CollegeBoard AP

CHEMISTRY

Course Description

Effective Fall 2012

AP Course Descriptions are updated regularly. Please visit AP Central® (apcentral.collegeboard.org) to determine whether a more recent Course Description PDF is available.

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 more than 5,900 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.

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About the AP® Program

AP® enables students to pursue college-level studies while still in high school. Through more than 30 courses, each culminating in a rigorous exam, AP provides willing and academically prepared students with the opportunity to earn college credit, advanced placement, or both. Taking AP courses also demonstrates to college admission officers that students have sought out the most rigorous course work available to them.

Each AP course is modeled upon a comparable college course, and college and university faculty play a vital role in ensuring that AP courses align with college-level standards. Talented and dedicated AP teachers help AP students in classrooms around the world develop and apply the content knowledge and skills they will need in college.

Each AP course concludes with a college-level assessment developed and scored by college and university faculty as well as experienced AP teachers. AP Exams are an essential part of the AP experience, enabling students to demonstrate their mastery of college-level course work. More than 90 percent of four-year colleges and universities in the United States grant students credit, placement, or both on the basis of successful AP Exam scores. Universities in more than 60 countries recognize AP Exam scores in the admission process and/or award credit and placement for qualifying scores. Visit www.collegeboard.org/ap/creditpolicy to view AP credit and placement policies at more than 1,000 colleges and universities.

Performing well on an AP Exam means more than just the successful completion of a course; it is a pathway to success in college. Research consistently shows that students who score a 3 or higher on AP Exams typically experience greater academic success in college and are more likely to graduate on time than otherwise comparable non-AP peers. Additional AP studies are available at www.collegeboard.org/apresearchsummaries.

Offering AP Courses and Enrolling Students

This course description details the essential information required to understand the objectives and expectations of an AP course. The AP Program unequivocally supports the principle that each school develops and implements its own curriculum that will enable students to develop the content knowledge and skills described here.

Schools wishing to offer AP courses must participate in the AP Course Audit, a process through which AP teachers' syllabi are reviewed by college faculty. The AP Course Audit was created at the request of College Board members who sought a means for the College Board to provide teachers and administrators with clear guidelines on curricular and resource requirements for AP courses and to help colleges and universities validate courses marked "AP" on students' transcripts. This process ensures that AP teachers' syllabi meet or exceed the curricular and resource expectations that college and secondary school faculty have established for college-level courses. For more information on the AP Course Audit, visit www.collegeboard.org/apcourseaudit.

How AP Courses and Exams Are Developed

AP courses and exams are designed by committees of college faculty and expert AP teachers who ensure that each AP subject reflects and assesses college-level expectations. AP Development 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 coursework reflects current scholarship and advances in the discipline. To find a list of each subject's current AP Development Committee members, please visit apcentral.collegeboard.org/developmentcommittees.

The AP Development Committees are also responsible for drawing clear and well-articulated connections between the AP course and AP Exam — work that includes designing and approving exam specifications and exam questions. 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 there is an appropriate spread of difficulty across the questions.

Throughout AP course and exam development, the College Board gathers feedback from various stakeholders in both secondary schools and higher education institutions. This feedback is carefully considered to ensure that AP courses and exams are able to provide students with a college-level learning experience and the opportunity to demonstrate their qualifications for advanced placement upon college entrance.

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 weighted results of the computer-scored multiple-choice questions. These composite, weighted raw scores are converted into the reported AP Exam scores of 5, 4, 3, 2, and 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 Exam 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.

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.

AP Chemistry

THE COURSE

The AP Chemistry course is designed to be the equivalent of the general chemistry course usually taken during the first college year. For some students, this course enables them to undertake, in their first year, second-year work in the chemistry sequence at their institution or to register in courses in other fields where general chemistry is a prerequisite. For other students, the AP Chemistry course fulfills the laboratory science requirement and frees time for other courses.

AP Chemistry should meet the objectives of a good college general chemistry course. Students in such a course should attain a depth of understanding of fundamentals and a reasonable competence in dealing with chemical problems. The course should contribute to the development of the students' abilities to think clearly and to express their ideas, orally and in writing, with clarity and logic. The college course in general chemistry differs qualitatively from the usual first secondary school course in chemistry with respect to the kind of textbook used, the topics covered, the emphasis on chemical calculations and the mathematical formulation of principles, and the kind of laboratory work done by students. Quantitative differences appear in the number of topics treated, the time spent on the course by students, and the nature and the variety of experiments done in the laboratory. *Secondary schools that wish to offer an AP Chemistry course must be prepared to provide a laboratory experience equivalent to that of a typical college course.*

Prerequisites

The AP Chemistry course is designed to be taken only after the successful completion of a first course in high school chemistry. Surveys of students who take the AP Chemistry Exam indicate that the probability of achieving a score of 3 or higher is significantly greater for students who successfully complete a first course in high school chemistry prior to undertaking the AP course. *Thus it is strongly recommended that credit in a first-year high school chemistry course be a prerequisite for enrollment in an AP Chemistry class. In addition, the recommended mathematics prerequisite for an AP Chemistry class is the successful completion of a second-year algebra course.*

The advanced work in chemistry should not displace any other part of the student's science curriculum. It is highly desirable that a student have a course in secondary school physics and a four-year college-preparatory program in mathematics.

Time Allocations

Developing the requisite intellectual and laboratory skills required of an AP Chemistry student demands that adequate classroom and laboratory time be scheduled. Surveys of students taking the AP Chemistry Exam indicate that performance improved as both total instructional time and time devoted to laboratory work increased.

At least six class periods or the equivalent per week should be scheduled for an AP Chemistry course. Of the total allocated time, a minimum of one double period per week or the equivalent, preferably in a single session, should be spent engaged in laboratory work. Time devoted to class and laboratory demonstrations should not be counted as part of the laboratory period.

Students in an AP Chemistry course should spend at least five hours a week in individual study outside of the classroom.

Textbooks

Current college textbooks are probably the best indicators of the level of the college general chemistry course that AP Chemistry is designed to represent. A contemporary college chemistry text that stresses principles and concepts and their relation to the descriptive chemistry on which they are based should be selected. Even the more advanced secondary school texts cannot serve adequately as texts for an AP course that aims to achieve its objectives. A list of example textbooks appropriate for use in this course is available on the AP Chemistry Course Home Page at AP Central (apcentral.collegeboard.org/chemistry).

The Teachers' Resources section of AP Central (apcentral.collegeboard.org) has a searchable database of chemistry resources. Many of these resources have been reviewed and rated by experienced AP Chemistry teachers.

Topic Outline

The importance of the theoretical aspects of chemistry has brought about an increasing emphasis on these aspects of the content of general chemistry courses. Topics such as the structure of matter, kinetic theory of gases, chemical equilibria, chemical kinetics, and the basic concepts of thermodynamics are now being presented in considerable depth.

If the objectives of a college-level general chemistry course are to be achieved, instruction should be done by a teacher who has completed an undergraduate major program in chemistry including at least a year's work in physical chemistry. Teachers with such training are best able to present a course with adequate breadth and depth and to develop students' abilities to use the fundamental facts of the science in their reasoning. Because of the nature of the AP course, the teacher needs time for extra preparation for both class and laboratory and should have a teaching load that is adjusted accordingly.

Chemistry is broad enough to permit flexibility in its teaching, and college teachers exercise considerable freedom in methods and arrangements of topics in the effort to reach the objectives of their courses. The AP Chemistry Development Committee has no desire to impose greater uniformity on secondary schools than now exists in colleges.

The following list of topics for an AP course is intended to be a *guide* to the level and breadth of treatment expected rather than to be a syllabus. The percentage after each major topic indicates the approximate proportion of multiple-choice questions on the exam that pertain to the topic.

