OH^- is present with very small concentration.

Question 15

Big Idea	3 Changes in matter involve the rearrangement and/or reorganization of atoms and/or the transfer of electrons.
Science Practice	7.1 The student can connect phenomena and models across spatial and temporal scales.
Learning Objective	3.1 Students can translate among macroscopic observations of change, chemical equations, and particle views.

(A)	This option is incorrect. Point *U* is substantially beyond the equivalence point and so OH^- is present in the solution with substantial concentration.
(B)	**This option is correct. Na^+, OH^-, and A^- ions are all present in large concentration. The ratio of species is also correct, since at point *U*, the concentrations of Na^+, A^-, and OH^- should be approximately 3:2:1.**
(C)	This option is incorrect. Since point *U* is substantially beyond the equivalence point, HA will be present in very small concentration. This is inconsistent with the two HA molecules shown in this option.
(D)	This option is incorrect. Since point *U* is substantially beyond the equivalence point, HA will be present in very small concentration. This is inconsistent with the four HA molecules shown in this option.

Question 16

Essential Knowledge	6.C.1 Chemical equilibrium reasoning can be used to describe the proton-transfer reactions of acid-base chemistry.
Science Practice	5.1 The student can analyze data to identify patterns or relationships.
Learning Objective	6.13 The student can interpret titration data for monoprotic or polyprotic acids involving titration of a weak or strong acid by a strong base (or a weak or strong base by a strong acid) to determine the concentration of the titrant and the pK_a for a weak acid, or the pK_b for a weak base.

(A)	This option is incorrect. At the half-equivalence point, $[HA] = [A^-]$. Point *R* is before the half-equivalence point, and $[HA] > [A^-]$.
(B)	This option is incorrect. Point *S* is the half-equivalence point, at which $[HA] = [A^-]$.
(C)	**This option is correct. At the half-equivalence point, $[HA] = [A^-]$. Since point *T* is after the half-equivalence point but within the buffer region, [HA] and $[A^-]$ will both be present with large concentration with $[A^-] > [HA]$.**
(D)	This option is incorrect. Point *U* is well past the equivalence point, with a pH greater than 12. The concentration of HA will therefore be very small, and much less than half that of A^-.

Question 17

Essential Knowledge	1.E.2 Conservation of atoms makes it possible to compute the masses of substances involved in physical and chemical processes. Chemical processes result in the formation of new substances, and the amount of these depends on the number and the types and masses of elements in the reactants, as well as the efficiency of the transformation.
Science Practice	5.1 The student can analyze data to identify patterns or relationships.
Learning Objective	1.20 The student can design and/or interpret data from an experiment that uses titration to determine the concentration of an analyte in a solution.
(A)	This option is incorrect. The experimental error will be in a direction that increases the estimated concentration of the acid, as discussed in option B.
(B)	**This option is correct. The relation $M_1V_1 = M_2V_2$ at the equivalence point (40.0 mL) gives a concentration of 0.0800 M. If the endpoint of the titration is measured past the actual endpoint, then the moles of base added to reach the endpoint is overestimated and this will lead to an overestimation of the number of moles of acid, and so a calculated concentration that is somewhat larger than the actual concentration.**
(C)	This option is incorrect. An acid concentration of 0.125 M would place the equivalence point at 60.0 mL instead of the observed 40.0 mL.
(D)	This option is incorrect. An acid concentration of 0.125 M would place the equivalence point at 60.0 mL instead of the observed 40.0 mL.

Question 18

Essential Knowledge	5.A.1 Temperature is a measure of the average kinetic energy of atoms and molecules.
Science Practices	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain. 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.
Learning Objective	5.2 The student is able to relate temperature to the motions of particles, either via particulate representations, such as drawings of particles with arrows indicating velocities, and/or via representations of average kinetic energy and distribution of kinetic energies of the particles, such as plots of the Maxwell-Boltzmann distribution.
(A)	This option is incorrect. See option D.
(B)	This option is incorrect. See option D.
(C)	This option is incorrect. See option D.
(D)	**This option is correct. The average kinetic energy is a function only of temperature, and each vessel has the same temperature.**

Question 19

Essential Knowledge		2.A.2 The gaseous state can be effectively modeled with a mathematical equation relating various macroscopic properties. A gas has neither a definite volume nor a definite shape; because the effects of attractive forces are minimal, we usually assume that the particles move independently.
Science Practice		2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objective		2.6 The student can apply mathematical relationships or estimation to determine macroscopic variables for ideal gases.
(A)	This option is incorrect. See the explanation for option B.	
(B)	**This option is correct. Since all three containers are at the same temperature, the number of particles per unit volume is directly proportional to the pressure. The density is the mass per unit volume, so the density is proportional to the product of the pressure and the molar mass. This product is greatest for container B.**	
(C)	This option is incorrect. See the explanation for option B.	
(D)	This option is incorrect. See the explanation for option B.	

Question 20

Essential Knowledge		2.B.1 London dispersion forces are attractive forces present between all atoms and molecules. London dispersion forces are often the strongest net intermolecular force between large molecules.
Science Practice		6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective		2.11 The student is able to explain the trends in properties and/or predict properties of samples consisting of particles with no permanent dipole on the basis of London dispersion forces.
(A)	This option is incorrect. See the explanation for option C.	
(B)	This option is incorrect. See the explanation for option C.	
(C)	**This option is correct. Condensation will occur at the lowest pressure for the gas with the strongest intermolecular interactions. Since all of these gases are nonpolar, the interactions are dominated by London dispersion forces, which are largest for the most polarizable species. Since butane is the largest species, it is the most polarizable.**	
(D)	This option is incorrect. See the explanation for option C.	

Question 21

Essential Knowledge	1.A.2 Chemical analysis provides a method for determining the relative number of atoms in a substance, which can be used to identify the substance or determine its purity.
Science Practices	2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 6.1 The student can justify claims with evidence.
Learning Objective	1.3 The student is able to select and apply mathematical relationships to mass data in order to justify a claim regarding the identity and/or estimated purity of a substance.

(A)	**This option is correct. An impurity that contains no carbon will decrease the mass percent of carbon relative to the pure substance. The mass percent of carbon in the sample is lower than that of pure glucose. So this option is consistent with the observation.**
(B)	This option is incorrect. Ribose has the same empirical formula as glucose (CH_2O) and so has the same mass percent of carbon as glucose. A ribose impurity would therefore have no effect on the measured mass percent of carbon and so cannot account for the low mass percent of carbon in the sample.
(C)	This option is incorrect. Since fructose is an isomer of glucose, it has the same mass percent of carbon as glucose. A fructose impurity would therefore have no effect on the measured mass percent of carbon and so cannot account for the low mass percent of carbon in the sample.
(D)	This option is incorrect. Sucrose has a higher mass percent of carbon than glucose. This can be seen by comparing the number of atoms in two glucose molecules, which is equivalent to $C_{12}H_{24}O_{12}$, to that in one sucrose molecule, $C_{12}H_{22}O_{11}$. Since sucrose has more carbon, relative to hydrogen and oxygen, a sucrose impurity would raise the mass percent of carbon in the sample. This is opposite to the experimentally observed effect.

Question 22

Essential Knowledge	6.C.1 Chemical equilibrium reasoning can be used to describe the proton-transfer reactions of acid-base chemistry.
Science Practices	2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	6.16 The student can identify a given solution as being the solution of a monoprotic weak acid or base (including salts in which one ion is a weak acid or base) and calculate the pH and concentration of all species in the solution and/or infer the relative strengths of the weak acids or bases from given equilibrium concentrations.
(A)	This option is incorrect. A weak base solution will have a basic pH. The pH range of 2-3 corresponds to an acidic solution.
(B)	This option is incorrect. A weak base solution will have a basic pH. The pH range of 5-6 corresponds to an acidic solution.
(C)	This option is incorrect. See option D for an estimation of the pH.
(D)	**This option is correct. The equilibrium expression for a weak base, B, is $K_b = \frac{[HB^+][OH^-]}{[B]}$. Here [B] = 0.01 *M*, $K_b = 4 \times 10^{-4}$ and $[HB^+] = [OH^-]$.** **Therefore $[OH^-] = \sqrt{K_b \times 0.01}$.** **This corresponds to $\sqrt{4 \times 10^{-6}}$ or 2×10^{-3}. The pOH is therefore somewhat less than 3, making the pH somewhat larger than 11. The pH therefore lies within the range of this option, pH = 11-12.**

Question 23

Essential Knowledge	2.C.4 The localized electron bonding model describes and predicts molecular geometry using Lewis diagrams and the VSEPR model.
Science Practice	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Learning Objective	2.21 The student is able to use Lewis diagrams and VSEPR to predict the geometry of molecules, identify hybridization, and make predictions about polarity.
(A)	This option is incorrect. Although the molecular formulas are similar, the geometries are not similar and the differences in geometry lead to substantial differences in polarity.
(B)	This option is incorrect. Although C and S do have similar electronegativities, this implies only that the bond dipoles are similar in the two molecules. The differences in geometry cause the bond dipoles to cancel in CO_2 but not SO_2, leading to substantially different net dipoles for the molecules and substantial differences in polarity.
(C)	This option is incorrect. The lone pair on the sulfur is an important difference between these molecules. However, the most important effect of this lone pair is its influence on the molecular geometry, which causes SO_2 to be a bent molecule.
(D)	**This option is correct. Both the C-O and S-O bonds are polar, due to the different electronegativities of the bonded atoms. However, the CO_2 molecule is linear and so the bond dipoles cancel and the molecule has no net dipole. In SO_2, the molecule is bent and so the bond dipoles do not cancel and a net dipole is present. The polarity of the two substances differs because of the differences in geometry, which is a direct consequence of the number of electron domains around the central atom (2 in CO_2 and 3 in SO_2), as stated in this option.**

Question 24

Enduring Understanding	4.C Many reactions proceed via a series of elementary reactions.
Science Practice	6.5 The student can evaluate alternative scientific explanations.
Learning Objective	4.7 The student is able to evaluate alternative explanations, as expressed by reaction mechanisms, to determine which are consistent with data regarding the overall rate of a reaction, and data that can be used to infer the presence of a reaction intermediate.

(A)	This option is incorrect. A unimolecular reaction is one involving a single reactant molecule. The first step of this mechanism corresponds to a collision between two NO molecules, making it a bimolecular reaction.
(B)	This option is incorrect. The fast and reversible character of the first step in the mechanism will establish an equilibrium. Increasing the concentration of NO will shift this equilibrium to the product side, increasing the concentration of the N_2O_2 intermediate. This increase in N_2O_2 will lead to an increase in the rate of the second step of the mechanism and so increase the overall rate of the reaction.
(C)	This option is incorrect. The rate constant for this reaction depends on temperature. In particular, the slow character of the second step in the reaction mechanism implies a substantial activation energy.
(D)	**This option is correct. The fast and reversible character of the first step in the mechanism will establish an equilibrium in which the concentration of the intermediate N_2O_2 is directly proportional to $[NO_2]^2$. The overall rate of the reaction is given by the second step, for which the rate is proportional to the product $[N_2O_2][O_2]$. Since $[N_2O_2\ ]$ is directly proportional to $[NO_2]^2$ from step 1, substitution yields an overall reaction rate law of rate = $k\,[NO_2]^2[O_2]$, as stated in this option.**

Question 25

Essential Knowledge	2.B.3 Intermolecular forces play a key role in determining the properties of substances, including biological structures and interactions.
Science Practice	6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.
Learning Objective	2.16 The student is able to explain the properties (phase, vapor pressure, viscosity, etc.) of small and large molecular compounds in terms of the strengths and types of intermolecular forces.

(A)	This option is incorrect. Both Br_2 and I_2 form molecular solids.
(B)	This option is incorrect. The boiling point is established by the strength of the intermolecular forces. The covalent bonds remain intact on boiling and so their strength does not influence the boiling points.
(C)	**This option is correct. Since both Br_2 and I_2 are nonpolar, London dispersion forces establish the boiling points. The larger electron cloud in I_2 gives it a greater polarizability and therefore stronger London dispersion forces. The higher boiling point of I_2 is therefore due to the greater polarizability of I_2, as stated in this option.**
(D)	This option is incorrect. The bond polarity is related to the difference in electronegativity of the bonded atoms. Here, the bonds are between identical elements and so the bonds are nonpolar.

Question 26

Essential Knowledge	2.A.2 The gaseous state can be effectively modeled with a mathematical equation relating various macroscopic properties. A gas has neither a definite volume nor a definite shape; because the effects of attractive forces are minimal, we usually assume that the particles move independently.
Science Practices	1.3 The student can refine representations and models of natural or man-made phenomena and systems in the domain. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.
Learning Objective	2.5 The student is able to refine multiple representations of a sample of matter in the gas phase to accurately represent the effect of changes in macroscopic properties on the sample.