I. Structure of Matter (20%)

A. Atomic theory and atomic structure
   1. Evidence for the atomic theory
   2. Atomic masses; determination by chemical and physical means
   3. Atomic number and mass number; isotopes
   4. Electron energy levels: atomic spectra, quantum numbers, atomic orbitals
   5. Periodic relationships including, for example, atomic radii, ionization energies, electron affinities, oxidation states

B. Chemical bonding
   1. Binding forces
      a. Types: ionic, covalent, metallic, hydrogen bonding, van der Waals (including London dispersion forces)
      b. Relationships to states, structure, and properties of matter
      c. Polarity of bonds, electronegativities
   2. Molecular models
      a. Lewis structures
      b. Valence bond: hybridization of orbitals, resonance, sigma and pi bonds
      c. VSEPR
   3. Geometry of molecules and ions, structural isomerism of simple organic molecules and coordination complexes; dipole moments of molecules; relation of properties to structure

C. Nuclear chemistry: nuclear equations, half-lives, and radioactivity; chemical applications

II. States of Matter (20%)

A. Gases
   1. Laws of ideal gases
      a. Equation of state for an ideal gas
      b. Partial pressures
   2. Kinetic molecular theory
      a. Interpretation of ideal gas laws on the basis of this theory
      b. Avogadro's hypothesis and the mole concept
      c. Dependence of kinetic energy of molecules on temperature
      d. Deviations from ideal gas laws

B. Liquids and solids
   1. Liquids and solids from the kinetic-molecular viewpoint
   2. Phase diagrams of one-component systems
   3. Changes of state, including critical points and triple points
   4. Structure of solids; lattice energies

C. Solutions
   1. Types of solutions and factors affecting solubility
   2. Methods of expressing concentration (use of normalities is not tested)
   3. Raoult's law and colligative properties (nonvolatile solutes); osmosis
   4. Nonideal behavior (qualitative aspects)

III. Reactions (35–40%)

A. Reaction types
   1. Acid-base reactions; concepts of Arrhenius, Brønsted-Lowry and Lewis; coordination complexes; amphoterism
   2. Precipitation reactions
   3. Oxidation-reduction reactions
      a. Oxidation number
      b. The role of the electron in oxidation-reduction
      c. Electrochemistry: electrolytic and galvanic cells; Faraday's laws; standard half-cell potentials; Nernst equation; prediction of the direction of redox reactions

B. Stoichiometry
   1. Ionic and molecular species present in chemical systems: net ionic equations
   2. Balancing of equations, including those for redox reactions
   3. Mass and volume relations with emphasis on the mole concept, including empirical formulas and limiting reactants

C. Equilibrium
   1. Concept of dynamic equilibrium, physical and chemical; Le Chatelier's principle; equilibrium constants
   2. Quantitative treatment
      a. Equilibrium constants for gaseous reactions: K_p, K_c
      b. Equilibrium constants for reactions in solution
         (1) Constants for acids and bases; pK; pH
         (2) Solubility product constants and their application to precipitation and the dissolution of slightly soluble compounds
         (3) Common ion effect; buffers; hydrolysis

D. Kinetics
   1. Concept of rate of reaction
   2. Use of experimental data and graphical analysis to determine reactant order, rate constants and reaction rate laws
   3. Effect of temperature change on rates
   4. Energy of activation; the role of catalysts
   5. The relationship between the rate-determining step and a mechanism

E. Thermodynamics
   1. State functions
   2. First law: change in enthalpy; heat of formation; heat of reaction; Hess's law; heats of vaporization and fusion; calorimetry
   3. Second law: entropy; free energy of formation; free energy of reaction; dependence of change in free energy on enthalpy and entropy changes
   4. Relationship of change in free energy to equilibrium constants and electrode potentials

IV. Descriptive Chemistry (10–15%)

Knowledge of specific facts of chemistry is essential for an understanding of principles and concepts. These descriptive facts, including the chemistry involved in environmental and societal issues, should not be isolated from the principles being studied but should be taught throughout the course to illustrate and illuminate the principles. The following areas should be covered:

1. Chemical reactivity and products of chemical reactions
2. Relationships in the periodic table: horizontal, vertical and diagonal with examples from alkali metals, alkaline earth metals, halogens, and the first series of transition elements
3. Introduction to organic chemistry: hydrocarbons and functional groups (structure, nomenclature, chemical properties)

V. Laboratory (5–10%)

The differences between college chemistry and the usual secondary school chemistry course are especially evident in the laboratory work. The AP Chemistry Exam includes some questions based on experiences and skills students acquire in the laboratory:

- making observations of chemical reactions and substances
- recording data
- calculating and interpreting results based on the quantitative data obtained
- communicating effectively the results of experimental work

For information on the requirements for an AP Chemistry laboratory program, the *Guide for the Recommended Laboratory Program* is included on pages 29–39 of this book. The guide describes the general requirements for an AP Chemistry laboratory program and contains a list of recommended experiments. Also included in the guide are resources that AP Chemistry teachers should find helpful in developing a successful laboratory program.

Colleges have reported that some AP students, while doing well on the exam, have been at a serious disadvantage because of inadequate laboratory experience. Meaningful laboratory work is important in fulfilling the requirements of a college-level course of a laboratory science and in preparing a student for sophomore-level chemistry courses in college.

Because chemistry professors at some institutions ask to see a record of the laboratory work done by an AP student before making a decision about granting credit, placement or both, in the chemistry program, students should keep a laboratory notebook that includes reports of their laboratory work in such a fashion that the reports can be readily reviewed.

Chemical Calculations

The following list summarizes types of problems either explicitly or implicitly included in the preceding material. Attention should be given to significant figures, precision of measured values, and the use of logarithmic and exponential relationships. Critical analysis of the reasonableness of results is to be encouraged.

1. Percentage composition
2. Empirical and molecular formulas from experimental data
3. Molar masses from gas density, freezing-point and boiling-point measurements
4. Gas laws, including the ideal gas law, Dalton's law and Graham's law
5. Stoichiometric relations using the concept of the mole; titration calculations
6. Mole fractions; molar and molal solutions
7. Faraday's laws of electrolysis
8. Equilibrium constants and their applications, including their use for simultaneous equilibria
9. Standard electrode potentials and their use; Nernst equation
10. Thermodynamic and thermochemical calculations
11. Kinetics calculations

THE EXAM

The AP Chemistry Exam has two main parts, Section I and Section II, that contribute equally (50 percent each) toward the final score. Section I consists of 75 multiple-choice questions that cover a broad range of topics. Section II consists of six free-response questions: three multipart quantitative questions, one question on writing balanced chemical equations and answering a short question for three different sets of reactants, and two multipart questions that are essentially nonquantitative.

Teachers should not try to prepare students to answer every question in Section I of the exam. To be broad enough in scope to give every student who has covered an adequate amount of material an opportunity to make a good showing, the exam must be so comprehensive that no student should be expected to make a perfect or near-perfect score.

A period of 90 minutes is allotted for Section I of the exam. Section II is divided into two parts: for Part A (55 minutes), students are allowed the use of a calculator, but for Part B (40 minutes), no calculators are permitted.

Every Section II of the exam will contain one quantitative question that is based on chemical equilibrium and one question that is based on laboratory. The laboratory question may appear in Part A and be quantitative, or it may appear in Part B and require little or no calculation.

In past AP Chemistry Examinations, the practice for writing units associated with changes in thermodynamic quantities in given reactions has been to use kJ/mol and kJ/(mol·K) for energy and entropy changes, respectively. Starting in May 2012, the use of the term "mol_{rxn}" (read aloud as "mole reaction" or "mole of reaction") in thermodynamic units will be phased in as a move toward a standard practice in the AP Chemistry Examination. Specifically, the term mol_{rxn} will be used in the denominator when quantities such as changes in enthalpy, Gibbs free energy, and entropy are expressed in the context of given reactions. For example, consider the reaction represented below.

$$2\ Al(s)\ +\ 3\ Cl_2(g)\ \rightarrow\ 2\ AlCl_3(s)$$

For this reaction, $\Delta H^\circ = -1411\ kJ/mol_{rxn}$, $\Delta G^\circ = -1260\ kJ/mol_{rxn}$, and $\Delta S^\circ = -505\ J/(mol_{rxn} \cdot K)$. In each case, the values given are for the reaction that occurs as written, specifically with the coefficients referring to numbers of moles of substances (not individual atoms or molecules).

Calculators

The policy regarding the use of calculators on the AP Chemistry Exam was developed to address the rapid expansion of the capabilities of scientific calculators, which include not only programming and graphing functions but also the availability of stored equations and other data. For the section of the exam in which calculators are permitted, students should be allowed to use the calculators to which they are accustomed, except as noted below.* On the other hand, they should not have access to information in their calculators that is not available to other students, if that information is needed to answer the questions.

Therefore, calculators are not permitted on the *multiple-choice section* of the AP Chemistry Exam. The purpose of the multiple-choice section is to assess the breadth of students' knowledge and understanding of the basic concepts of chemistry. The multiple-choice questions emphasize conceptual understanding as well as qualitative and simple quantitative applications of principles. Many chemical and physical principles and relationships are quantitative by nature and can be expressed as equations. Knowledge of the underlying basic definitions and principles, expressed as equations, is a part of the content of chemistry that should be learned by chemistry students and will continue to be assessed in the multiple-choice section. However, any numeric calculations that require use of these equations in the multiple-choice section will be limited to simple arithmetic so that they can be done quickly, either mentally or with paper and pencil. Also, in some questions the answer choices differ by several orders of magnitude so that the questions can be answered by estimation. Refer to sample questions on pages 15–17 (#6, 8, 11, 12, 16, and 17), which can be answered using simple arithmetic or by estimation. Students should be encouraged to develop their skills not only in estimating answers but also in recognizing answers that are physically unreasonable or unlikely.