(A)	This option is incorrect. The correct pressure is 4.5 atm, as described below for option B.
(B)	**This option is correct. Since the volume of the three original containers are equal, the pressures are proportional to the number of atoms in the containers, which are in the ratio of 2:1:6. The pressure in the first container is given as 2 atm, therefore the pressures in the three containers are 2 atm, 1 atm, and 6 atm, respectively. If these were combined into a single container with a volume equal to that of the original vessels (1 liter), the total pressure would be the sum of these partial pressures, corresponding to 9 atm. The final container has a volume of 2 liters, which lowers the pressure by a factor of 2, to 4.5 atm.**
(C)	This option is incorrect. This option would be correct if the gases were combined in a 1-liter container, as opposed to the 2-liter container stated in the problem.
(D)	This option is incorrect. This option is obtained if one mistakenly assumes that doubling the size of the final container from 1 to 2 liters doubles the pressure as opposed to cutting it in half.

Question 27

Essential Knowledge	5.C.2 The net energy change during a reaction is the sum of the energy required to break the bonds in the reactant molecules and the energy released in forming the bonds of the product molecules. The net change in energy may be positive for endothermic reactions where energy is required, or negative for exothermic reactions where energy is released.
Science Practices	2.3 The student can estimate numerically quantities that describe natural phenomena. 7.1 The student can connect phenomena and models across spatial and temporal scales. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.
Learning Objective	5.8 The student is able to draw qualitative and quantitative connections between the reaction enthalpy and the energies involved in the breaking and formation of chemical bonds.

(A)	This option is incorrect. Steps 1 and 2 break favorable intermolecular interactions and so are both endothermic.
(B)	This option is incorrect. The final step establishes favorable intermolecular interactions between solute and solvent and so is exothermic.
(C)	This option is incorrect. This option corresponds to the opposite of the correct response, as explained in option D below.
(D)	**This option is correct. In steps 1 and 2, favorable intermolecular interactions are broken and this increases the enthalpy, corresponding to an endothermic process. In step 3, favorable intermolecular interactions are established, which decreases the enthalpy, corresponding to an exothermic process. (The sign of the enthalpy change for the overall process is established by the difference in magnitude between these enthalpy changes, and so the overall process can be either endothermic or exothermic.)**

Question 28

Big Idea	3 Changes in matter involve the rearrangement and/or reorganization of atoms and/or the transfer of electrons.
Science Practices	1.5 The student can re-express key elements of natural phenomena across multiple representations in the domain. 7.1 The student can connect phenomena and models across spatial and temporal scales.
Learning Objective	3.1 Students can translate among macroscopic observations of change, chemical equations, and particle views.
(A)	This option is incorrect. The solution corresponds to AgCl solid with $NaNO_3$ in solution. Since excess NaCl was added, the drawing should show Na^+ and Cl^- in solution.
(B)	This option is incorrect. There should be Na^+ and NO_3^- ions in solution. In addition, since K_{sp} is small, the concentration of Ag^+ should be very low, and far below that of Na^+ and NO_3^-.
(C)	**This option is correct. The addition of excess NaCl will cause there to be additional Na^+ and Cl^- ions in the solution, along with NO_3^- ions remaining from the original $AgNO_3$ solution. Due to the low K_{sp}, almost all of the Ag^+ ions have precipitated from solution.**
(D)	This option is incorrect. Since K_{sp} is very small, the concentration of Ag^+ should be very low, and far below that of Na^+ and NO_3^-. In this drawing, Ag^+ has a concentration equal to that of Na^+ and NO_3^-.

Question 29

Essential Knowledge	2.A.2 The gaseous state can be effectively modeled with a mathematical equation relating various macroscopic properties. A gas has neither a definite volume nor a definite shape; because the effects of attractive forces are minimal, we usually assume that the particles move independently.
Science Practices	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	2.4 The student is able to use KMT and concepts of intermolecular forces to make predictions about the macroscopic properties of gases, including both ideal and nonideal behaviors.
(A)	This option is incorrect. The principal effect on the pressure is a change in the number of particles in the vessel, not the strength of their interactions.
(B)	This option is incorrect. The principal effect on the pressure is a change in the number of particles in the vessel, not the strength of their interactions. In addition, an increase in intermolecular attractions would serve to decrease the pressure, unlike the observed increase in pressure.
(C)	**This option is correct. The number of particles in the vessel increases as the system reaches equilibrium. This increases the frequency of collisions with the walls and thus increases the pressure, as stated in this option.**
(D)	This option is incorrect. The speed of the particles influences pressure only via the temperature, and since the reaction is carried out at constant temperature, the only relevant variable regarding pressure is the number of particles in the container.

Question 30

Essential Knowledge	6.A.3 When a system is at equilibrium, all macroscopic variables, such as concentrations, partial pressures, and temperature, do not change over time. Equilibrium results from an equality between the rates of the forward and reverse reactions, at which point $Q = K$.
Science Practice	7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.
Learning Objective	6.3 The student can connect kinetics to equilibrium by using reasoning about equilibrium, such as Le Chatelier's principle, to infer the relative rates of the forward and reverse reactions.
(A)	This option is incorrect. Since the concentration of reactant species decreases as the reaction progresses, the rate of the forward reaction decreases.
(B)	This option is incorrect. Since the concentration of reactant species decreases as the reaction progresses, the rate of the forward reaction changes.
(C)	**This option is correct. As the reaction reaches equilibrium, the rate of the forward reaction decreases and the rate of the reverse reaction increases. Equilibrium is reached when the forward and reverse rates are equal. The statement in this option, that the forward rate decreases to a constant value, is therefore correct.**
(D)	This option is incorrect. The rate of the forward reaction decreases as the reaction progresses; however, equilibrium is established when the forward and reverse reaction rates are equal. The rate of the forward reaction therefore reaches a steady nonzero value, not zero as stated in this option.

Question 31

Essential Knowledge	3.A.2 Quantitative information can be derived from stoichiometric calculations that utilize the mole ratios from the balanced chemical equations. The role of stoichiometry in real-world applications is important to note so that it does not seem to be simply an exercise done only by chemists.
Science Practice	2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objective	3.3 The student is able to use stoichiometric calculations to predict the results of performing a reaction in the laboratory and/or to analyze deviations from the expected results.
(A)	This option is incorrect. If the system is allowed to reach equilibrium, the pressure is 1.40 atm, as indicated in the stimulus to the question. This question specifically asks for the reaction going to completion.
(B)	**This option is correct. It demonstrates recognition of the stoichiometry of the provided reaction and application of mole ratios (1 mole of reactant decomposing to produce 2 moles of product) to determine the total pressure of the system, should it go to completion.**
(C)	This option is incorrect. This answer can be achieved by doubling the equilibrium pressure, which demonstrates confusion on what the equilibrium pressure represents in relation to the stoichiometry of the reaction.
(D)	This option is incorrect. This answer can be achieved by forgetting that the partial pressure of the reactant is equal to zero if the reaction goes to completion.

Question 32

Essential Knowledge	6.A.3 When a system is at equilibrium, all macroscopic variables, such as concentrations, partial pressures, and temperature, do not change over time. Equilibrium results from an equality between the rates of the forward and reverse reactions, at which point $Q = K$.
Science Practice	2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objective	6.5 The student can, given data (tabular, graphical, etc.) from which the state of a system at equilibrium can be obtained, calculate the equilibrium constant, K.
(A)	This option is incorrect. K_p is not greater than 1 based on the equilibrium pressure of the system provided in the stimulus.
(B)	**This option is correct. It demonstrates the ability to use an ICE chart or a K_p expression to determine the amount of change needed to reach equilibrium conditions: the pressure of the reactant drops by 0.40 atm and the products increase by 0.40 atm each, giving a total pressure of 1.40 atm.** $K_p = \frac{(0.40\text{ atm})^2}{(0.60\text{ atm})} < 1$
(C)	This option is incorrect. Each of the partial pressures of the products at equilibrium would have to be exactly equal to the square root of the equilibrium pressure of the reactant to achieve a K of 1.
(D)	This option is incorrect. Enough information is provided in the problem to calculate a value of K_p and compare its magnitude to 1.

Question 33

Essential Knowledge	6.A.3 When a system is at equilibrium, all macroscopic variables, such as concentrations, partial pressures, and temperature, do not change over time. Equilibrium results from an equality between the rates of the forward and reverse reactions, at which point $Q = K$.
Science Practice	7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.
Learning Objective	6.3 The student can connect kinetics to equilibrium by using reasoning about equilibrium, such as Le Chatelier's principle, to infer the relative rates of the forward and reverse reactions.
(A)	This option is incorrect. The rate of the reverse reaction would increase, but the rate would not be zero at equilibrium.
(B)	**This option is correct. It demonstrates recognition that the rate of the reverse reaction would rapidly increase upon the injection of more Cl_2 because a greater concentration of reactant (Cl_2 in this case) means an increase in the reaction rate. It also demonstrates understanding that as more Cl_2 is consumed and the system returns to equal forward and reverse reaction rates (i.e., equilibrium), the reverse rate will decrease and reach a new non-zero value that is higher than the original value.**
(C)	This option is incorrect. While increasing the concentration of Cl_2 will increase the reaction rate initially, it would not be possible for the reverse rate to be less than it was in the initial equilibrium, given the greater concentration of Cl_2.
(D)	This option is incorrect. Increasing the concentration of Cl_2 would increase the reaction rate, but it would not do so slowly if the time for injection and mixing is negligible, as the question states; as Cl_2 is consumed by the reverse reaction, the rate should drop some, not only increase.

Question 34

Essential Knowledge	5.B.3 Chemical systems undergo three main processes that change their energy: heating/cooling, phase transitions, and chemical reactions.
Science Practices	2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 2.3 The student can estimate numerically quantities that describe natural phenomena.
Learning Objective	5.6 The student is able to use calculations or estimations to relate energy changes associated with heating/cooling a substance to the heat capacity, relate energy changes associated with a phase transition to the enthalpy of fusion/vaporization, relate energy changes associated with a chemical reaction to the enthalpy of the reaction, and relate energy changes to $P\Delta V$ work.
(A)	This option is incorrect. Reversing the exothermic process described in the stimulus reverses the direction of energy flow. Also, the stoichiometry of the reaction indicates that the energy value in the equation is for a half mole of Cl_2, not a full mole of Cl_2.
(B)	This option is incorrect. Reversing the exothermic process described in the stimulus reverses the direction of energy flow.
(C)	**This option is correct. It demonstrates understanding of the magnitude of the energy change based on the stoichiometry of the reaction and the correct direction of the energy transfer based on reversing the reaction.**
(D)	This option is incorrect. It correctly predicts the direction of the energy flow, but it does not correctly reflect the stoichiometry of the reaction.

Question 35

Essential Knowledge	3.A.2 Quantitative information can be derived from stoichiometric calculations that utilize the mole ratios from the balanced chemical equations. The role of stoichiometry in real-world applications is important to note so that it does not seem to be simply an exercise done only by chemists.
Science Practice	2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objective	3.4 The student is able to relate quantities (measured mass of substances, volumes of solutions, or volumes and pressures of gases) to identify stoichiometric relationships for a reaction, including situations involving limiting reactants and situations in which the reaction has not gone to completion.
(A)	This option is incorrect. Equal masses of K and Cl_2 do not have a 1:1/2 mole ratio, as required by the balanced chemical equation provided in the stimulus.
(B)	This option is incorrect. Since the molar mass of K is more than half that of Cl_2, there are fewer than twice the moles of K than Cl_2, so K cannot be the limiting reactant.
(C)	**This option is correct. It demonstrates correct calculation or recognition of the limiting reactant in the setup, based on moles of each reactant and the stoichiometry of the reaction and that the product of the reaction will also be present at the reaction conclusion.**
(D)	This option is incorrect. The reaction proceeds until one or both of the reactants have been completely consumed, so both reactants cannot remain in the reaction vessel upon reaction completion.

Question 36

Essential Knowledge	5.C.2 The net energy change during a reaction is the sum of the energy required to break the bonds in the reactant molecules and the energy released in forming the bonds of the product molecules. The net change in energy may be positive for endothermic reactions where energy is required, or negative for exothermic reactions where energy is released.
Science Practice	2.3 The student can estimate numerically quantities that describe natural phenomena.
Learning Objective	5.8 The student is able to draw qualitative and quantitative connections between the reaction enthalpy and the energies involved in the breaking and formation of chemical bonds.

(A)	This option is incorrect. The formation of an ionic bond releases energy, but adding an electron to a gaseous halogen atom also releases energy.
(B)	**This option is correct. It demonstrates understanding of the exothermic processes listed in the stimulus that are a result of bond formation and Coulombic attractions: the electron affinity of Cl(*g*) and the ionic-bond formation between K^+(*g*) and Cl^-(*g*), both of which can be estimated to have a negative enthalpy value.**
(C)	This option is incorrect. Bond breaking always requires energy; it is not an exothermic process.
(D)	This option is incorrect. Both ionization of a K atom and breaking a Cl-Cl bond require the addition of energy and so are endothermic processes.

Question 37

Essential Knowledge	5.E.2 Some physical or chemical processes involve both a decrease in the internal energy of the components ($\Delta H° < 0$) under consideration and an increase in the entropy of those components ($\Delta S° > 0$). These processes are necessarily "thermodynamically favored" ($\Delta G° < 0$).
Science Practice	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	5.13 The student is able to predict whether or not a physical or chemical process is thermodynamically favored by determination of (either quantitatively or qualitatively) the signs of both $\Delta H°$ and $\Delta S°$, and calculation or estimation of $\Delta G°$ when needed.