Calculators (with the exceptions previously noted) will be allowed only during the first 55 minutes (Part A) of the free-response section of the exam. During this time, students will work on three problems. **Any programmable or graphing calculator may be used, and students will NOT be required to erase their calculator memories before or after the exam.** Students will not be allowed to move on to the

***Exceptions to calculator use.** Calculators that are not permitted are PowerBooks and portable/handheld computers; electronic writing pads or pen-input/stylus-driven devices (e.g., Palm, PDAs, Casio ClassPad 300); pocket organizers; models with QWERTY (i.e., typewriter) keypads (e.g., TI-92 Plus, Voyage 200); models with paper tapes; models that make noise or "talk"; models that require an electrical outlet; cell phone calculators. Students may not share calculators.

last portion of the free-response section until time is called and all calculators are put away. For the last 40 minutes (Part B) of the exam, students will work without calculators on the remaining portion of the free-response section.

Equation Tables

Tables containing equations commonly used in chemistry are printed in the free-response (Section II) exam booklet for students to use when taking the free-response section. The equation tables are NOT permitted for use with the multiple-choice section. In general, the equations for each year's exam are printed and distributed with the Course Description at least a year in advance so that students can become accustomed to using them throughout the year. However, because the equation tables will be provided with the exam, students will NOT be allowed to bring their own copies to the exam room. The latest version of the equation tables is shown on pages 12–13 of this booklet.

One of the purposes of providing the tables of commonly used equations for use with the free-response section is to address the issue of equity for those students who do not have access to equations stored in their calculators. The availability of these equations to all students means that in the scoring of the free-response sections, little or no credit will be awarded for simply writing down equations or for answers unsupported by explanations or logical development.

The equations in the tables express relationships that are encountered most frequently in an AP Chemistry course and exam. However, they do not include all equations that might possibly be used. For example, they do not include many equations that can be derived by combining others in the tables. Nor do they include equations that are simply special cases of any that are in the tables. Students are responsible for understanding the physical principles that underlie each equation and for knowing the conditions for which each equation is applicable.

The equations are grouped in tables according to major content category. Within each table, the symbols used for the variables in that table are defined. However, in some cases the same symbol is used to represent different quantities in different tables. It should be noted that there is no uniform convention among textbooks for the symbols used in writing equations. The equation tables follow many common conventions, but in some cases consistency was sacrificed for the sake of clarity.

In summary, the purpose of minimizing numerical calculations in both sections of the exam and providing equations with the free-response section is to place greater emphasis on the understanding and application of fundamental chemical principles and concepts. For solving problems and writing essays, a sophisticated programmable or graphing calculator, or the availability of stored equations, is no substitute for a thorough grasp of the chemistry involved.

ADVANCED PLACEMENT CHEMISTRY EQUATIONS AND CONSTANTS

ATOMIC STRUCTURE

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

$\lambda = \dfrac{h}{m\upsilon} \qquad p = m\upsilon$

$E_n = \dfrac{-2.178 \times 10^{-18}}{n^2}$ joule

E = energy
ν = frequency
λ = wavelength
p = momentum
υ = velocity
n = principal quantum number
m = mass

Speed of light, $c = 3.0 \times 10^8$ m s^{-1}

Planck's constant, $h = 6.63 \times 10^{-34}$ J s

Boltzmann's constant, $k = 1.38 \times 10^{-23}$ J K^{-1}

Avogadro's number $= 6.022 \times 10^{23}$ mol^{-1}

Electron charge, $e = -1.602 \times 10^{-19}$ coulomb

1 electron volt per atom = 96.5 kJ mol^{-1}

EQUILIBRIUM

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

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

$K_w = [OH^-][H^+] = 1.0 \times 10^{-14}$ @ 25°C
$= K_a \times K_b$

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

$14 = pH + pOH$

$pH = pK_a + \log\dfrac{[A^-]}{[HA]}$

$pOH = pK_b + \log\dfrac{[HB^+]}{[B]}$

$pK_a = -\log K_a,\ pK_b = -\log K_b$

$K_p = K_c(RT)^{\Delta n}$,
where Δn = moles product gas − moles reactant gas

Equilibrium Constants
K_a (weak acid)
K_b (weak base)
K_w (water)
K_p (gas pressure)
K_c (molar concentrations)

THERMOCHEMISTRY/KINETICS

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

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

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

$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$
$= -RT \ln K = -2.303\,RT \log K$
$= -n\mathscr{F}E^\circ$

$\Delta G = \Delta G^\circ + RT \ln Q = \Delta G^\circ + 2.303\,RT \log Q$

$q = mc\Delta T$

$C_p = \dfrac{\Delta H}{\Delta T}$

$\ln[A]_t - \ln[A]_0 = -kt$

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

$\ln k = \dfrac{-E_a}{R}\left(\dfrac{1}{T}\right) + \ln A$

S° = standard entropy
H° = standard enthalpy
G° = standard free energy
E° = standard reduction potential
T = temperature
n = moles
m = mass
q = heat
c = specific heat capacity
C_p = molar heat capacity at constant pressure
E_a = activation energy
k = rate constant
A = frequency factor

Faraday's constant, $\mathscr{F}$ = 96,500 coulombs per mole of electrons

Gas constant, R = 8.31 J mol^{-1} K^{-1}
= 0.0821 L atm mol^{-1} K^{-1}
= 62.4 L torr mol^{-1} K^{-1}
= 8.31 volt coulomb mol^{-1} K^{-1}

GASES, LIQUIDS, AND SOLUTIONS

$$PV = nRT$$

$$\left(P + \frac{n^2 a}{V^2}\right)(V - nb) = nRT$$

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

$$P_{total} = P_A + P_B + P_C + ...$$

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

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

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

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

$$u_{rms} = \sqrt{\frac{3kT}{m}} = \sqrt{\frac{3RT}{\boldsymbol{M}}}$$

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

$$KE \text{ per mole} = \frac{3}{2} RT$$

$$\frac{r_1}{r_2} = \sqrt{\frac{\boldsymbol{M}_2}{\boldsymbol{M}_1}}$$

molarity, M = moles solute per liter solution

molality = moles solute per kilogram solvent

$$\Delta T_f = iK_f \times \text{molality}$$

$$\Delta T_b = iK_b \times \text{molality}$$

$$\pi = iMRT$$

$$A = abc$$

P = pressure
V = volume
T = temperature
n = number of moles
D = density
m = mass
υ = velocity

u_{rms} = root-mean-square speed
KE = kinetic energy
r = rate of effusion
$\boldsymbol{M}$ = molar mass
π = osmotic pressure
i = van't Hoff factor
K_f = molal freezing-point depression constant
K_b = molal boiling-point elevation constant
A = absorbance
a = molar absorptivity
b = path length
c = concentration
Q = reaction quotient
I = current (amperes)
q = charge (coulombs)
t = time (seconds)
E° = standard reduction potential
K = equilibrium constant

OXIDATION-REDUCTION; ELECTROCHEMISTRY

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

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

$$E_{cell} = E^{\circ}_{cell} - \frac{RT}{n\mathcal{F}} \ln Q = E^{\circ}_{cell} - \frac{0.0592}{n} \log Q \quad @\ 25^{\circ}C$$

$$\log K = \frac{nE^{\circ}}{0.0592}$$

Gas constant, $R = 8.31 \text{ J mol}^{-1} \text{ K}^{-1}$
$= 0.0821 \text{ L atm mol}^{-1} \text{ K}^{-1}$
$= 62.4 \text{ L torr mol}^{-1} \text{ K}^{-1}$
$= 8.31 \text{ volt coulomb mol}^{-1} \text{ K}^{-1}$

Boltzmann's constant, $k = 1.38 \times 10^{-23} \text{ J K}^{-1}$

K_f for H_2O = $1.86 \text{ K kg mol}^{-1}$

K_b for H_2O = $0.512 \text{ K kg mol}^{-1}$

1 atm = 760 mm Hg
= 760 torr

STP = 0.00°C and 1.0 atm

Faraday's constant, $\mathcal{F}$ = 96,500 coulombs per mole of electrons

Sample Multiple-Choice Questions

The following multiple-choice questions provide a representative subset of those used in previous AP Chemistry Exams. There are two types of multiple-choice questions. The first type consists of five lettered headings followed by a list of numbered phrases. For each numbered phrase, the student is instructed to select the one heading that is most closely related to it. Each heading may be used once, more than once, or not at all in each group.

Questions 1–3 refer to atoms of the following elements.

(A) Lithium
(B) Carbon
(C) Nitrogen
(D) Oxygen
(E) Fluorine

1. In the ground state, have only 1 electron in each of the three *p* orbitals

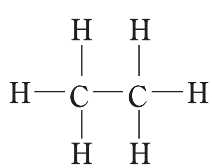
2. Have the smallest atomic radius

3. Have the smallest value for first ionization energy

The majority of the multiple-choice questions consist of questions or incomplete statements followed by five suggested answers or completions. The student is instructed to select the one that is best in each case.

4. Which of the following species is NOT planar?

(A) CO_3^{2-}
(B) NO_3^-
(C) ClF_3
(D) BF_3
(E) PCl_3



5. The hybridization of the carbon atoms in the molecule represented above can be described as

(A) *sp*
(B) sp^2
(C) sp^3
(D) dsp^2
(E) d^2sp

6. The half-life of ^{55}Cr is about 2.0 hours. The delivery of a sample of this isotope from the reactor to a certain laboratory requires 12 hours. About what mass of such material should be shipped in order that 1.0 mg of ^{55}Cr is delivered to the laboratory?

   (A) 130 mg
   (B) 64 mg
   (C) 32 mg
   (D) 11 mg
   (E) 1.0 mg

7. At constant temperature, the behavior of a sample of a real gas more closely approximates that of an ideal gas as its volume is increased because the

   (A) collisions with the walls of the container become less frequent
   (B) average molecular speed decreases
   (C) molecules have expanded
   (D) average distance between molecules becomes greater
   (E) average molecular kinetic energy decreases

8. A sealed vessel contains 0.200 mol of oxygen gas, 0.100 mol of nitrogen gas, and 0.200 mol of argon gas. The total pressure of the gas mixture is 5.00 atm. The partial pressure of the argon is

   (A) 0.200 atm
   (B) 0.500 atm
   (C) 1.00 atm
   (D) 2.00 atm
   (E) 5.00 atm

9. Which of the following accounts for the fact that liquid CO_2 is <u>not</u> observed when a piece of solid CO_2 (dry ice) is placed on a lab bench?

   (A) The phase diagram for CO_2 has no triple point.
   (B) The normal boiling point of CO_2 is lower than its normal freezing point.
   (C) $CO_2(s)$ is a molecular solid.
   (D) The critical pressure for CO_2 is approximately 1 atm.
   (E) The triple point for CO_2 is above 1 atm.

10. If ΔG for a certain reaction has a negative value at 298 K, which of the following must be true?

    I. The reaction is exothermic.
    II. The reaction occurs spontaneously at 298 K.
    III. The rate of the reaction is fast at 298 K.

    (A) I only
    (B) II only
    (C) I and II only
    (D) II and III only
    (E) I, II, and III

$$2\ SO_2(g) + O_2(g) \rightarrow 2\ SO_3(g)$$

11. A mixture of gases containing 0.20 mol of SO_2 and 0.20 mol of O_2 in a 4.0 L flask reacts to form SO_3. If the temperature is 25°C, what is the pressure in the flask after reaction is complete?

    (A) $\frac{0.4(0.082)(298)}{4}$ atm

    (B) $\frac{0.3(0.082)(298)}{4}$ atm

    (C) $\frac{0.2(0.082)(298)}{4}$ atm

    (D) $\frac{0.2(0.082)(25)}{4}$ atm

    (E) $\frac{0.3(0.082)(25)}{4}$ atm

12. A solution prepared by mixing 10 mL of 1 *M* HCl and 10 mL of 1.2 *M* NaOH has a pH of

    (A) 0 (B) 1 (C) 7 (D) 13 (E) 14

13. All of the following reactions can be defined as Lewis acid-base reactions EXCEPT

    (A) $Al(OH)_3(s) + OH^-(aq) \rightarrow Al(OH)_4^-(aq)$
    (B) $Cl_2(g) + H_2O(l) \rightarrow HOCl(aq) + H^+(aq) + Cl^-(aq)$
    (C) $SnCl_4(s) + 2\ Cl^-(aq) \rightarrow SnCl_6^{2-}(aq)$
    (D) $NH_4^+(g) + NH_2^-(g) \rightarrow 2\ NH_3(g)$
    (E) $H^+(aq) + NH_3(aq) \rightarrow NH_4^+(aq)$

14. Which of the following represents a process in which a species is reduced?

    (A) $Ca(s) \rightarrow Ca^{2+}(aq)$
    (B) $Hg(l) \rightarrow Hg_2^{2+}(aq)$
    (C) $Fe^{2+}(aq) \rightarrow Fe^{3+}(aq)$
    (D) $NO_3^-(aq) \rightarrow NO(g)$
    (E) $SO_3^{2-}(aq) \rightarrow SO_4^{2-}(aq)$

$$Cd^{2+}(aq) + 2\ e^- \rightleftarrows Cd(s) \quad E^\circ = -0.41\ V$$
$$Cu^+(aq) + e^- \rightleftarrows Cu(s) \quad E^\circ = +0.52\ V$$
$$Ag^+(aq) + e^- \rightleftarrows Ag(s) \quad E^\circ = +0.80\ V$$

15. Based on the standard electrode potentials given above, which of the following is the strongest reducing agent?

    (A) $Cd(s)$ (B) $Cd^{2+}(aq)$ (C) $Cu(s)$ (D) $Ag(s)$ (E) $Ag^+(aq)$

16. A sample of $CaCO_3$ (molar mass 100. g) was reported as being 30. percent Ca. Assuming no calcium was present in any impurities, the percent of $CaCO_3$ in the sample is

(A) 30% (B) 40% (C) 70% (D) 75% (E) 100%

$$2\ Al(s) + 6\ HCl(aq) \rightarrow 2\ AlCl_3(aq) + 3\ H_2(g)$$

17. According to the reaction represented above, about how many grams of aluminum (atomic mass 27 g) are necessary to produce 0.50 mol of hydrogen gas at 25°C and 1.00 atm?

(A) 1.0 g
(B) 9.0 g
(C) 14 g
(D) 27 g
(E) 56 g

$$\ldots Cr_2O_7^{2-}(aq) + \ldots HNO_2(aq) + \ldots H^+(aq) \rightarrow \ldots Cr^{3+}(aq) + \ldots NO_3^-(aq) + \ldots H_2O(l)$$

18. When the equation for the redox reaction represented above is balanced and all coefficients are reduced to lowest whole-number terms, the coefficient for $H_2O(l)$ is

(A) 3 (B) 4 (C) 5 (D) 6 (E) 8

19. Which of the following equations represents the net reaction that occurs when gaseous hydrofluoric acid reacts with solid silicon dioxide?

(A) $2\ H^+(aq) + 2\ F^-(aq) + SiO_2(s) \rightarrow SiOF_2(s) + H_2O(l)$
(B) $4\ F^-(aq) + SiO_2(s) \rightarrow SiF_4(g) + 2\ O^{2-}(aq)$
(C) $4\ HF(g) + SiO_2(s) \rightarrow SiF_4(g) + 2\ H_2O(l)$
(D) $4\ HF(g) + SiO_2(s) \rightarrow Si(s) + 2\ F_2(g) + 2\ H_2O(l)$
(E) $2\ H_2F(g) + Si_2O_2(s) \rightarrow 2\ SiF(g) + 2\ H_2O(l)$

20. The ionization constant for acetic acid is 1.8×10^{-5}; that for hydrocyanic acid is 4×10^{-10}. In 0.1 M solutions of sodium acetate and sodium cyanide, it is true that

(A) $[H^+]$ equals $[OH^-]$ in each solution
(B) $[H^+]$ exceeds $[OH^-]$ in each solution
(C) $[H^+]$ of the sodium acetate solution is less than that of the sodium cyanide solution
(D) $[OH^-]$ of the sodium acetate solution is less than that of the sodium cyanide solution
(E) $[OH^-]$ for the two solutions is the same

$$HCl > HC_2H_3O_2 > HCN > H_2O > NH_3$$

21. Five acids are listed above in the order of decreasing acid strength. Which of the following reactions must have an equilibrium constant with a value less than 1?

(A) $HCl(aq) + CN^-(aq) \rightleftarrows HCN(aq) + Cl^-(aq)$
(B) $HCl(aq) + H_2O(l) \rightleftarrows H_3O^+(aq) + Cl^-(aq)$
(C) $HC_2H_3O_2(aq) + OH^-(aq) \rightleftarrows C_2H_3O_2^-(aq) + H_2O(l)$
(D) $H_2O(aq) + NH_2^-(aq) \rightleftarrows NH_3(aq) + OH^-(aq)$
(E) $HCN(aq) + C_2H_3O_2^-(aq) \rightleftarrows HC_2H_3O_2(aq) + CN^-(aq)$

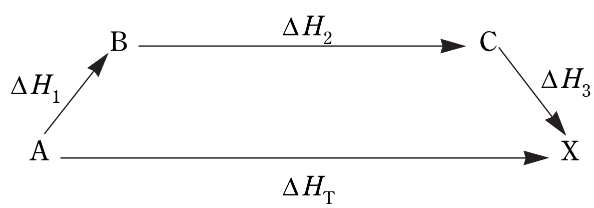
Experiment	*Initial* [X] *(mol L^{-1})*	*Initial* [Y] *(mol L^{-1})*	*Initial Rate of Formulation of* Z *(mol L^{-1} min^{-1})*
1	0.10	0.30	4.0×10^{-4}
2	0.20	0.60	1.6×10^{-3}
3	0.20	0.30	4.0×10^{-4}

22. The data in the table above were obtained for the reaction X + Y → Z. Which of the following is the rate law for the reaction?