(A)	**This option is correct. It predicts correctly that the sign of the free energy change would be negative (thermodynamically favorable since it goes to completion) and driven by an enthalpy change, since the overall reaction listed in the stimulus is exothermic. The reaction is not driven by an entropy change because the entropy of the system decreases as reactants convert to products.**
(B)	This option is incorrect. The reaction is observed to go to completion (so is favorable), and the entropy of the system decreases; the entropy change does not drive the reaction.
(C)	This option is incorrect. The reaction is thermodynamically favorable, but the entropy change is not a factor driving the reaction toward the products.
(D)	This option is incorrect. The reaction is favorable and driven only by the enthalpy change.

Question 38

Essential Knowledge	5.C.2 The net energy change during a reaction is the sum of the energy required to break the bonds in the reactant molecules and the energy released in forming the bonds of the product molecules. The net change in energy may be positive for endothermic reactions where energy is required, or negative for exothermic reactions where energy is released.
Science Practice	7.1 The student can connect phenomena and models across spatial and temporal scales.
Learning Objective	5.8 The student is able to draw qualitative and quantitative connections between the reaction enthalpy and the energies involved in the breaking and formation of chemical bonds.

(A)	This option is incorrect. Two atoms (or two moles of atoms) of chlorine are each gaining one electron (or one mole of electrons), requiring a coefficient of 2 in front of the y term.
(B)	This option is incorrect. It does not account for two atoms of chlorine gaining electrons.
(C)	**This option is correct. It correctly tracks the ionization of diatomic chlorine, which requires both the endothermic breaking of the Cl-Cl covalent bond and the exothermic electron affinity of the separated chlorine atoms (of which there are two, yielding the coefficient on the y term). The negative sign is not required for the y term because the addition of an electron to a chlorine atom is exothermic, already implying a negative sign by convention.**
(D)	This option is incorrect. The question asks specifically about ionizing one mole of diatomic chlorine molecules, not one-half of a mole.

Question 39

Essential Knowledge	2.A.2 The gaseous state can be effectively modeled with a mathematical equation relating various macroscopic properties. A gas has neither a definite volume nor a definite shape; because the effects of attractive forces are minimal, we usually assume that the particles move independently.
Science Practices	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	2.4 The student is able to use KMT and concepts of intermolecular forces to make predictions about the macroscopic properties of gases, including both ideal and nonideal behaviors.
(A)	**This option is correct. It demonstrates understanding that gases with similar molar masses (HCl = 36 g/mol and CH_3NH_2 = 31 g/mol) at the same temperature will travel with similar average speeds, resulting in a solid being formed at roughly equal distances from each cotton ball.**
(B)	This option is incorrect. The molar mass of NH_3 is less than half of the molar mass of HCl, meaning NH_3 molecules will travel with greater average speed, and the solid will form closer to the cotton ball on the left.
(C)	This option is incorrect. The molar mass of HBr is more than double that of CH_3NH_3, which would result in a solid closer to the cotton ball on the left.
(D)	This option is incorrect. The molar mass of HBr is almost five times as large as that of NH_3, which would result in the least centered solid of any of the choices, residing far on the left side of the tube.

Question 40

Essential Knowledge	1.C.1 Many properties of atoms exhibit periodic trends that are reflective of the periodicity of electronic structure.
Science Practice	3.1 The student can pose scientific questions.
Learning Objective	1.11 The student can analyze data, based on periodicity and the properties of binary compounds, to identify patterns and generate hypotheses related to the molecular design of compounds for which data are not supplied.
(A)	**This option is correct. It recognizes that phosphorus atoms contain one additional valence electron over the silicon atoms that make up the bulk of the material, and that these additional mobile charges will increase the conductivity of the silicon material.**
(B)	This option is incorrect. While phosphorus does have additional protons, the particles in the nucleus are bound and are not able to move throughout the material like electrons can.
(C)	This option is incorrect. While germanium atoms do have more electrons than silicon atoms, the number of valence electrons is the same as in silicon, and it will not improve the conductivity of the material anywhere nearly as effectively as adding an impurity with a different valence electron count.
(D)	This option is incorrect. Germanium atoms have an additional electron shell, and they are therefore larger than silicon atoms, not smaller.

Question 41

Essential Knowledge	1.D.3 The interaction of electromagnetic waves or light with matter is a powerful means to probe the structure of atoms and molecules, and to measure their concentration.
Science Practice	4.1 The student can justify the selection of the kind of data needed to answer a particular scientific question.
Learning Objective	1.15 The student can justify the selection of a particular type of spectroscopy to measure properties associated with vibrational or electronic motions of molecules.
(A)	This option is incorrect. Infrared light, not UV and visible, is matched to the vibrational states of chemical bonds in molecules.
(B)	This option is incorrect. While electromagnetic radiation can be used to remove an electron from atoms and molecules, the energy of visible and UV light is insufficient to overcome both the bond energy and ionization energy.
(C)	**This option is correct. It correctly justifies the observations about the molecules by recognizing that visible light and ultraviolet light can promote electrons to higher energy levels in atoms and molecules. Ultraviolet light is more energetic than visible light, so there must be some lower energy electronic transitions available in I_2 molecules that are not present in N_2 molecules; visible light would be a useful tool for differentiating I_2 from N_2 (which is exhibited by iodine vapor having a deep purple color and nitrogen gas being colorless).**
(D)	This option is incorrect. Molecular mass is unrelated to UV and visible light spectroscopy; molecular mass would only be relevant if conducting a mass spectrometry experiment.

Question 42

Essential Knowledge	2.D.2 Metallic solids are good conductors of heat and electricity, have a wide range of melting points, and are shiny, malleable, ductile, and readily alloyed.
Science Practice	7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.
Learning Objective	2.25 The student is able to compare the properties of metal alloys with their constituent elements to determine if an alloy has formed, identify the type of alloy formed, and explain the differences in properties using particulate level reasoning.
(A)	This option is incorrect. The number of available oxidation states for these metals is not related to the hardness of the alloy.
(B)	This option is incorrect. The melting points of the component metals are unrelated to the hardness of the alloy.
(C)	**This option is correct. It reflects the data provided that the radii of Cu atoms is smaller than Ag atoms, which would prevent movement of Ag atoms in the alloy by creating points where Ag atoms could not slip past other atoms, making the overall alloy less deformable (i.e., less malleable).**
(D)	This option is incorrect. London dispersion forces are not a significant factor in the nature of the metallic bond, and weaker interparticle forces would likely increase, not decrease, malleability.

Question 43

Essential Knowledge		1.B.1 The atom is composed of negatively charged electrons, which can leave the atom, and a positively charged nucleus that is made of protons and neutrons. The attraction of the electrons to the nucleus is the basis of the structure of the atom. Coulomb's Law is qualitatively useful for understanding the structure of the atom.
Science Practice		6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.
Learning Objective		1.5 The student is able to explain the distribution of electrons in an atom or ion based upon data.
(A)	This option is incorrect. The presence or lack of electron-electron repulsions in the 2*p* sublevel would have no detectable effect on the amount of energy needed to remove a 1*s* electron from an atom.	
(B)	This option is incorrect. The increased electron-electron repulsions in the oxygen atoms would have no detectable effect on the attraction of the 1*s* electrons to the nucleus of either atom, as both atoms have the same number of electrons (and hence the same degree of electron-electron repulsion) in the 1*s* sublevel.	
(C)	This option is incorrect. Electron shielding involves inner electrons reducing the effective pull from the nucleus on outer electrons. Electrons in the 2*p* sublevel would have negligible, if any, shielding effect on the 1*s* electrons.	
(D)	**This option is correct. It correctly explains the differences in the provided PES spectra for the energies required to remove electrons from the 1*s* sublevel, based on the increased Coulombic attraction to the nucleus due to a greater number of protons in the nucleus of the oxygen atom than in the nucleus of the nitrogen atom.**	

Question 44

Essential Knowledge		2.B.3 Intermolecular forces play a key role in determining the properties of substances, including biological structures and interactions.
Science Practice		6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.
Learning Objective		2.16 The student is able to explain the properties (phase, vapor pressure, viscosity, etc.) of small and large molecular compounds in terms of the strengths and types of intermolecular forces.
(A)	This option is incorrect. Covalent bonds within molecules do not break when boiling occurs; boiling only involves molecules having enough energy to overcome interparticle attractions.	
(B)	This option is incorrect. While the C-F bond is more polar than the C-H bond, the boiling point data indicate that the London dispersion forces between nonane molecules must be greater than the combined dipole-dipole attractions and London dispersion forces between molecules of 2,3,4-trifluoropentane.	
(C)	**This option is correct. It correctly explains the higher boiling point of nonane due to the increased size and surface area of the electron cloud (yielding greater polarizability), which leads to more significant London dispersion forces between nonane molecules than between molecules of 2,3,4-trifluoropentane.**	
(D)	This option is incorrect. Greater separation between molecules would have only slight effects on boiling point, and, if anything, the greater spacing between carbon chains in nonane would be consistent with a lower boiling point, not higher.	

Question 45

Essential Knowledge	3.C.3 Electrochemistry shows the interconversion between chemical and electrical energy in galvanic and electrolytic cells.
Science Practice	2.3 The student can estimate numerically quantities that describe natural phenomena.
Learning Objective	3.12 The student can make qualitative or quantitative predictions about galvanic or electrolytic reactions based on half-cell reactions and potentials and/or Faraday's laws.

(A)	This option is incorrect. Molar coefficients do not affect cell potential, so dividing by 3 does not yield the correct cell potential, even though reversing reaction Y and combining it with X yields a net reaction for Z that has molar coefficients 3 times greater than those in the equation given for Z.
(B)	**This option is correct. It predicts the standard cell potential for cell Z by reversing the net reaction for galvanic cell Y and adding it to the net reaction for cell X. Molar coefficients do not affect cell potential, so no further mathematical manipulations are necessary. (This is one method among several of reaching the correct answer.)**
(C)	This option is incorrect. Multiplying the cell potential by 3 does not yield the correct cell potential for Z, since molar coefficients do not affect cell potential.
(D)	This option is incorrect. The reaction in cell Y must be reversed, reversing the sign on the cell potential. Adding the net reaction from X and Y together does not yield the reaction given for Z without this reversal.

Question 46

Essential Knowledge	3.C.3 Electrochemistry shows the interconversion between chemical and electrical energy in galvanic and electrolytic cells.
Science Practice	5.1 The student can analyze data to identify patterns or relationships.
Learning Objective	3.13 The student can analyze data regarding galvanic or electrolytic cells to identify properties of the underlying redox reactions.

(A)	This option is incorrect. Fe^{2+} ions are reduced only in cell Y, not cell Z.
(B)	This option is incorrect. Fe atoms are oxidized only in cell Z, not cell Y.
(C)	**This option is correct. It correctly tracks the oxidation numbers of the iron, based on the net reactions for each galvanic cell: Fe^{2+} ions are reduced to iron metal in galvanic cell Y, and Fe atoms are oxidized to Fe^{2+} ions in galvanic cell Z.**
(D)	This option is incorrect. Oxidation involves the loss of electrons, which does not happen to the Fe^{2+} ions in galvanic cell Y. Reduction involves the gain of electrons, which does not happen to the Fe atoms in the galvanic cell Z.

Question 47

Essential Knowledge	3.C.3 Electrochemistry shows the interconversion between chemical and electrical energy in galvanic and electrolytic cells.
Science Practice	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	3.12 The student can make qualitative or quantitative predictions about galvanic or electrolytic reactions based on half-cell reactions and potentials and/or Faraday's laws.
(A)	This option is incorrect. Since Fe^{2+} ions are a reactant in cell Y and a product in cell Z, increasing the concentration of Fe^{2+} ions cannot increase the voltage in both cells.
(B)	This option is incorrect. Since Fe^{2+} ions are a reactant in cell Y and a product in cell Z, increasing the concentration of Fe^{2+} ions cannot decrease the voltage in both cells.
(C)	**This option is correct. It correctly predicts that increasing the Fe^{2+} ion concentration will increase the voltage for cell Y, where Fe^{2+} ions are reactants. Increasing the Fe^{2+} ion concentration will decrease the voltage for cell Z, where Fe^{2+} ions are products.**
(D)	This option is incorrect. It states the exact opposite of what would occur (see option C).

Question 48

Essential Knowledge	6.C.1 Chemical equilibrium reasoning can be used to describe the proton-transfer reactions of acid-base chemistry.
Science Practices	2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	6.16 The student can identify a given solution as being the solution of a monoprotic weak acid or base (including salts in which one ion is a weak acid or base), and calculate the pH and concentration of all species in the solution and/or infer the relative strengths of the weak acids or bases from given equilibrium concentrations.
(A)	**This option is correct. It correctly identifies that Acid 1 is a weak acid, and that it must have the lowest acid-dissociation constant since it has the highest pH (closest to neutral) at each of the provided concentrations.**
(B)	This option is incorrect. The pH values provided for this acid reflect the behavior of a strong acid using the relationship $pH = -\log[H_3O^+]$.
(C)	This option is incorrect. While the data on Acid 3 is consistent with a weak acid, the pH is lower than Acid 1 at all concentrations, indicating a greater degree of ionization than Acid 1.
(D)	This option is incorrect. While the data on Acid 4 is consistent with a weak acid, the pH is fairly close to Acid 2, indicating that it has a larger K_a value than Acid 1.