(A) Rate = $k[X]^2$
(B) Rate = $k[Y]^2$
(C) Rate = $k[X][Y]$
(D) Rate = $k[X]^2[Y]$
(E) Rate = $k[X][Y]^2$

$$A \rightarrow X$$

23. The enthalpy change for the reaction represented above is ΔH_T. This reaction can be broken down into a series of steps as shown in the diagram:



A relationship that must exist among the various enthalpy changes is

(A) $\Delta H_T - \Delta H_1 - \Delta H_2 - \Delta H_3 = 0$
(B) $\Delta H_T + \Delta H_1 + \Delta H_2 + \Delta H_3 = 0$
(C) $\Delta H_3 - (\Delta H_1 + \Delta H_2) = \Delta H_T$
(D) $\Delta H_2 - (\Delta H_3 + \Delta H_1) = \Delta H_T$
(E) $\Delta H_T + \Delta H_2 = \Delta H_1 + \Delta H_3$

24. What formula would be expected for a binary compound of barium and nitrogen?

(A) Ba_3N_2 (B) Ba_2N_3 (C) Ba_2N (D) BaN_2 (E) BaN

25. All of the following statements about the nitrogen family of elements are true EXCEPT:

(A) It contains both metals and nonmetals.
(B) The electronic configuration of the valence shell of the atom is ns^2np^3.
(C) The only oxidation states exhibited by members of this family are –3, 0, +3, +5.
(D) The atomic radii increase with increasing atomic number.
(E) The boiling points increase with increasing atomic number.

26. Of the following organic compounds, which is LEAST soluble in water at 298 K?

(A) CH_3OH, methanol
(B) $CH_3CH_2CH_2OH$, l-propanol
(C) C_6H_{14}, hexane
(D) $C_6H_{12}O_6$, glucose
(E) CH_3COOH, ethanoic (acetic) acid

27. Which of the following salts forms a basic solution when dissolved in water?

(A) NaCl
(B) $(NH_4)_2SO_4$
(C) $CuSO_4$
(D) K_2CO_3
(E) NH_4NO_3

28. The molecular mass of a substance can be determined by measuring which of the following?

I. Osmotic pressure of a solution of the substance
II. Freezing point depression of a solution of the substance
III. Density of the gas (vapor) phase of the substance

(A) I only
(B) III only
(C) I and II only
(D) II and III only
(E) I, II, and III

29. The table below summarizes the reactions of a certain unknown solution when treated with bases.

		Results	
Sample	*Reagent*	*Limited Amount of Reagent*	*Excess Reagent*
I	NaOH (*aq*)	White precipitate	Precipitate dissolves
II	NH_3(*aq*)	White precipitate	White precipitate

Which of the following metallic ions could be present in the unknown solution?

(A) Ca^{2+} (*aq*)
(B) Zn^{2+} (*aq*)
(C) Ni^{2+} (*aq*)
(D) Al^{3+} (*aq*)
(E) Ag^{+} (*aq*)

Answers to Multiple-Choice Questions

1 – C	7 – D	13 – B	19 – C	25 – C
2 – E	8 – D	14 – D	20 – D	26 – C
3 – A	9 – E	15 – A	21 – E	27 – D
4 – E	10 – B	16 – D	22 – B	28 – E
5 – C	11 – B	17 – B	23 – A	29 – D
6 – B	12 – D	18 – B	24 – A	

Sample Free-Response Questions

The Section II free-response questions from the May 2007 AP Chemistry Exam appear below. For this section of the exam, students are provided with a periodic table, a table of standard reduction potentials, and a table containing various equations and constants. Additional free-response questions (and scoring guidelines) are available at AP Central.

Part A

Time—55 minutes

YOU MAY USE YOUR CALCULATOR FOR PART A.

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. Attention should be paid to significant figures.

Be sure to write all your answers to the questions on the lined pages following each question in the booklet with the pink cover. Do NOT write your answers on the green insert.

Answer Questions 1, 2, and 3. The Section II score weighting for each question is 20 percent.

$$HF(aq) + H_2O(l) \rightleftarrows H_3O^+(aq) + F^-(aq) \qquad K_a = 7.2 \times 10^{-4}$$

1. Hydrofluoric acid, $HF(aq)$, dissociates in water as represented by the equation above.

   (a) Write the equilibrium-constant expression for the dissociation of $HF(aq)$ in water.

   (b) Calculate the molar concentration of H_3O^+ in a 0.40 M $HF(aq)$ solution.

   $HF(aq)$ reacts with $NaOH(aq)$ according to the reaction represented below.

   $$HF(aq) + OH^-(aq) \rightarrow H_2O(l) + F^-(aq)$$

   A volume of 15 mL of 0.40 M $NaOH(aq)$ is added to 25 mL of 0.40 M $HF(aq)$ solution. Assume that volumes are additive.

   (c) Calculate the number of moles of $HF(aq)$ remaining in the solution.

   (d) Calculate the molar concentration of $F^-(aq)$ in the solution.

   (e) Calculate the pH of the solution.

$$N_2(g) + 3\,F_2(g) \rightarrow 2\,NF_3(g) \qquad \Delta H^\circ_{298} = -264 \text{ kJ mol}^{-1};\ \Delta S^\circ_{298} = -278 \text{ J K}^{-1}\text{ mol}^{-1}$$

2. The following questions relate to the synthesis reaction represented by the chemical equation in the box above.

   (a) Calculate the value of the standard free energy change, ΔG°_{298}, for the reaction.

   (b) Determine the temperature at which the equilibrium constant, K_{eq}, for the reaction is equal to 1.00. (Assume that ΔH° and ΔS° are independent of temperature.)

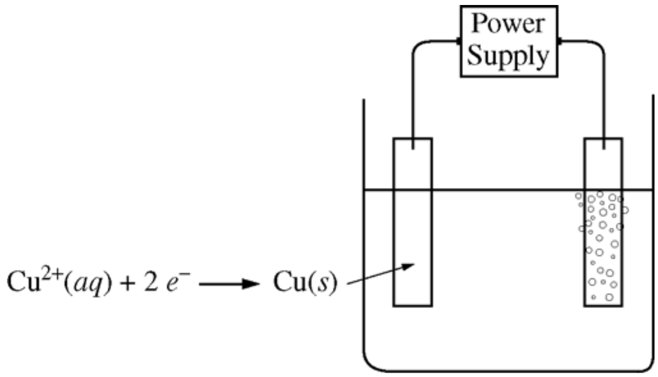
   (c) Calculate the standard enthalpy change, ΔH°, that occurs when a 0.256 mol sample of $NF_3(g)$ is formed from $N_2(g)$ and $F_2(g)$ at 1.00 atm and 298 K.

   The enthalpy change in a chemical reaction is the difference between energy absorbed in breaking bonds in the reactants and energy released by bond formation in the products.

   (d) How many bonds are formed when two molecules of NF_3 are produced according to the equation in the box above?

   (e) Use both the information in the box above and the table of average bond enthalpies below to calculate the average enthalpy of the F – F bond.

Bond	Average Bond Enthalpy (kJ mol^{-1})
N≡N	946
N–F	272
F – F	?



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

Half-Reaction	$E°$(V)
$O_2(g) + 4\,H^+(aq) + 4\,e^- \rightarrow 2\,H_2O(l)$	+1.23
$Cu^{2+}(aq) + 2\,e^- \rightarrow Cu(s)$	+0.34

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

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

(c) Predict the algebraic sign of $\Delta G°$ for the reaction. Justify your prediction.

(d) Calculate the value of $\Delta G°$ for the reaction.

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

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

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

Part B

Time—40 minutes

NO CALCULATORS MAY BE USED FOR PART B.

Answer Question 4 below. The Section II score weighting for this question is 10 percent.

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

EXAMPLE:

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

(i) Balanced equation:

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

(ii) Which substance is oxidized in the reaction?

Mg is oxidized.

(a) A solution of sodium hydroxide is added to a solution of lead(II) nitrate.

(i) Balanced equation:

(ii) If 1.0 L volumes of 1.0 *M* solutions of sodium hydroxide and lead(II) nitrate are mixed together, how many moles of product(s) will be produced? Assume the reaction goes to completion.

(b) Excess nitric acid is added to solid calcium carbonate.

(i) Balanced equation:

(ii) Briefly explain why statues made of marble (calcium carbonate) displayed outdoors in urban areas are deteriorating.

(c) A solution containing silver(I) ion (an oxidizing agent) is mixed with a solution containing iron(II) ion (a reducing agent).

(i) Balanced equation:

(ii) If the contents of the reaction mixture described above are filtered, what substance(s), if any, would remain on the filter paper?

Answer Question 5 and Question 6. The Section II score weighting for these questions is 15 percent each.

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. Examples and equations may be included in your responses where appropriate. Specific answers are preferable to broad, diffuse responses.

$$5\,Fe^{2+}(aq) + MnO_4^{-}(aq) + 8\,H^{+}(aq) \rightarrow 5\,Fe^{3+}(aq) + Mn^{2+}(aq) + 4\,H_2O(l)$$

5. The mass percent of iron in a soluble iron(II) compound is measured using a titration based on the balanced equation above.

(a) What is the oxidation number of manganese in the permanganate ion, $MnO_4^{-}(aq)$?

(b) Identify the reducing agent in the reaction represented above.

The mass of a sample of the iron(II) compound is carefully measured before the sample is dissolved in distilled water. The resulting solution is acidified with $H_2SO_4(aq)$. The solution is then titrated with $MnO_4^{-}(aq)$ until the end point is reached.

(c) Describe the color change that occurs in the flask when the end point of the titration has been reached. Explain why the color of the solution changes at the end point.

(d) Let the variables g, M, and V be defined as follows:

g = the mass, in grams, of the sample of the iron(II) compound

M = the molarity of the $MnO_4^{-}(aq)$ used as the titrant

V = the volume, in liters, of $MnO_4^{-}(aq)$ added to reach the end point

In terms of these variables, the number of moles of $MnO_4^{-}(aq)$ added to reach the end point of the titration is expressed as $M \times V$. Using the variables defined above, the molar mass of iron (55.85 g mol^{-1}), and the coefficients in the balanced chemical equation, write the expression for each of the following quantities.

(i) The number of moles of iron in the sample

(ii) The mass of iron in the sample, in grams

(iii) The mass percent of iron in the compound

(e) What effect will adding too much titrant have on the experimentally determined value of the mass percent of iron in the compound? Justify your answer.

6. Answer the following questions, which pertain to binary compounds.

(a) In the box provided below, draw a complete Lewis electron-dot diagram for the IF_3 molecule.

(b) On the basis of the Lewis electron-dot diagram that you drew in part (a), predict the molecular geometry of the IF_3 molecule.

(c) In the SO_2 molecule, both of the bonds between sulfur and oxygen have the same length. Explain this observation, supporting your explanation by drawing in the box below a Lewis electron-dot diagram (or diagrams) for the SO_2 molecule.

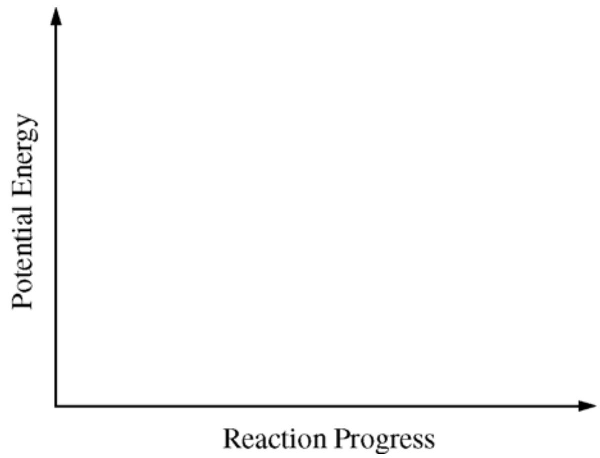
(d) On the basis of your Lewis electron-dot diagram(s) in part (c), identify the hybridization of the sulfur atom in the SO_2 molecule.

The reaction between $SO_2(g)$ and $O_2(g)$ to form $SO_3(g)$ is represented below.

$$2\ SO_2(g) + O_2(g) \rightleftarrows 2\ SO_3(g)$$

The reaction is exothermic. The reaction is slow at 25°C; however, a catalyst will cause the reaction to proceed faster.

(e) Using the axes provided on the next page, draw the complete potential-energy diagram for both the catalyzed and uncatalyzed reactions. Clearly label the curve that represents the catalyzed reaction.



(f) Predict how the ratio of the equilibrium pressures, $\dfrac{p_{SO_2}}{p_{SO_3}}$, would change when the temperature of the uncatalyzed reaction mixture is increased. Justify your prediction.

(g) How would the presence of a catalyst affect the change in the ratio described in part (f)? Explain.

STOP

END OF EXAM

GUIDE FOR THE RECOMMENDED LABORATORY PROGRAM

The authors of this laboratory guide are the following former members of the AP Chemistry Development Committee.

Peter Demmin, Amherst Central High School, N.Y.
Paula Herron, Whitney M. Young Magnet School, Chicago
George Miller, University of California, Irvine
Jerry Mullins, Plano Senior High School, Texas
Arden Zipp, State University College at Cortland, N.Y.

The College Board gratefully acknowledges their contribution.

Introduction

To qualify for accreditation by the American Chemical Society, college chemistry departments typically schedule a weekly laboratory period of three hours. Therefore, it is critical that laboratory work be an important part of an AP Chemistry course so that the course is comparable to a college general chemistry course. Analysis of data from AP Chemistry examinees regarding the length of time they spent per week in the laboratory shows that increased laboratory time is correlated with higher AP scores. The AP Chemistry Development Committee has produced this guide to help teachers and administrators understand the role that laboratory work should play in every AP Chemistry course. This information supplements the guidance provided by the topic outline, which should also be consulted for the most up-to-date information on expectations.

This document does not attempt to provide detailed instructions for experiments, as committee members believe that these are readily available in a number of standard laboratory manuals. Furthermore, it is important that the AP Chemistry laboratory program be adapted to local conditions, even while it aims to offer the students a well-rounded experience with experimental chemistry.

Models showing how several instructors in widely different circumstances have tackled the problems inherent in establishing a high-quality program in AP Chemistry, including laboratory work, are described in considerable detail in the *AP Chemistry Teacher's Guide,* published by the College Board (go to AP Central or see page 40 for ordering information).

General Requirements

The school faculty and administration must make an appropriate commitment for successful implementation of an AP Chemistry course that is designed to be the equivalent of the first-year college course in laboratory chemistry. There are a number of facets to this commitment that must be present for a quality program, including facilities, teacher preparation and training, scheduling and supplies. A brief review of these items is included in this section. Teachers and administrators must work together to achieve these goals.

School Resources

1. A separate operating and capital budget should be established with the understanding that the per-pupil expenditures for this course will be substantially higher than those for regular high school laboratory science courses. Adequate laboratory facilities should be provided so that each student has a work space where equipment and materials can be left overnight if necessary. Sufficient laboratory glassware for the anticipated enrollment and appropriate instruments (sensitive balances, spectrophotometers and pH meters) should be provided.
2. Students in AP Chemistry should have access to computers with software appropriate for processing laboratory data and writing reports.
3. A laboratory assistant should be provided in the form of a paid or unpaid aide. Parent volunteers, if well organized, may be able to help fill such a role.
4. Flexible or modular scheduling must be implemented in order to meet the time requirements identified in the course outline. Some schools are able to assign daily double periods so that laboratory and quantitative problem-solving skills may be fully developed. At the very least, a weekly extended laboratory period is needed. *It is not possible to complete high-quality AP laboratory work within standard 45- to 50-minute periods.*

Teacher Preparation Time

Because of the nature of the AP Chemistry course, the teacher needs extra time to prepare for laboratory work. Therefore, adequate time must be allotted during the academic year for teacher planning and testing of laboratory experiments.

In the first year of starting an AP Chemistry course, one month of summer time and one additional period each week are also necessary for course preparation work. In subsequent years, an AP Chemistry teacher routinely requires one extra period each week to devote to course preparation.

Teacher Professional Development

AP Chemistry teachers need to stay abreast of current developments in teaching college chemistry. This is done through contacts with college faculty and with high school teacher colleagues. Schools should offer stipends and travel support to enable their teachers to attend workshops and conferences. An adequate budget should be established at the school to support professional development of the AP Chemistry teacher. The following are examples of such opportunities.

1. One- or two-week AP Summer Institutes (supported by the College Board) are offered in several locations.
2. One-day AP conferences are sponsored by College Board regional offices. At these, presentations are made by experienced AP or college-level teachers, many of whom have been AP Exam Readers or members of the Development Committee.
3. AP institutes covering several disciplines are offered as two- or three-day sessions during the school year. These are also organized by College Board regional offices and are held at hotels or universities.

4. Additional opportunities are often provided by local colleges or universities, or by local sections of the American Chemical Society. These can be in the form of one-day workshops, weekend retreats or summer courses. All offer excellent networking possibilities for AP Chemistry teachers, who can exchange ideas with their colleagues and build long-term support relationships.

Skills and Procedures

When a fact appears opposed to a long train of deductions it invariably proves to be capable of bearing some other interpretation.
—Sherlock Holmes in *A Study in Scarlet*

Laboratory Program Goals

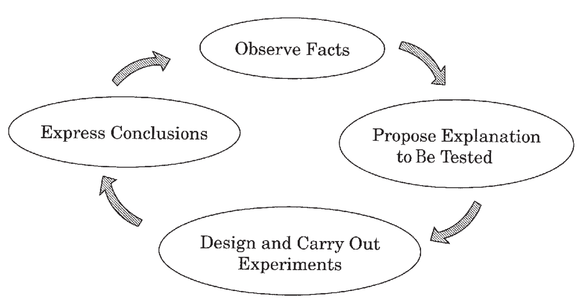
The chemistry laboratory is the place where students learn about the behavior of matter by firsthand observation — to see what actually happens when the " stuff " that makes up the world is "prodded" and "poked." The observations students make may be in marked contrast to preconceived notions of what "should happen" according to textbooks or simplistic theoretical models. The laboratory is the place to learn the difference between observations/recorded data (i.e., facts) and the ideas, inferences, explanations, models (i.e., theories) that may be used to interpret them but are often incomplete or never actually observed.