Question 49

Essential Knowledge	6.C.1 Chemical equilibrium reasoning can be used to describe the proton-transfer reactions of acid-base chemistry.
Science Practice	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Learning Objective	6.12 The student can reason about the distinction between strong and weak acid solutions with similar values of pH, including the percent ionization of the acids, the concentrations needed to achieve the same pH, and the amount of base needed to reach the equivalence point in a titration.

(A)	This option is incorrect. The pH values provided for various concentrations of Acid 1 are not reflective of a strong acid.
(B)	**This option is correct. It is based on recognition that HCl is a strong acid and reasoning that in every case the concentration of Acid 2 is equal to the H_3O^+ ion concentration, indicating 100 percent dissociation.**
(C)	This option is incorrect. The pH values provided for various concentrations of Acid 3 are not reflective of a strong acid.
(D)	This option is incorrect. The pH values provided for various concentrations of Acid 4 are not reflective of a strong acid.

Question 50

Essential Knowledge	6.C.1 Chemical equilibrium reasoning can be used to describe the proton-transfer reactions of acid-base chemistry.
Science Practice	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	6.17 The student can, given an arbitrary mixture of weak and strong acids and bases (including polyprotic systems), determine which species will react strongly with one another (i.e., with $K > 1$), and what species will be present in large concentrations at equilibrium.

(A)	This option is incorrect. The pH value provided for the 1.0 *M* solution of Acid 1 indicates that the $[OH^-]$ is many orders of magnitude less than any of the other substances in solution.
(B)	This option is incorrect. The pH value provided for the 1.0 *M* solution of Acid 1 indicates that the $[H_3O^+]$ is more than one order of magnitude less than 1.0 *M*.
(C)	**This option is correct. It correctly determines that Acid 1 is a weak acid, which has a small degree of ionization. In the 1.0 *M* solution, the protonated form of the acid will have the highest concentration.**
(D)	This option is incorrect. The conjugate base for the acid would have an equal concentration to the $[H_3O^+]$, which is more than one order of magnitude less than 1.0 *M*.

Question 51

Essential Knowledge	6.C.1 Chemical equilibrium reasoning can be used to describe the proton-transfer reactions of acid-base chemistry.
Science Practice	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Learning Objective	6.12 The student can reason about the distinction between strong and weak acid solutions with similar values of pH, including the percent ionization of the acids, the concentrations needed to achieve the same pH, and the amount of base needed to reach the equivalence point in a titration.
(A)	This option is incorrect. Initial acid concentration as opposed to pH determines the volume of base required.
(B)	This option is incorrect. Initial acid concentration as opposed to pH determines the volume of base required.
(C)	This option is incorrect. Initial acid concentration as opposed to pH determines the volume of base required.
(D)	**This option is correct. Since the concentrations of the acids are identical, the same volume of base is required to reach the equivalence point.**

Question 52

Essential Knowledge	6.C.2 The pH is an important characteristic of aqueous solutions that can be controlled with buffers. Comparing pH to pK_a allows one to determine the protonation state of a molecule with a labile proton.
Science Practice	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	6.20 The student can identify a solution as being a buffer solution and explain the buffer mechanism in terms of the reactions that would occur on addition of acid or base.
(A)	This option is incorrect. The pH does not change much because the solution is a buffer.
(B)	This option is incorrect. The pH does not change much because the solution is a buffer.
(C)	**This option is correct. Acid 1 is a weak acid because the starting pH is higher than expected for complete dissociation. The added base converts half of the weak acid to its conjugate base, creating a buffer solution. If concentrated acid is added to the buffer solution, the acid reacts with the conjugate base, thereby keeping the pH roughly constant.**
(D)	This option is incorrect. The dominant species in solution are the weak acid and its conjugate base. There is very little OH^- ion in the buffer solution.

Question 53

Essential Knowledge	4.D.2 Important classes in catalysis include acid-base catalysis, surface catalysis, and enzyme catalysis.
Science Practice	6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.
Learning Objective	4.9 The student is able to explain changes in reaction rates arising from the use of acid-base catalysts, surface catalysts, or enzyme catalysts, including selecting appropriate mechanisms with or without the catalyst present.
(A)	**This option is correct. Cl(*g*) is a catalyst for the reaction. The presence of Cl(*g*) decreases the activation energy and increases the rate.**
(B)	This option is incorrect. Cl(*g*) does not decrease the rate as it promotes the decomposition of ozone.
(C)	This option is incorrect. The equilibrium constant does not change with addition of a reactant, nor does the equilibrium constant have to do with overall reaction rate.
(D)	This option is incorrect. The equilibrium constant does not change with addition of a reactant, nor does the equilibrium constant have to do with overall reaction rate.

Question 54

Big Idea	2 Chemical and physical properties of materials can be explained by the structure and the arrangement of atoms, ions, or molecules and the forces between them.
Science Practice	7.1 The student can connect phenomena and models across spatial and temporal scales.
Learning Objective	2.1 Students can predict properties of substances based on their chemical formulas and provide explanations of their properties based on particle views.
(A)	**This option is correct. The Cl^- ion is larger than the F^- ion so the attractive interactions in NaCl are weaker than in NaF.**
(B)	This option is incorrect. The bonding is weaker in NaCl and it is ionic, not covalent.
(C)	This option is incorrect. The ions are spaced farther apart in NaCl compared with MgO, but this makes the bonding weaker and the boiling point for NaCl lower.
(D)	This option is incorrect. The boiling point for NaCl is lower. Moreover, more energy is required to transfer two electrons from Mg to O than to transfer one electron from Na to Cl.

Question 55

Essential Knowledge	6.C.2 The pH is an important characteristic of aqueous solutions that can be controlled with buffers. Comparing pH to pK_a allows one to determine the protonation state of a molecule with a labile proton.
Science Practice	2.3 The student can estimate numerically quantities that describe natural phenomena.
Learning Objective	6.18 The student can design a buffer solution with a target pH and buffer capacity by selecting an appropriate conjugate acid-base pair and estimating the concentrations needed to achieve the desired capacity.
(A)	This option is incorrect. This solution would not be a buffer solution.
(B)	This option is incorrect. The pK_a of $HC_3H_5O_2$ is not close to 7.5.
(C)	**This option is correct. The pK_a of HClO is close to 7.5.**
(D)	This option is incorrect. The pK_a of C_6H_5OH is not close to 7.5.

Question 56

Essential Knowledge	2.A.3 Solutions are homogenous mixtures in which the physical properties are dependent on the concentration of the solute and the strengths of all interactions among the particles of the solutes and solvent.
Science Practice	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Learning Objective	2.9 The student is able to create or interpret representations that link the concept of molarity with particle views of solutions.
(A)	This option is incorrect. The solution in Z is the most dilute. The number of ions per volume is the smallest, contradicting that the concentrations of $Mg(NO_3)_2$ is 4.0 *M*.
(B)	This option is incorrect. The metal ion concentrations are not equal in all three solutions.
(C)	This option is incorrect. The relationship of concentrations in X and Y are correct, but the concentration of Mg^{2+} is not equal in Y and Z. The number of ions is equal, but the volume is twice as large in Z.
(D)	**This option is correct. The concentration of Mg^{2+} in Y is half the concentration of Ag^+ in X. The concentration of Mg^{2+} in Z is half of what it is in Y because the volume doubled.**

Question 57

Essential Knowledge	4.A.2 The rate law shows how the rate depends on reactant concentrations.
Science Practice	5.1 The student can analyze data to identify patterns or relationships.
Learning Objective	4.2 The student is able to analyze concentration versus time data to determine the rate law for a zeroth-, first-, or second-order reaction.
(A)	This option is incorrect. A plot of [A] versus *t* is not a straight line.
(B)	**This option is correct. A plot of ln[A] versus *t* is a straight line.**
(C)	This option is incorrect. A plot of 1/[A] versus *t* is not a straight line.
(D)	This option is incorrect. The linearity of the plot of ln[A] versus *t* suggests the reaction order is 1, not 3.

Question 58

Essential Knowledge	1.C.1 Many properties of atoms exhibit periodic trends that are reflective of the periodicity of electronic structure.
Science Practice	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	1.9 The student is able to predict and/or justify trends in atomic properties based on location on the periodic table and/or the shell model.

(A)	This option is incorrect. The ionization energy of potassium is smaller than that of calcium.
(B)	**This option is correct. Potassium is larger than calcium because it has a smaller effective nuclear charge. Because potassium is larger, less energy is required to remove an electron from it than is required to remove an electron from calcium.**
(C)	This option is incorrect. The relative radii and ionization energies of potassium and calcium are both incorrect.
(D)	This option is incorrect. The atomic radius of potassium is larger than that of calcium.

Question 59

Essential Knowledge	2.B.2 Dipole forces result from the attraction among the positive ends and negative ends of polar molecules. Hydrogen bonding is a strong type of dipole-dipole force when very electronegative atoms (N, O, and F) are involved.
Science Practice	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Learning Objective	2.13 The student is able to describe the relationships between the structural features of polar molecules and the forces of attraction between the particles.

(A)	This option is incorrect. The accommodation of bond angles does not account for differences in bond lengths.
(B)	**This option is correct. There is a shorter covalent bond between H and F within the molecules and longer hydrogen bond between the H in one molecule and the F in a second molecule.**
(C)	This option is incorrect. Different isotopes do not cause significant differences in bond lengths.
(D)	This option is incorrect. Repulsions between nonbonding pairs of electrons do not account for differences in bond lengths.

Question 60

Essential Knowledge	6.A.3 When a system is at equilibrium, all macroscopic variables, such as concentrations, partial pressures, and temperature, do not change over time. Equilibrium results from an equality between the rates of the forward and reverse reactions, at which point $Q = K$.
Science Practice	2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objective	6.5 The student can, given data (tabular, graphical, etc.) from which the state of a system at equilibrium can be obtained, calculate the equilibrium constant, K.

(A)	This option is incorrect. See option B.
(B)	**This option is correct. Each molecule of $COCl_2$ that decomposes creates two moles of gas. When the number of moles of $COCl_2$ decreases such that the pressure is 0.8 atm, there is 0.2 mol of each of the product gas. The equilibrium constant $K = (0.2)(0.2)/(0.8) = 0.050$.**
(C)	This option is incorrect. See option B.
(D)	This option is incorrect. See option B. This assumes that K_p is equal to the original pressure in the flask.

Answers to Multiple-Choice Questions

1 – C
2 – C
3 – A
4 – A
5 – D
6 – D
7 – B
8 – D
9 – B
10 – C
11 – B
12 – B
13 – C
14 – A
15 – B
16 – C
17 – B
18 – D
19 – B
20 – C
21 – A
22 – D
23 – D
24 – D
25 – C
26 – B
27 – D
28 – C
29 – C
30 – C
31 – B
32 – B
33 – B
34 – C
35 – C
36 – B
37 – A
38 – C
39 – A
40 – A
41 – C
42 – C
43 – D
44 – C
45 – B
46 – C
47 – C
48 – A
49 – B
50 – C
51 – D
52 – C
53 – A
54 – A
55 – C
56 – D
57 – B
58 – B
59 – B
60 – B

Free-Response Section

Section II is the free-response part of the exam. This section contains two types of free-response questions (long and short), and the student will have a total of 90 minutes to complete them all.

Due to the emphasis on quantitative skills and the application of mathematical methods in the questions on the free-response section, students will be allowed to use a scientific/graphing calculator on the entire free-response section. Students will also be supplied with a formula list and periodic table as part of their testing materials to use on both the multiple-choice and free-response sections.

Information for Free-Response Question 1

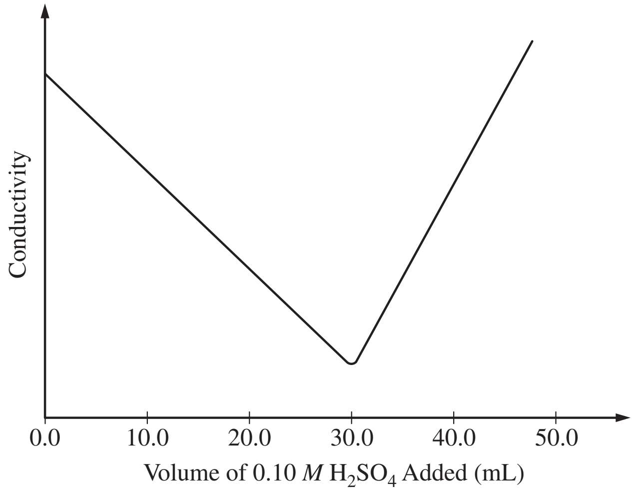
Timing	The student should spend approximately 20 minutes on this question.
Essential Knowledge/ Big Ideas	1.E.2 Conservation of atoms makes it possible to compute the masses of substances involved in physical and chemical processes. Chemical processes result in the formation of new substances, and the amount of these depends on the number and the types and masses of elements in the reactants, as well as the efficiency of the transformation. Big Idea 3: Changes in matter involve the rearrangement and/or reorganization of atoms and/or the transfer of electrons. 3.A.1 A chemical change may be represented by a molecular, ionic, or net ionic equation. 6.C.3 The solubility of a substance can be understood in terms of chemical equilibrium.
Science Practices	1.5 The student can re-express key elements of natural phenomena across multiple representations in the domain. 4.2 The student can design a plan for collecting data to answer a particular scientific question. 5.1 The student can analyze data to identify patterns or relationships. 7.1 The student can connect phenomena and models across spatial and temporal scales.
Learning Objectives	1.19 The student can design, and/or interpret data from, an experiment that uses gravimetric analysis to determine the concentration of an analyte in a solution. 3.1 Students can translate among macroscopic observations of change, chemical equations, and particle views. 3.2 The student can translate an observed chemical change into a balanced chemical equation and justify the choice of equation type (molecular, ionic, or net ionic) in terms of utility for the given circumstances. 6.23 The student can interpret data regarding the relative solubility of salts in terms of factors (common ions, pH) that influence the solubility.