Chemistry is an experimental science that is most effectively learned through direct experience. Therefore, while computer simulations may be useful to extend or reinforce chemical concepts, they are not adequate substitutes for direct "hands-on" laboratory experience.

The laboratory program that is adopted should challenge every student's ability to:

- think analytically and to reduce problems to identifiable, answerable questions;
- understand problems expressed as experimental questions;
- design and carry out experiments that answer questions;
- manipulate data acquired during an experiment — perhaps even to guide progress;
- make conclusions and evaluate the quality and validity of such conclusions;
- propose further questions for study; and
- communicate accurately and meaningfully about observations and conclusions.

The program of laboratory investigations should be seen as a cyclic continuum of inquiry rather than a linear sequence of steps with a beginning and an end.



Toward this goal, the ideal program should not only allow students to gain experience with traditional laboratory exercises (such as those suggested later) but also provide opportunities for students to carry out novel investigations.

Laboratory Performance Skills

> *To play a violin, one needs to know how to handle it properly. To do a meaningful experiment, one must mix and measure just as properly.*
>
> —Sienko, Plane, and Marcus, 1984

Physical Manipulations

Students must learn the skills necessary to use ordinary equipment such as:

- beakers, flasks, test tubes, crucibles, evaporating dishes, watch glasses, burners, plastic and glass tubing, stoppers, valves, spot plates, funnels, reagent bottles, wash bottles, and droppers;

and measuring equipment, including:

- balances (single pan, double pan, triple beam), thermometers (°C), barometers, graduated cylinders, burets, volumetric pipets, graduated pipets, volumetric flasks, ammeters and voltmeters, pH meters, and spectrophotometers.

Processes and Procedures

Familiarity (more than a single day's experience) with such general types of chemical laboratory work as the following is important:

- synthesis of compounds (solid and gas)
- separations (precipitation and filtration, dehydration, centrifugation, distillation, chromatography)
- observing and recording phase changes (solid—liquid—gas)
- titration using indicators and meters
- spectrophotometry/colorimetry
- devising and utilizing a scheme for qualitative analysis of ions in solution
- gravimetric analysis

Some colleges have laboratory practical exams in which students must perform certain operations accurately within time constraints. Even though this is not part of the AP Chemistry Exam, such exercises are useful in providing students with goals for the development and practice of their laboratory skills.

Observations and Data Manipulation

Students must practice the art of making careful observations and of recording accurately what they observe. Too frequently students confuse *what they see* with *what they think they are supposed to see.* They should be encouraged to be accurate reporters even when this seems to conflict with what the textbook or laboratory procedure has led them to expect. Several great discoveries were made this way (e.g., penicillin and Teflon).

Interpretation of proper observations is also important. Students should be familiar with finding evidence of chemical change (color change, precipitate formation, temperature change, gas evolution, etc.) and its absence (for example, in the identification of spectator ions).

Students should know how to make and interpret quantitative measurements correctly. This includes knowing which piece of apparatus is appropriate. For example, a student should be able to select the correct glassware to dispense *about* 50 mL and the best glassware to dispense *precisely* 10.00 mL of a solution.

Students need a great deal of practice in recording and reporting both qualitative and quantitative information. They should be encouraged to do this properly and at the time that the information is obtained. Often this means anticipating the need to prepare a table in which to record the information to be gathered or a graph on which to plot it. For example, when graphs are prepared during the experiment rather than at some later time, discordant data can often be detected immediately and measurements repeated with little lost time. This is preferable to finding out later that most of the time spent on the experiment was wasted because of an error or misreading.

Students should be given ample opportunity to evaluate their own data, to do their own calculations and to puzzle over their own errors. They should learn to distinguish between mistakes (blunders) and scientific (experimental) errors. In the latter case, they should also be able to distinguish between systematic and random errors and know how to evaluate their final conclusions in the context of experimental reliability. Even when time does not permit repetition of experiments, students should be asked to comment on how they could have improved their measurements in order to arrive at a more precise conclusion. If extensive computational assistance is available (e.g., a spreadsheet computer program), students should be using it, but they should have full understanding of the operations involved and not just blindly enter numbers to get a “magic” result.

Communication, Group Collaboration, and the Laboratory Record

Laboratory work is an excellent way to help students develop and practice communication skills. Success in subsequent work in chemistry depends heavily on an ability to communicate about chemical observations, ideas, and conclusions. Students must learn to recognize that claiming a knowledge and understanding of chemistry is relatively useless unless they can communicate this knowledge effectively to others.

By working together in a truly collaborative manner to plan and carry out experiments, students learn appropriate oral communication skills as well as how to build social team relationships important to their future scientific work. They must be encouraged to take full individual responsibility for the success of the collaboration and not be a sleeping partner ready to blame the rest of the team for failure. Properly operating teams can assist the instructor greatly by taking over much of the responsibility for preparation and selection of materials, for ensuring safe manipulations and for cleaning up the laboratory. Effective teams can accomplish more in a given time by working in parallel.

Students must learn how to keep proper records of their experimental work. Even when teams perform experiments, each student should be responsible for making his or her own record of the data obtained. In group work, this ideally leads to double or triple checking of all actions and results, which helps to avoid mistakes and reinforces the idea that the entire team is responsible for the overall experiment. Student laboratory records should form part of the ongoing assessment and evaluation for the course.

If students are required to keep proper records of all experimental work done in the course, they will end the year with a document that is a source of pride and that demonstrates the growth of their skills. *This record is an important document that may be requested by the Chemistry Department at a college or university when a decision is needed regarding credit or placement in more advanced chemistry courses.*

Laboratory Safety

The conditions under which AP Chemistry courses are offered vary widely as to facilities and equipment. This is also true for colleges and universities offering general chemistry courses. However, it is important that certain concerns regarding laboratory safety be addressed in all programs. This is important not only for student and instructor safety at the time but also so that students who enter more advanced courses in chemistry have a considerable and expected familiarity with safe laboratory practices.

1. All facilities should conform to federal, state, and local laws and guidelines as they pertain to the safety of students and instructors.
2. Teachers with a limited background in chemistry should receive additional training specifically related to laboratory safety for chemistry laboratories before beginning an assignment in an AP Chemistry course.
3. Laboratory experiments and demonstrations should not be carried out by AP Chemistry students if they could expose the students to risks or hazards that are inappropriate for learning in the instructional sequence (e.g., explosion experiments that do not have any learning objective).
4. Students should be fully informed of potential laboratory hazards relating to chemicals and apparatus before performing specific experiments. If possible, students themselves should research needed safety information in advance online or at a library or local college.
5. Storage and disposal of hazardous chemicals must always be done in accordance with local regulations and policies. As far as possible, the students as well as the instructor should know what these regulations are.

Basic laboratory safety instruction for students should be an integral part of each laboratory experience. Topics that should be covered include:

- simple first aid for cuts and thermal and chemical burns;
- use of safety goggles, eye washes, body showers, fire blankets, and fire extinguishers;

- safe handling of glassware, hot plates, burners, and other heating devices, and electrical equipment;
- proper interpretation of Material Safety Data Sheets (MSDS) and hazard warning labels; and
- proper use and reuse practices (including proper labeling of interim containers) for reagent bottles.

A successful AP Chemistry laboratory program will instill in each student a true, lifelong "safety sense" that will ensure his or her safe transition into more advanced laboratory work in college or university laboratories or into the industrial workplace environment.

Recommended Experiments

Because there is a required laboratory-based question on the free-response section of the AP Chemistry Exam, the inclusion of appropriate experiments in each AP Chemistry course is important for student success. Data show that student scores on the AP Chemistry Exam improve with increased time spent in the laboratory.

It is unlikely that every student will complete all of the 22 laboratory experiments below while enrolled in an AP Chemistry course. Some of these experiments, in whole or in part, may be performed during a student's first course in chemistry before the student takes the AP Chemistry course. Also, when planning a laboratory program, it may be useful to consider the experiments in various ways. For example, they might be grouped according to the skills and techniques that the experiments require; e.g., experiments 6, 7, 8, 11 and 19 are all related to titrations. Alternatively, they might be divided on the basis of the chemical concepts that they explore and reinforce; e.g., experiments 8, 20 and 21 all relate to oxidation-reduction and electrochemistry. The major consideration when selecting experiments should be to provide students with the broadest laboratory experience possible.