Characteristics of a STRONG Response	Part (a) The student is able to write a correct equation for the neutralization reaction and a correct equation for the precipitation reaction. The equations are balanced net ionic equations with appropriate charges on the ions. Part (b) The student is able to identify either the Ba^{2+} ion or the OH^{-} ion as the chemical species that enable the solution to conduct electricity. The student is able to use the precipitation reaction to explain that the concentration of Ba^{2+} decreases as solid $BaSO_4$ is formed and use the neutralization reaction to explain that OH^{-} decreases due to reaction with the strong acid. Part (c) The student can use the graph to calculate the molarity of the original solution of $Ba(OH)_2$. In determining the original $Ba(OH)_2$ solution molarity, the student can calculate the number of moles of the titrant added at the equivalence point. The student can use this information to calculate the correct original concentration of $Ba(OH)_2$. Part (d) The student understands that the concentrations of Ba^{2+} and SO_4^{2-} are equal and correctly uses the expression $K_{sp} = [Ba^{2+}] \times [SO_4^{2-}] = 1.0 \times 10^{-10}$ to determine the concentration. The student is able to correctly calculate the K_{sp} . The student understands that the concentration of Ba^{2+} and SO_4^{2-} is equal. The student uses the equation $K_{sp} = [Ba^{2+}] \times [SO_4^{2-}] = 1.0 \times 10^{-10}$. Part (e) The student can explain the decrease in Ba^{2+} ion by using equilibrium reasoning, either by applying Le Chatelier's principle to the dissolution reaction for $BaSO_4$ or by referring to the common ion effect.
Characteristics of a GOOD Response	Part (a) The student is able to write an equation for the neutralization reaction and an equation for the precipitation reaction. The equations may not be balanced. Part (b) The student is able to identify either the Ba^{2+} ion or OH^{-} ion as the chemical species that will enable the solution to conduct electricity. The student uses only one reaction to explain the decrease in conductivity, including only the decrease in Ba^{2+} via the precipitation reaction or the decrease in OH^{-} via the neutralization reaction. Part (c) The student can determine the number of moles of titrant needed at the equivalence point, however he or she cannot successfully use this information to calculate the correct original concentration of $Ba(OH)_2$. Part (d) The student attempts to use the K_{sp} expression to calculate the solubility. However, the student makes an error in the solubility computation, such as failing to take the square root of K_{sp} to get the concentration. Part (e) The student can explain the decrease in Ba^{2+} ion by using equilibrium reasoning, either by applying Le Chatelier's principle to the dissolution reaction for $BaSO_4$ or by referring to the common ion effect. However, additional factors are included that contradict the student's earlier statements.

Characteristics of a WEAK Response	Part (a) The student is able to write the neutralization reaction but has difficulty with the precipitation reaction. The precipitation reaction may be written in combination with the neutralization reaction, as in $Ba(OH)_2 + H_2SO_4 \rightarrow BaSO_4 + 2\ H_2O$. Part (b) The student incorrectly identifies the species responsible for the conductivity. The student is unable to explain the decrease in conductivity based on the reactions from part (a). Part (c) The student can determine the number of moles of titrant needed at the equivalence point, however he or she cannot successfully use this information to calculate the correct original concentration of $Ba(OH)_2$. Part (d) The student is not able to connect the experimental situation to the solubility of $BaSO_4$. Part (e) The student uses stoichiometry, instead of equilibrium reasoning, to explain the change in Ba^{2+} concentration.

Scoring Guidelines for Free-Response Question 1

Question 1
(10 Points)



A student performs an experiment in which the conductivity of a solution of $Ba(OH)_2$ is monitored as the solution is titrated with 0.10 M H_2SO_4. The original volume of the $Ba(OH)_2$ solution is 25.0 mL. A precipitate of $BaSO_4$ ($K_{sp} = 1.0 \times 10^{-10}$) formed during the titration. The data collected from the experiment are plotted in the graph above.

(a) As the first 30.0 mL of 0.10 M H_2SO_4 are added to the $Ba(OH)_2$ solution, two types of chemical reactions occur simultaneously. On the lines provided below, write the balanced net-ionic equations for (i) the neutralization reaction and (ii) the precipitation reaction.

(i) Equation for neutralization reaction: ______________________________

(ii) Equation for precipitation reaction: ______________________________

$Ba^{2+}(aq) + SO_4^{2-}(aq) \rightarrow BaSO_4(s)$ $H^+(aq) + OH^-(aq) \rightarrow H_2O(l)$	1 point is earned for <u>each</u> correct product. 1 point is earned for the correct reactants with atoms <u>and</u> charges balanced in <u>both</u> reactions.

(b) The conductivity of the $Ba(OH)_2$ solution decreases as the volume of added 0.10 M H_2SO_4 changes from 0.0 mL to 30.0 mL.

(i) Identify the chemical species that enable the solution to conduct electricity as the first 30.0 mL of 0.10 M H_2SO_4 are added.

$Ba^{2+}(aq)$ and/or $OH^-(aq)$	1 point is earned for either ion.

(ii) On the basis of the equations you wrote in part (a), explain why the conductivity decreases.

As the titration approaches the equivalence point, $Ba^{2+}(aq)$ ions are removed from solution by the precipitation reaction, <u>and</u> $OH^-(aq)$ ions are removed from solution by the neutralization reaction.	1 point is earned for each correct explanation. <u>Note</u>: response must refer to <u>both</u> reactions for full credit.

(c) Using the information in the graph, calculate the molarity of the original $Ba(OH)_2$ solution.

moles $Ba(OH)_2$ = moles H_2SO_4 (at equivalence point) moles $H_2SO_4 = \frac{0.10\text{ mol}}{1.0\text{ L}} \times 0.030\text{ L} = 0.0030\text{ mol}$ $[Ba(OH)_2] = \frac{\text{mol }Ba(OH)_2}{\text{volume of original solution}} =$ $\frac{0.0030\text{ mol}}{0.025\text{ L}} = 0.12\ M$	1 point is earned for the correct determination of the number of moles of titrant added at the equivalence point (can be implicit). 1 point is earned for the correct calculation of the original concentration of $Ba(OH)_2(aq)$.

(d) Calculate the concentration of $Ba^{2+}(aq)$ in the solution at the equivalence point (after exactly 30.0 mL of 0.10 M H_2SO_4 are added).

$K_{sp} = [Ba^{2+}] \times [SO_4^{2-}] = 1.0 \times 10^{-10}$ $[Ba^{2+}] = [SO_4^{2-}]$ $[Ba^{2+}] = \sqrt{1.0 \times 10^{-10}} = 1.0 \times 10^{-5}\ M$	1 point is earned for the correct calculation based on K_{sp}.

(e) The concentration of $Ba^{2+}(aq)$ in the solution decreases as the volume of added 0.10 M H_2SO_4 increases from 30.0 mL to 31.0 mL. Explain.

Because of the common ion effect, adding sulfate ions to an equilibrium reaction involving sulfate ions will cause the reaction to consume the added ions as a new equilibrium is established. Consequently, more $BaSO_4(s)$ is formed, causing the $Ba^{2+}(aq)$ concentration to decrease.	1 point is earned for a correct explanation, which must use an equilibrium argument (for example, citing the common ion effect or Le Chatelier's principle) rather than a stoichiometric argument.

Information for Free-Response Question 2

Timing	The student should spend approximately 20 minutes on this question.
Essential Knowledge	5.B.3 Chemical systems undergo three main processes that change their energy: heating/cooling, phase transitions, and chemical reactions. 5.B.4 Calorimetry is an experimental technique that is used to measure the change in energy of a chemical system. 6.A.2 The current state of a system undergoing a reversible reaction can be characterized by the extent to which reactants have been converted to products. The relative quantities of reaction components are quantitatively described by the reaction quotient, *Q*. 6.A.4 The magnitude of the equilibrium constant, *K*, can be used to determine whether the equilibrium lies toward the reactant side or the product side.
Science Practices	2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 2.3 The student can estimate numerically quantities that describe natural phenomena. 4.2 The student can design a plan for collecting data to answer a particular scientific question. 5.1 The student can analyze data to identify patterns or relationships.
Learning Objectives	5.6 The student is able to use calculations or estimations to relate energy changes associated with heating/cooling a substance to the heat capacity, relate energy changes associated with a phase transition to the enthalpy of fusion/vaporization, relate energy changes associated with a chemical reaction to the enthalpy of the reaction, and relate energy changes to $P\Delta V$ work. 5.7 The student is able to design and/or interpret the results of an experiment in which calorimetry is used to determine the change in enthalpy of a chemical process (heating/cooling, phase transition, or chemical reaction) at constant pressure. 6.2 The student can, given a manipulation of a chemical reaction or set of reactions (e.g., reversal of reaction or addition of two reactions), determine the effects of that manipulation on *Q* or *K*. 6.7 The student is able, for a reversible reaction that has a large or small *K*, to determine which chemical species will have very large versus very small concentrations at equilibrium.

Characteristics of a STRONG Response	Part (a) The student is able to analyze the provided data to assess the level of precision in the measurements and correctly conclude that it is not sufficient to report an answer to two significant figures due to the choice of glassware. The student can correctly list two changes to the procedure that will result in a more precise result: using the more precise volumetric glassware and increasing the concentration of the reactant solutions. The explanation includes that using the more precise glassware allows the volume (50.0 mL) to be measured to three significant figures. The explanation also articulates that using the more concentrated solutions results in a greater release of energy without a larger volume of solution to heat, which increases the temperature change to a level where three significant figures can be maintained. Part (b) The student is able to calculate the enthalpy of reaction in kJ/mol with correct sign or direction of energy flow, given the provided solution quantities and amount of energy released. The calculation includes the correct calculation of moles of reaction (given that the coefficients in the reaction are all 1), as well as dividing the heat released by the moles of reaction. The answer is reported with the proper sign (negative) or indication of direction of energy flow (released). The student can articulate that the calorimeter and thermometer absorb energy from the reaction, resulting in a calculated value of the reaction enthalpy that is lower (less exothermic) than it would be had the energy absorbed by the calorimeter and thermometer been taken into account. The student can identify the net ionic equation for the chemical reaction and correctly determine that it is the reverse of the equation for K_w, resulting in a K value that is very large. The student can articulate that reactions with very large K values go essentially to completion. Part (c) The student is able to determine a specific procedural error that would result in a higher calculated reaction enthalpy by reasoning which experimental variants would result in a higher than expected value of the temperature change. Highlighted errors may include an erroneously low initial temperature recording, an erroneously high final temperature recording (or both), or using the more concentrated solutions in place of the 1.00 M solutions and not realizing it. Justification includes correct mapping of variables and articulation that the highlighted error would result in a larger temperature change, which in turn results in a higher calculated value for the reaction enthalpy.

Characteristics of a GOOD Response	Part (a) The student is able to evaluate the experimental results to determine that the data are insufficient to report a conclusion with two significant figures due to the choice of imprecise volumetric glassware. The student can propose one change to the procedure that will result in three significant figures and correctly explain how the proposed change will increase the precision of the results. The student may have difficultly listing or explaining how the second change would result in a calculation with precision to three significant figures. Part (b) The student is able to calculate the moles of reaction from the data provided and set up the ratio between heat released and the moles of reaction. The student can articulate that the calorimeter and thermometer absorb energy and will decrease calculated enthalpy of reaction. The student may be able to determine the net ionic equation for the reaction but may have difficulty recognizing the relationship between this reaction and the reaction associated with K_w. Part (c) The student can articulate the connection between the temperature change and the magnitude of the enthalpy change and reason that a larger ΔT term is necessary. The student may have difficulty identifying an experimental error that will result in a larger value for ΔT.
Characteristics of a WEAK Response	Part (a) The student may be able to identify that the experimental data are not sufficient to report an answer to two significant figures but may have difficulty justifying why the data are insufficient. The student may incorrectly conclude that the data are sufficient to report the answer to two significant figures. The student may be able to suggest one change to the experimental conditions to increase the level of precision beyond one significant figure, or the student may be able to list a change but be unable to explain how it will increase the precision. Part (b) The student may be able to set up the ratio between heat released and moles of reaction or may calculate the moles of reaction incorrectly. The student may omit the sign or direction of the energy flow in the calculated ΔH term. The student may be able to reiterate that the thermometer and calorimeter absorb energy but may incorrectly predict the effect on the reaction enthalpy. The student is unable to identify the net ionic equation's relationship to K_w or to use that relationship to justify that the reaction is likely to go to completion. Part (c) The student may be able to articulate the relationship between a larger ΔT value and a larger ΔH value, or the student may incorrectly assign an inverse relationship. The student may suggest an experimental error that moves the ΔH value in the wrong direction (i.e., results in a smaller temperature change rather than larger) or may suggest an experimental error that does not affect ΔH (e.g., using larger volumes of the 1.00 M solutions).

Scoring Guidelines for Free-Response Question 2

Question 2
(10 Points)

A student is given the task of determining the enthalpy of reaction for the reaction between HCl(*aq*) and NaOH(*aq*). The following materials are available.

1.00 *M* HCl(*aq*)	1.00 *M* NaOH(*aq*)	distilled water
2.00 *M* HCl(*aq*)	2.00 *M* NaOH(*aq*)	goggles
insulated cups with covers	gloves	lab coat
thermometer (± 0.1°C)	stirring rod	

The student may select from the glassware listed in the table below.

Glassware Items	Precision
250 mL Erlenmeyer flasks	± 25 mL
100 mL beakers	± 10 mL
100 mL graduated cylinders	± 0.1 mL

(a) The student selects two 100 mL beakers, uses them to measure 50 mL each of 1.00 *M* HCl(*aq*) solution and 1.00 *M* NaOH(*aq*) solution, and measures an initial temperature of 24.5°C for each solution. Then the student pours the two solutions into an insulated cup, stirs the mixture, covers the cup, and records a maximum temperature of 29.9°C.

(i) Is the experimental design sufficient to determine the enthalpy of reaction to a precision of two significant figures? Justify your answer.

No. The use of the beakers to measure 50 mL ±10 mL of solutions limits the precision of the volume measurements and of the calculations to ±20% or 1 significant figure.	1 point is earned for the correct answer with the correct explanation.

(ii) List two specific changes to the experiment that will allow the student to determine the enthalpy of reaction to a precision of three significant figures. Explain.

Use graduated cylinders to measure the volumes of acid and base allowing a volume precision of ±0.1 mL or 3 significant figures for a volume of 50.0 mL. AND Use the 2.00 *M* HCl and 2.00 *M* NaOH solutions (instead of 1.00 *M*) to get a larger ΔT, thereby improving the relative precision in ΔT to ±1%.	1 point is earned for the change of glassware to graduated cylinders with a proper explanation. 1 point is earned for using the 2.00 *M* solutions for improved relative precision in temperature. Note: doubling the volumes will not increase ΔT or significantly improve volume precision.

(b) A second student is given two solutions, 75.0 mL of 1.00 *M* HCl and 75.0 mL of 1.00 *M* NaOH, each at 25.0°C. The student pours the solutions into an insulated cup, stirs the mixture, covers the cup, and records the maximum temperature of the mixture.

(i) The student calculates the amount of heat evolved in the experiment to be 4.1 kJ. Calculate the student's experimental value for the enthalpy of reaction, in kJ/mol$_{rxn}$.

$75.0 \text{ mL} \times \dfrac{1.00 \text{ mol HCl (or NaOH)}}{1000 \text{ mL}} = 0.0750 \text{ mol HCl (or NaOH)}$	1 point is earned for the correct calculation of moles of reactants.
$\Delta H = \dfrac{-4.1 \text{ kJ}}{0.0750 \text{ mol of reactants}} = -55 \text{ kJ/mol}_{rxn}$	1 point is earned for the correct substitution and answer.

(ii) The student assumes that the thermometer and the calorimeter do not absorb energy during the reaction. Does this assumption result in a calculated value of the enthalpy of reaction that is higher than, lower than, or the same as it would have been had the heat capacities of the thermometer and calorimeter been taken into account? Justify your answer.

The calculated value of the enthalpy of reaction will be lower (smaller or less negative) than it would have been had the thermometer and calorimeter been taken into account.	1 point is earned for the correct prediction.
The thermometer and calorimeter will absorb some of the heat of reaction. This lost heat is ignored in the original calculation of ΔH_{rxn}, making it smaller in magnitude (less negative). OR The actual heat capacity of the system is the sum of the heat capacities of the water, thermometer, and calorimeter. The assumed heat capacity of the system (water only) is less than the actual value, resulting in a lower (less negative) calculated value of ΔH_{rxn}.	1 point is earned for an acceptable justification.

(iii) One assumption in interpreting the results of the experiment is that the reaction between HCl(*aq*) and NaOH(*aq*) goes to completion. Justify the validity of this assumption in terms of the equilibrium constant for the reaction.

$H^+ + OH^- \rightarrow H_2O$, the reaction between HCl(*aq*) and NaOH(*aq*), is the reverse of $H_2O \rightarrow H^+ + OH^-$, the autoionization of water (for which $K = K_w = 1.0 \times 10^{-14}$). Thus the value of K for the neutralization reaction is the reciprocal of K_w, or 1.0×10^{14}, a very large number. Thus the neutralization reaction goes virtually to completion.	1 point is earned for the correct justification.

(c) A third student calculates a value for the enthalpy of reaction that is significantly higher than the accepted value.

(i) Identify a specific error in procedure made by the student that will result in a calculated value for the enthalpy of reaction that is higher than the accepted value. (Vague statements like "human error" or "incorrect calculations" will not earn credit.)

The student read the thermometer incorrectly in such a way to result in a calculated value of ΔT that was too high (either read T_i too low or read T_f too high). OR The student mistakenly used 2.00 M acid and 2.00 M base, thinking they were both 1.00 M.	1 point is earned for an acceptable procedural error that results in a higher calculated value.

(ii) Explain how the error that you identified in part (c)(i) leads to a calculated value for the enthalpy of reaction that is higher than the accepted value.

The calculation of the molar enthalpy of reaction may be expressed as Molar $\Delta H_{rxn} = -\dfrac{\text{mass}_{soln} \times c \times \Delta T}{n_{rxn}}$. If there is a measurement error that results in a ΔT that is too high, the magnitude (i.e., the absolute value) of the calculated molar enthalpy of reaction will be too high.	1 point is earned for an explanation that is consistent with the stated procedural error.

Information for Free-Response Question 3

Timing	The student should spend approximately 20 minutes on this question.
Essential Knowledge	2.A.2 The gaseous state can be effectively modeled with a mathematical equation relating various macroscopic properties. A gas has neither a definite volume nor a definite shape; because the effects of attractive forces are minimal, we usually assume that the particles move independently. 6.A.3 When a system is at equilibrium, all macroscopic variables, such as concentrations, partial pressures, and temperature, do not change over time. Equilibrium results from an equality between the rates of the forward and reverse reactions, at which point $Q = K$. 6.B.1 Systems at equilibrium respond to disturbances by partially countering the effect of the disturbance (Le Chatelier's principle).
Science Practices	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 2.3 The student can estimate numerically quantities that describe natural phenomena. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objectives	2.6 The student can apply mathematical relationships or estimation to determine macroscopic variables for ideal gases. 6.4 The student can, given a set of initial conditions (concentrations or partial pressures) and the equilibrium constant, K, use the tendency of Q to approach K to predict and justify the prediction as to whether the reaction will proceed toward products or reactants as equilibrium is approached. 6.5 The student can, given data (tabular, graphical, etc.) from which the state of a system at equilibrium can be obtained, calculate the equilibrium constant, K. 6.6 The student can, given a set of initial conditions (concentrations or partial pressures) and the equilibrium constant, K, use stoichiometric relationships and the law of mass action (Q equals K at equilibrium) to determine qualitatively and/or quantitatively the conditions at equilibrium for a system involving a single reversible reaction. 6.8 The student is able to use Le Chatelier's principle to predict the direction of the shift resulting from various possible stresses on a system at chemical equilibrium.

Characteristics of a STRONG Response	Part (a) The student is able to provide the correct setup and correct calculations: $\text{moles}_{SO_2Cl_2} = \frac{m}{\boldsymbol{M}} = \frac{4.32\text{ g}}{134.96\text{ g/mol}} = 0.0320\text{ mol}$ $p_{SO_2Cl_2} = \frac{nRT}{V} = \frac{(0.0320\text{ mol})(0.0821\text{ L·atm/mol·K})(400.\text{ K})}{1.50\text{ L}}$ $= 0.701\text{ atm}$ Part (b) The student is able to provide the correct setup and correct calculation of pressure. **Pressures at equilibrium at 400. K:** $SO_2Cl_2(g) \rightarrow SO_2(g) + Cl_2(g)$ Total $0.701 - x$ x x $0.701 + x$ $p_{total} = 0.701 + x = 1.26\text{ atm}$ $x = p_{SO_2} = p_{Cl_2} = 0.56\text{ atm}$ $p_{SO_2Cl_2} = 0.701 - x = 0.14\text{ atm}$ Part (c) The student can correctly set up and calculate the following: $K_p = \frac{p_{SO_2} \cdot p_{Cl_2}}{p_{SO_2Cl_2}}$ $K_p = \frac{(0.56)(0.56)}{0.14} = 2.2$ Part (d) The student is able to effectively articulate that at a higher temperature, K_p will <u>increase</u>. The student can also reason that according to Le Chatelier's principle, raising the temperature of an endothermic reaction at equilibrium increases the value of K_p and produces more products. Part (e) The student can reason that the amount of SO_2Cl_2 in the container will <u>decrease</u>. The student can also reason that initially $Q_p = 1.0 < 2.2. = K_p$, thus the reaction will consume SO_2Cl_2 as it proceeds in the forward direction towards equilibrium.

Characteristics of a GOOD Response	Part (a) The student is able to provide a correct setup for the calculations but potentially provides a wrong answer: $\text{moles}_{SO_2Cl_2} = \frac{m}{\boldsymbol{M}} = \frac{4.32\text{ g}}{134.96\text{ g/mol}} = 0.0320\text{ mol}$ $p_{SO_2Cl_2} = \frac{nRT}{V} = \frac{(0.0320\text{ mol})(0.0821\text{ L}\cdot\text{atm/mol}\cdot\text{K})(400.\text{ K})}{1.50\text{ L}}$ $= 0.701\text{ atm}$ Part (b) The student is able to provide a correct set up but potentially makes mistakes in the calculation of pressure. Pressures at equilibrium at 400. K: $\begin{array}{ccccc} SO_2Cl_2(g) & \rightarrow SO_2(g) & + & Cl_2(g) & \text{Total} \\ 0.701 - x & x & & x & 0.701 + x \end{array}$ $p_{total} = 0.701 + x = 1.26\text{ atm}$ $x = 0.56\text{ atm}$ Part (c) The student can provide the correct setup but potentially makes mistakes in the calculations: $K_p = \frac{p_{SO_2} \cdot p_{Cl_2}}{p_{SO_2Cl_2}} \qquad K_p = \frac{(0.56)(0.56)}{0.14} = [\text{incorrect number}]$ Part (d) The student is able to reason only that at a higher temperature, K_p will increase due to Le Chatelier's principle. Part (e) The student can qualitatively reason that the amount of SO_2Cl_2 in the container will decrease.
Characteristics of a WEAK Response	Part (a) The student is able to provide a correct mole calculation but makes mistakes in the formula used to calculate pressure: $\text{moles}_{SO_2Cl_2} = \frac{m}{\boldsymbol{M}} = \frac{4.32\text{ g}}{134.96\text{ g/mol}} = 0.0320\text{ mol}$ Part (b) The student is able to provide a correct setup, but does not perform any calculations. Pressures at equilibrium at 400. K: $\begin{array}{cccc} SO_2Cl_2(g) & \rightarrow SO_2(g) & + & Cl_2(g) \\ 0.701 - x & x & & x \end{array}$ Part (c) The student can provide a less detailed, partially correct setup and performs no calculations. For example, $K = (P_B)\,(P_C)\,/\,(P_A)$ Part (d) The student may predict that K_p will decrease. Part (e) The student can predict the change in SO_2Cl_2 but may provide a less correct rationale for the prediction such as: The amount of SO_2Cl_2 in the container will decrease because the reaction is endothermic.

Scoring Guidelines for Free-Response Question 3

Question 3
(10 Points)

$$SO_2Cl_2(g) \rightleftarrows SO_2(g) + Cl_2(g)$$

A 4.32 g sample of liquid SO_2Cl_2 is placed in a rigid, evacuated 1.50 L reaction vessel. As the container is heated to 400. K, the sample vaporizes completely and starts to decompose according to the equation above. The decomposition reaction is endothermic.

(a) If no decomposition occurred, what would be the pressure, in atm, of the $SO_2Cl_2(g)$ in the vessel at 400. K ?

Assuming no decomposition, $\text{moles}_{SO_2Cl_2} = \frac{m}{\boldsymbol{M}} = \frac{4.32\text{ g}}{134.96\text{ g/mol}} = 0.0320\text{ mol}$ $p_{SO_2Cl_2} = \frac{nRT}{V} = \frac{(0.0320\text{ mol})(0.0821\text{ L·atm/mol·K})(400.\text{ K})}{1.50\text{ L}}$ $= 0.701$ atm	1 point is earned for the correct calculation of moles of SO_2Cl_2 (may be implicit). 1 point is earned for the correct calculation of the pressure.

(b) When the system has reached equilibrium at 400. K, the total pressure in the container is 1.26 atm. Calculate the partial pressures, in atm, of $SO_2Cl_2(g)$, $SO_2(g)$, and $Cl_2(g)$ in the container at 400. K.

Pressures at equilibrium at 400. K: $SO_2Cl_2(g) \rightarrow SO_2(g) + Cl_2(g)$ Total $0.701 - x$ x x $0.701 + x$ $p_{total} = 0.701 + x = 1.26$ atm $x = p_{SO_2} = p_{Cl_2} = 0.56$ atm $p_{SO_2Cl_2} = 0.701 - x = 0.14$ atm	1 point is earned for the correct setup. 1 point is earned for the correct calculation of pressures.

(c) For the decomposition reaction at 400. K,

(i) write the equilibrium-constant expression for K_p for the reaction, and

$K_p = \frac{p_{SO_2} \cdot p_{Cl_2}}{p_{SO_2Cl_2}}$	1 point is earned for the correct K_p expression. <u>Note</u>: the pressure subscripts must be specific (i.e., SO_2, Cl_2, and SO_2Cl_2 — NOT, e.g., A, B, C, and D).

(ii) calculate the value of the equilibrium constant, K_p.

$K_p = \frac{(0.56)(0.56)}{0.14} = 2.2$	1 point is earned for the correct calculation of K_p that is consistent with the K_p expression stated in part (c)(i) and with the partial pressures calculated in part (b).

(d) The temperature of the equilibrium mixture is increased to 425 K. Will the value of K_p increase, decrease, or remain the same? Justify your prediction.

At a higher temperature, K_p will <u>increase</u>. According to Le Chatelier's principle, raising the temperature of an endothermic reaction at equilibrium adds a thermal stress that increases the value of K_p and produces more products.	1 point is earned for the correct prediction. 1 point is earned for a proper justification in terms of Le Chatelier's principle.

(e) In another experiment, the original partial pressures of $SO_2Cl_2(g)$, $SO_2(g)$, and $Cl_2(g)$ are 1.0 atm each at 400. K. Predict whether the amount of $SO_2Cl_2(g)$ in the container will increase, decrease, or remain the same. Justify your prediction.

The amount of SO_2Cl_2 in the container will <u>decrease</u>. Initially $Q_p = 1.0 < 2.2. = K_p$, thus the reaction will consume SO_2Cl_2 as it proceeds in the forward direction to reestablish equilibrium.	1 point is earned for the correct prediction. 1 point is earned for an acceptable justification. <u>Note</u>: the justification must consider the relative values of Q_p and K_p.

Information for Free-Response Question 4

Timing	The student should spend approximately 7–8 minutes on this question.
Essential Knowledge/ Enduring Understanding	4.B.1 Elementary reactions can be unimolecular or involve collisions between two or more molecules. 4.B.2 Not all collisions are successful. To get over the activation energy barrier, the colliding species need sufficient energy. Also, the orientations of the reactant molecules during the collision must allow for the rearrangement of reactant bonds to form product bonds. 4.C Many reactions proceed via a series of elementary reactions.
Science Practices	6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices. 6.5 The student can evaluate alternative scientific explanations. 7.1 The student can connect phenomena and models across spatial and temporal scales.
Learning Objectives	4.4 The student is able to connect the rate law for an elementary reaction to the frequency and success of molecular collisions, including connecting the frequency and success to the order and rate constant, respectively. 4.5 The student is able to explain the difference between collisions that convert reactants to products and those that do not in terms of energy distributions and molecular orientation. 4.7 The student is able to evaluate alternative explanations, as expressed by reaction mechanisms, to determine which are consistent with data regarding the overall rate of a reaction, and data that can be used to infer the presence of a reaction intermediate.
Characteristics of a STRONG Response	Part (a)(i) The student is able to connect the collision energy to the activation energy of the reaction. The reasoning is based on a clear understanding that a successful molecular collision must have energy sufficient to overcome the activation energy. The student may draw connections to the energy profile of the reaction by, for instance, noting that the collision energy must be sufficient to reach the transition state. The student may also draw connections between the activation energy and specific processes occurring in the reaction, for instance, by noting that the collision energy must be sufficient to begin breaking the F–F bond. Part (a)(ii) The student is able to identify the relative orientation of the molecules as a factor that is distinct from the collision energy and that influences the success of the collision. The student explanation connects the orientation required for a successful collision to processes occurring in the reaction. Such explanations may note that the orientation must allow for weakening of the F-F bond and formation of the N-F bond or draw particulate level diagrams comparing a successful and unsuccessful collision.

	Part (b) The student is able to - identify the first step in the mechanism as the rate-limiting step - generate the rate law for the first step in the mechanism, based on the coefficients of the reactants in the step and - connect the rate law of the overall reaction to the rate law of the first step in the mechanism, based on the first step being rate limiting
Characteristics of a GOOD Response	Part (a)(i) The student correctly states that the collision energy must be larger than the activation energy but does not connect the activation energy to the bond breaking and formation processes occurring in the reaction. Part (a)(ii) The student is able to identify the relative orientation of the molecules in the collision as a factor in establishing the success of the reaction; however, the explanation simply restates that orientation is important as opposed to drawing connections between orientation and the bond breaking and formation processes occurring in the reaction. Part (b) The student is able to identify the first step in the mechanism as rate limiting and write the rate law for the overall reaction based on the coefficients of the reactants in the first step. However, the student explanation does not make a clear distinction between the rate law of individual steps in the reaction mechanism and the rate law of the overall reaction.
Characteristics of a WEAK Response	Part (a)(i) The student may be able to state that the collision energy must be large but is unable to connect this to the concept of activation energy and instead reasons vaguely that more energy means more successful reactions. The student does not draw connections between the energy needed for a successful reaction and the bond breaking and formation processes occurring in the reaction. Part (a)(ii) The student is not able to identify relative orientation as a factor and instead chooses factors such as temperature or volume, which are not properties of the individual collision. The explanation may confuse the factors that influence the overall rate of a reaction, such as temperature and concentration, with the factors that lead to successful collision. Part (b) The student may recall that slow steps in a mechanism are rate limiting but be unable to use this to determine the rate law for the overall reaction.

Scoring Guidelines for Free-Response Question 4

Question 4

(4 Points)

$$2\ NO_2(g) + F_2(g) \rightarrow 2\ NO_2F(g)$$

It is proposed that the reaction represented above proceeds via the mechanism represented by the two elementary steps shown below.

Step I:	$NO_2 + F_2 \rightarrow NO_2F + F$	*(slow)*
Step II:	$NO_2 + F \rightleftarrows NO_2F$	*(fast reversible)*

(a) Step I of the proposed mechanism involves the collision between NO_2 and F_2 molecules. This step is slow even though such collisions occur very frequently in a mixture of $NO_2(g)$ and $F_2(g)$. Consider a specific collision between a molecule of NO_2 and a molecule of F_2.

(i) One factor that affects whether the collision will result in a reaction is the magnitude of the collision energy. Explain.

Successful molecular collisions must have sufficient energy in order to result in reaction. Only collisions with sufficient energy to overcome the activation energy barrier, E_a, will be able to reach the transition state and begin to break the F–F bond.	1 point is earned for a correct explanation that makes reference to the activation energy of the reaction.

(ii) Identify and explain one other factor that affects whether the collision will result in a reaction.

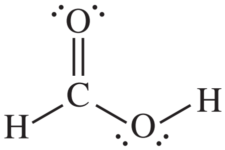
For a collision to be successful, the molecules must have the correct orientation.	1 point is earned for identifying the relative orientation of the colliding molecules.
Only collisions with the correct orientation will be able to begin to form an N–F bond and begin to break an F–F bond as the transition state is approached (that is, the molecules must contact each other at very specific locations on their surfaces for the transition state to be accessible).	1 point is earned for an explanation that makes reference to specific parts (atoms or bonds) of the reacting molecules.

(b) Consider the following potential rate laws for the reaction. Circle the rate law below that is consistent with the mechanism proposed above. Explain the reasoning behind your choice in terms of the details of the elementary steps of the mechanism.

rate = $k[NO_2]^2[F_2]$ rate = $k[NO_2][F_2]$

The rate law that is consistent with the mechanism is the one on the right above (rate = $k[NO_2][F_2]$). Step I is the slower step and the rate-determining step in the mechanism. Since Step I is an elementary reaction, its rate law is given by the stoichiometry of the reacting molecules, $\text{rate}_{\text{Step I}} = k_1[NO_2][F_2]$.	1 point is earned for identifying the correct rate law with a proper explanation. The explanation must correlate the overall rate law with the rate law derived from the stoichiometry of the slow step in the mechanism. Note: a statement relating the coefficients of the reactants in Step I to the exponents in the rate law indicates a correct understanding.

Information for Free-Response Question 5

Timing	The student should spend approximately 7–8 minutes on this question.
Essential Knowledge	2.C.4 The localized electron bonding model describes and predicts molecular geometry using Lewis diagrams and the VSEPR model.
Science Practice	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Learning Objective	2.21 The student is able to use Lewis diagrams and VSEPR to predict the geometry of molecules, identify hybridization, and make predictions about polarity.
Characteristics of a STRONG Response	Part (a)(i) The student is able to • identify the number of electron domains around the carbon atom (i.e., the steric number, SN, of the carbon atom) as 3 • connect SN = 3 to an ideal trigonal planar geometry, and therefore an ideal angle of 120° • reason about expected deviations from the ideal bond angle in terms of the presence of a double bond between the carbon and oxygen atoms Part (a)(ii) The student is able to • identify the steric number of the nitrogen atom as SN = 4 • connect SN = 4 to an ideal tetrahedral geometry, and therefore an ideal angle of 109.5° • reason about expected deviations from the ideal bond angle in terms of the presence of a lone pair of electrons on the nitrogen atom OR The student is able to note that there are resonance structures for the molecule. Part (b) The student is able to generate the Lewis structure for formic acid shown below, based on the requirements that the carbon atom has the same steric number, SN = 3, as in methanamide, and each atom must satisfy the octet rule. All bonds are drawn with the correct order, including the double bond between carbon and oxygen, and all lone pairs are shown correctly. 

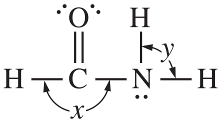
Characteristics of a GOOD Response	Part (a)(i) The student is able to identify the steric number of the carbon atom as SN = 3, and connect this to a trigonal planar geometry with an ideal angle of 120°. However, deviations from the ideal bond angle are not considered. Therefore, the student gives an angle of 120° but does not give any justification. Part (a)(ii) The student is able to identify the steric number of the nitrogen atom as SN = 4 and connect this to a tetrahedral geometry with an ideal angle of 109.5°. However, deviations from the ideal bond angle are not considered. Therefore, the student gives an angle of 109.5° but does not give any justification. Part (b) The student is able to generate a structure with the connectivity of formic acid, but fails to draw all bonds in the correct order, or fails to include all lone pairs.
Characteristics of a WEAK Response	Part (a)(i) The student has difficulty in determining the steric number of the carbon atom and using this to predict a molecular geometry. For instance, the student may incorrectly conclude that the carbon atom has a steric number of 4 due to the double bond between the C and O. Part (a)(ii) The student has difficulty in determining the steric number of the nitrogen atom and using this to predict a molecular geometry. Part (b) The student is able to generate a structure with the correct number of atoms but with one or more of the following flaws • some atoms have too few or too many electrons to satisfy the octet rule • the connectivity of the atoms is not that of formic acid • the number of electrons is not equal to the 18 valence electrons

Scoring Guidelines for Question 5

Question 5
(4 Points)

Methanamide, CH_3NO, is a liquid at 25°C.

(a) The complete Lewis electron-dot diagram for methanamide is shown below.



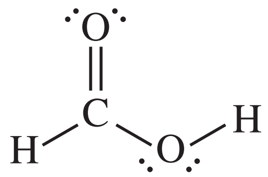
(i) In the molecule, angle *x* is not 180°. Estimate the observed angle. Justify your answer.

Angle *x* is approximately 120°. Three electron domains around the carbon atom will maximally separate the electrons and minimize the energy when the bond angles are 120°.	1 point is earned for the correct angle with justification. <u>Note</u>: accept 120° ± 10° for the angle (i.e., $110° \leq x \leq 130°$.) Also accept steric number (SN) = 3 or trigonal planar geometry for the justification in part (i) only.)

(ii) In the molecule, angle *y* is not 90°. Explain why in terms of electron domains (VSEPR model).

Angle *y* is approximately 109.5°. Four electron domains around the nitrogen atom will maximally separate the electrons and minimize the energy when the bond angles are 109.5°. OR Angle *y* is approximately 120°. Considering possible resonance structures involving a double bond between the C and N atoms, there are three electron domains around the nitrogen atom. In this case, minimization of energy leads to bond angles of approximately 120°.	1 point is earned for the correct justification for an angle different than 90°. <u>Note</u>: the justification need not give a specific bond angle, but it must mention the repulsion of 4 electron domains (or 3 electron domains, if resonance structures are mentioned).

(b) Consider a molecule with the formula CH_2O_2. The structure of this molecule has a geometry around the carbon atom similar to the geometry around carbon in methanamide. In the box provided below, draw the complete Lewis electron-dot diagram for the molecule.

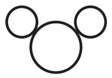
	2 points are earned for a correct Lewis electron-dot diagram for formic acid. Notes: 1 point is earned for the correct skeletal structure for formic acid with the C=O double bond (i.e., containing all five bonding pairs) but missing one or more lone pairs. Also, 1 point is earned for a Lewis electron-dot diagram representing (i) the correct molecular formula (CH_2O_2) (ii) with three electron domains and at least three bonded pairs of electrons around the carbon atom, with no more than three bonded pairs of electrons around any oxygen atom, and (iii) the proper distribution of all 18 electrons in accordance with the octet rule.

Information for Free-Response Question 6

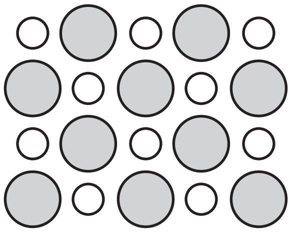
Timing	The student should spend approximately 7–8 minutes on this question.
Essential Knowledge	2.A.3 Solutions are homogenous mixtures in which the physical properties are dependent on the concentration of the solute and the strengths of all interactions among the particles of the solutes and solvent. 3.C.3 Electrochemistry shows the interconversion between chemical and electrical energy in galvanic and electrolytic cells.
Science Practices	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain. 5.1 The student can analyze data to identify patterns or relationships.
Learning Objectives	2.8 The student can draw and/or interpret representations of solutions that show the interactions between the solute and solvent. 3.13 The student can analyze data regarding galvanic or electrolytic cells to identify properties of the underlying redox reactions.
Characteristics of a STRONG Response	Part (a) The student is able to provide a sketch that shows: (1) one Li^+ ion and one Cl^- ion separated from each other, labeled, and charged; (2) each ion surrounded by at least two water molecules; (3) the water molecules are drawn as bent molecules with oxygen in the middle, and are oriented with the oxygen end pointed towards the Li^+ and the hydrogen end point toward the Cl^- ion. Part (b) The student is able to identify the following species at the cathode with the proper justification: $H_2(g)$ and $OH^-(aq)$ The hydrogen atoms in H_2O are reduced to H_2 at the cathode because this reaction has a less negative standard reduction potential than the reduction of lithium ions to $Li(s)$.
Characteristics of a GOOD Response	Part (a) The student is able to provide a sketch that shows: (1) one Li^+ ion and one Cl^- ion separated from each other, labeled and charged; and (2) the water molecules are drawn as bent molecules with oxygen in the middle, but the molecules are not oriented correctly around the two ions. Part (b) The student is able to identify one species at the cathode with the following justification: H_2 is produced at the cathode because this reaction is more favorable.
Characteristics of a WEAK Response	Part (a) The student is able to provide a sketch that shows: (1) LiCl with the two atoms attached to one another and/or at the bottom of the container; and (2) the water molecules are drawn as bent molecules with oxygen in the middle, but the molecules are not oriented correctly around the LiCl. Part (b) The student is able to correctly identify one species at the cathode with an incorrect justification such as: H_2 is produced at the cathode because it is a gas and forms bubbles.

Scoring Guidelines for Question 6

Question 6
(4 Points)



H_2O molecule

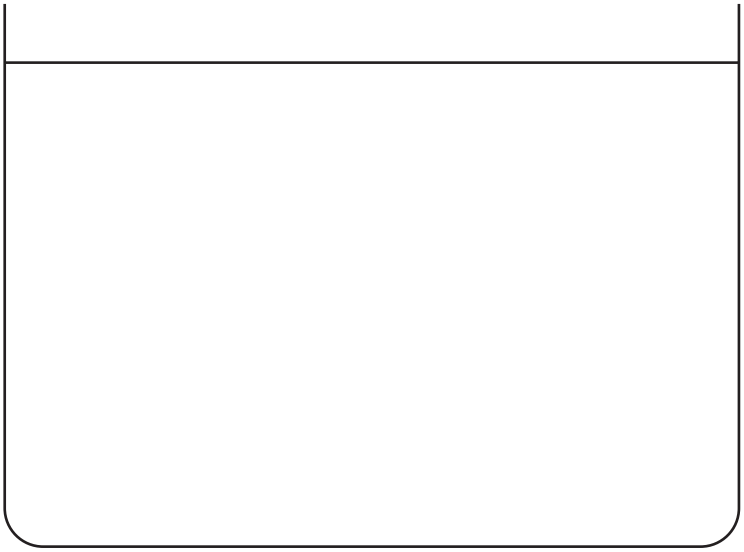


LiCl crystal

The structures of a water molecule and a crystal of LiCl(*s*) are represented above. A student prepares a 1.0 *M* solution by dissolving 4.2 g of LiCl(*s*) in enough water to make 100 mL of solution.

(a) In the space provided below, show the interactions of the components of LiCl(*aq*) by making a drawing that represents the different particles present in the solution. Base the particles in your drawing on the particles shown in the representations above. Include only one formula unit of LiCl and no more than ten molecules of water. Your drawing must include the following details.

- identity of ions (symbol and charge)
- the arrangement and proper orientation of the particles in the solution



LiCl (*aq*)

The sketch should clearly show: 1. a clear representation of at least one Li^+ ion and one Cl^- ion separated from each other, labeled, and charged; 2. each ion surrounded by at least two H_2O molecules; and 3. H_2O molecules with the proper orientation around each ion (i.e., the oxygen end of the water molecules closer to the lithium ion and the hydrogen end of the water molecules closer to the chloride ion).	1 point is earned for a correctly drawn and labeled particulate representation of the ions. (Representation must indicate that the smaller ion is Li^+. Representations that include more than one formula unit of LiCl (dissolved or undissolved) are acceptable as long as at least one of the formula units is separated into its ions and the ions are correctly labeled with their respective identities and charges.) 1 point is earned for a correctly drawn particulate representation of water molecules of hydration surrounding the ions. 1 point is earned for correctly representing the orientation of the water molecules of hydration with the proper polarity.

(b) The student passes a direct current through the solution and observes that chlorine gas is produced at the anode. Identify the chemical species produced at the cathode and justify your answer using the information given in the table below.

Half-reaction	Standard Reduction Potential at 25°C (V)
$Li^+(aq) + e^- \rightarrow Li(s)$	− 3.05
$2\ H_2O(l) + 2\ e^- \rightarrow H_2(g) + 2\ OH^-(aq)$	− 0.83

$H_2(g)$ and $OH^-(aq)$ The hydrogen atoms in H_2O are reduced to H_2 at the cathode because this reaction has a higher (more favorable or less negative) standard reduction potential than the reduction of lithium ions to Li(*s*).	1 point is earned for correctly identifying either of the chemical species produced at the cathode with the proper justification. Note: the justification must clearly indicate that “higher” means “less negative.” A “lower magnitude” negative value also earns the point.

Information for Free-Response Question 7

Timing	The student should spend approximately 7–8 minutes on this question.
Essential Knowledge	2.B.3 Intermolecular forces play a key role in determining the properties of substances, including biological structures and interactions. 6.C.2 The pH is an important characteristic of aqueous solutions that can be controlled with buffers. Comparing pH to pK_a allows one to determine the protonation state of a molecule with a labile proton.
Science Practices	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.3 The student can estimate numerically quantities that describe natural phenomena. 5.1 The student can analyze data to identify patterns or relationships. 6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objectives	2.15 The student is able to explain observations regarding the solubility of ionic solids and molecules in water and other solvents on the basis of particle views that include intermolecular interactions and entropic effects. 6.19 The student can relate the predominant form of a chemical species involving a labile proton (i.e., protonated/deprotonated form of a weak acid) to the pH of a solution and the pK_a associated with the labile proton.
Characteristics of a STRONG Response	Part (a) The student can predict that $In^-(aq)$ will be the predominant form of the acid in a buffer of pH of 7, based on • the ability of the buffer to maintain the pH at 7 and • the reasoning that since the solution pH is greater than the pK_a, the conjugate base form (In^-) will be the predominant form. Part (b) The student can explain the difference in color between the oil layers of the two beakers based on: • The yellow color of the oil layer is due to the presence of HIn in the oil layer. • Since HIn is neutral while In^- is charged, and since the oil layer is much less polar than water, HIn will be much more soluble than In^- in oil. • In beaker X, the pH of 3 in the buffer solution is less than pK_a, so the conjugate acid form (HIn) is the predominant form. Some of the HIn partitions into the oil layer, giving it a yellow color. • In beaker Y, the pH of 7 in the buffer solution is greater than pK_a, so the conjugated base form (In^-) is the predominant form. Since the charged In^- species is not soluble in oil, it remains in the buffer layer and the oil layer is colorless.

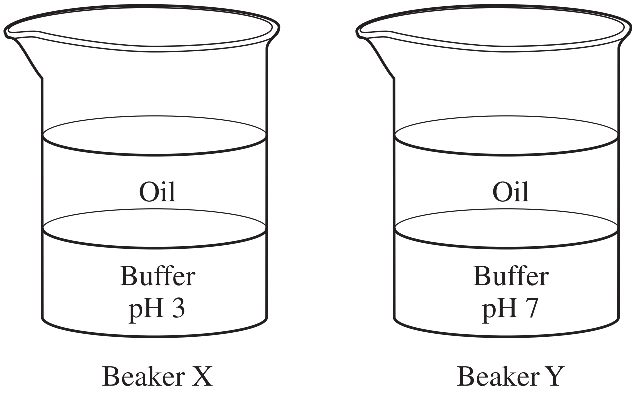
Characteristics of a GOOD Response	Part (a) The student connects pH to the relative concentrations of HIn and In^- through Le Chatelier's principle, with the low concentrations of H_3O^+ in a buffer with pH = 7 pushing the equilibrium towards In^-. However, the reasoning is not based on explicit comparison of pH and pK_a. Part (b) The student is able to reason about the differences between the two layers based on some of the relevant factors: • The yellow color of the oil layer is due to the presence of HIn in the oil layer. • Since HIn is neutral while In^- is charged, and since the oil layer is much less polar than water, HIn will be much more soluble in oil than In^-. • In beaker X, the pH of 3 in the buffer solution is less than pK_a, so the conjugate acid form (HIn) is the predominant form. Some of the HIn partitions into the oil layer, giving it a yellow color. • In beaker Y, the pH of 7 in the buffer solution is greater than pK_a, so the conjugated base form (In^-) is the predominant form. Since the charged In^- species is not soluble in oil, it remains in the buffer layer and the oil layer is colorless. However, key aspects of the reasoning are missing. For instance, the relative solubilities of HIn and In^- in oil and water may not be connected to forces between the particles. The larger concentration of HIn in beaker X than beaker Y may be connected to the difference in pH, but explicit comparisons to pK_a may be missing. The lack of a blue color in the oil layer in beaker Y may not be connected to the expected low solubility of In^- in oil.
Characteristics of a WEAK Response	Part (a) The student can reason in terms of an equilibrium between conjugate acid and base forms but is not able to connect the position of the equilibrium to the pH of the buffer solution. Part (b) The student may connect the yellow color of the oil layer in beaker Y to the presence of HIn and make vague connections between the presence of HIn and the pH of the buffer layer. However, the reasoning does not connect the relative concentrations of HIn and In^- to pH and pK_a. The reasoning also fails to connect the partitioning of HIn and In^- between water and oil to intermolecular forces.

Scoring Guidelines for Question 7

Question 7
(4 Points)

$$\underset{yellow}{HIn(aq)} + H_2O(l) \rightleftarrows \underset{blue}{In^-(aq)} + H_3O^+(aq)$$

The indicator HIn is a weak acid with a pK_a value of 5.0. It reacts with water as represented in the equation above. Consider the two beakers below. Each beaker has a layer of colorless oil (a nonpolar solvent) on top of a layer of aqueous buffer solution. In beaker X the pH of the buffer solution is 3, and in beaker Y the pH of the buffer solution is 7. A small amount of HIn is placed in both beakers. The mixtures are stirred well, and the oil and water layers are allowed to separate.



(a) What is the predominant form of HIn in the aqueous buffer in beaker Y, the acid form or the conjugate base form? Explain your reasoning.

The conjugate base form, $In^-(aq)$, is the predominant form of the indicator in the aqueous pH 7 buffer in beaker Y. This is because the pH is greater than the pK_a of HIn, causing the equilibrium to form a significant amount of products, $In^-(aq)$ and $H_3O^+(aq)$.	1 point is earned for correctly identifying $In^-(aq)$ as the predominant form in the aqueous layer of beaker Y because the solution is not acidic (may be implicit). 1 point is earned for stating that $pH > pK_a$ and that this causes the equilibrium to favor the products.

(b) In beaker X the oil layer is yellow, whereas in beaker Y the oil layer is colorless. Explain these observations in terms of both acid-base equilibria and interparticle forces.

At pH 3 the acid form $HIn(aq)$ predominates in the aqueous layer of beaker X because $pH < pK_a$. Since $HIn(aq)$ is a neutral molecule, some of it can dissolve in the oil layer of beaker X because of London dispersion interactions with the oil, causing the oil layer to be yellow. Since $In^-(aq)$ is charged, it will preferentially dissolve in the aqueous layer of beaker Y because of ion-dipole interactions with the water, leaving the oil layer colorless.	1 point is earned for explaining the yellow color in the oil layer of beaker X in terms of acid-base equilibrium and interparticle forces between HIn molecules and oil molecules. 1 point is earned for explaining the colorless oil layer of beaker Y in terms of interparticle forces between In^- ions and water molecules.

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