1. Determination of the formula of a compound

   Teacher preparation time: 2 hours
   Student completion time: 1½ hours
   Equipment: crucible and cover, tongs, analytical balance, support stand, triangle crucible support, burner

2. Determination of the percentage of water in a hydrate

   Teacher preparation time: 2 hours
   Student completion time: 1 hour
   Equipment: crucible and cover, tongs, test tube, analytical balance, support stand, triangle crucible support, wire gauze, burner

3. Determination of molar mass by vapor density

   Teacher preparation time: 2 hours
   Student completion time: 1½ hours
   Equipment: barometer, beaker, Erlenmeyer flask, graduated cylinder, clamp, analytical balance, support stand

4. Determination of molar mass by freezing-point depression

   Teacher preparation time: 1 hour
   Student completion time: 2 hours
   Equipment: test tube, thermometer, pipet, beaker, stirrer, stop-watch, ice

5. Determination of the molar volume of a gas

   Teacher preparation time: 1½ hours
   Student completion time: 2 hours
   Equipment: barometer, beaker, Erlenmeyer flask, test tubes, graduated cylinder, clamp, analytical balance, thermometer, rubber tubing

6. Standardization of a solution using a primary standard

   Teacher preparation time: 1 hour
   Student completion time: 2 hours
   Equipment: pipet, buret, Erlenmeyer flasks, volumetric flask, wash bottle, analytical balance, drying oven, desiccator, support stand, pH meter

7. Determination of concentration by acid-base titration, including a weak acid or weak base

   Teacher preparation time: 1½ hours
   Student completion time: 2 hours
   Equipment: pipet, buret, Erlenmeyer flasks, wash bottle, analytical balance, drying oven, desiccator, support stand and clamp, pH meter

8. Determination of concentration by oxidation-reduction titration

   Teacher preparation time: 1½ hours
   Student completion time: 2 hours
   Equipment: pipet, buret, Erlenmeyer flasks, wash bottle, analytical balance, drying oven, desiccator, support stand and clamp, pH meter as millivoltmeter

9. Determination of mass and mole relationship in a chemical reaction

   Teacher preparation time: 1 hour
   Student completion time: 2 hours
   Equipment: beaker, Erlenmeyer flask, graduated cylinder, hot plate, desiccator, analytical balance

10. Determination of the equilibrium constant for a chemical reaction

    Teacher preparation time: 1½ hours
    Student completion time: 2 hours
    Equipment: pipet, test tubes and/or cuvettes, volumetric flask, analytical balance, spectrophotometer (Spec 20 or 21)

11. Determination of appropriate indicators for various acid-base titrations; pH determination

    Teacher preparation time: 2 hours
    Student completion time: 2 hours

Equipment: pipet, Erlenmeyer flasks, graduated cylinder, volumetric flask, analytical balance, pH meter

12. Determination of the rate of a reaction and its order

    Teacher preparation time: 2 hours
    Student completion time: 2 hours
    Equipment: pipet, buret, Erlenmeyer flasks, graduated cylinder or gas measuring tubes, stopwatch, thermometer, analytical balance, support stand and clamp

13. Determination of enthalpy change associated with a reaction

    Teacher preparation time: ½ hour
    Student completion time: 2 hours
    Equipment: calorimeter (can be polystyrene cup), graduated cylinder, thermometer, analytical balance

14. Separation and qualitative analysis of cations and anions

    Teacher preparation time: 2–4 hours
    Student completion time: 3+ hours
    Equipment: test tubes, beaker, evaporating dish, funnel, watch glass, mortar and pestle, centrifuge, Pt or Ni test wire

15. Synthesis of a coordination compound and its chemical analysis

    Teacher preparation time: 2 hours
    Student completion time: 2+ hours
    Equipment: beaker, Erlenmeyer flask, evaporating dish, volumetric flask, pipet, analytical balance, test tubes/cuvettes, spectrophotometer

16. Analytical gravimetric determination

    Teacher preparation time: 1 hour
    Student completion time: 1½ hours
    Equipment: beakers, crucible and cover, funnel, desiccator, drying oven, Meker burner, analytical balance, support stand, and crucible support triangle

17. Colorimetric or spectrophotometric analysis

    Teacher preparation time: 1 hour
    Student completion time: 2 hours
    Equipment: pipet, buret, test tubes and/or cuvettes, spectrophotometer, buret support stand

18. Separation by chromatography

    Teacher preparation time: 1 hour
    Student completion time: 2 hours
    Equipment: test tubes, pipet, beaker, capillary tubes or open tubes or burets, ion exchange resin or silica gel (or filter paper strips, with heat lamp or blow dryer)

19. Preparation and properties of buffer solutions
    Teacher preparation time: 1 hour
    Student completion time: 1½ hours
    Equipment: pipet, beaker, volumetric flask, pH meter

20. Determination of electrochemical series
    Teacher preparation time: 1 hour
    Student completion time: 1 hour
    Equipment: test tubes and holder rack, beakers, graduated cylinder, forceps

21. Measurements using electrochemical cells and electroplating
    Teacher preparation time: 1½ hours
    Student completion time: 1½ hours
    Equipment: test tubes, beaker, filter flasks, filter crucibles and adapters, electrodes, voltmeter, power supply (battery)

22. Synthesis, purification, and analysis of an organic compound
    Teacher preparation time: ½ hour
    Student completion time: 2+ hours
    Equipment: Erlenmeyer flask, water bath, thermometer, burner, filter flasks, evaporating dish (drying oven), analytical balance, burets, support stand, capillary tubes

Microscale Experiments

One important change in chemistry laboratory instruction in recent years has been the introduction of microscale experiments. While the initial goal in this development may have been to improve safety by reducing the amounts of hazardous materials handled, several other benefits have been realized. These include:

- decreased cost of chemicals acquisition and disposal;
- reduced storage space requirements and safer storage;
- less need for elaborate laboratory facilities in schools;
- greater care needed by students to obtain and observe results;
- shorter experiment times as well as easier and faster cleanup; and
- ability to carry out some experiments that were once restricted to demonstrations because of their hazards in macroscale.

Some of these benefits are of particular interest to the AP Chemistry teacher because less time, poorer facilities, and fewer resources for laboratory work are available in high schools than in colleges and universities. Though not all laboratory experiments lend themselves to microscale or CBL™, many do. The time and resources saved by using microscale can be used for more trials or for additional experiments, thus enabling students to complete a more meaningful laboratory program than might be possible with only macroscale techniques.

The techniques employed and the supplies needed for microscale experiments are described in several of the laboratory manuals listed in the resources section of the *AP Chemistry Teacher's Guide* (read more about the guide below), or on AP Central. Typically, these experiments are carried out using plastic pipets and well trays, available at low cost from most laboratory supply houses. Some materials can be adapted from or replaced by items available at commercial restaurant supply and discount warehouses.

AP Chemistry teachers are encouraged to exchange information regarding effective microscale and macroscale laboratory experiments. This can readily be done through local AP workshops. Teachers should contact their College Board regional office to find out about such workshops. Also, it is strongly suggested that teachers contact local college or university Chemistry Departments and ask about their laboratory programs and their use of microscale techniques in general chemistry courses. The topic of "microscale laboratories" would make an ideal subject for a conference of chemistry instructors that could be organized by a local division of the American Chemical Society or other chemistry or science teacher's association. A regular feature on "The Microscale Laboratory" is included in the *Journal of Chemical Education.*

Many of the recommended experiments described in the previous section are suitable for AP Chemistry in a microscale version.

Resources

You will find it a very good practice to always verify your references, sir!

— Routh (1755–1854)

An excellent primary resource for tips and advice on how to begin or enhance an AP Chemistry laboratory program is the *AP Chemistry Teacher's Guide*. The guide includes syllabi from AP Chemistry teachers and college professors who teach general chemistry, as well as descriptions of laboratory programs and experiments. Go to AP Central or see page 40 for ordering information.

Publishers of general chemistry textbooks typically market an associated laboratory manual. Most laboratory manuals have instructor's guides or instructor's versions that provide invaluable help in preparing equipment and solutions. Many contain prelaboratory exercises for each experiment and special sections on safety, general techniques for using equipment and instructions for writing laboratory reports. Another important resource for laboratory reports is the *ACS Style Guide* (2nd edition, 1997), which is available from the American Chemical Society (www.acs.org).

Teachers who are beginning or adapting laboratory programs will find other helpful resources at AP Central. The Teachers' Resources section of the website offers reviews of textbooks, articles, websites and other teaching resources. At AP Central, teachers can also subscribe to a moderated electronic discussion group (EDG) and request advice or opinions regarding all issues relating to the teaching of AP Chemistry, including the laboratory.

Teacher Support

AP Central® (apcentral.collegeboard.org)

You can find the following Web resources at AP Central:

- AP Course Descriptions, information about the AP Course Audit, AP Exam questions and scoring guidelines, sample syllabi, and feature articles.
- A searchable Institutes and Workshops database, providing information about professional development events.
- The Course Home Pages (apcentral.collegeboard.org/coursehomepages), which contain articles, teaching tips, activities, lab ideas, and other course-specific content contributed by colleagues in the AP community.
- Moderated electronic discussion groups (EDGs) for each AP course, provided to facilitate the exchange of ideas and practices.

Additional Resources

Teacher's Guides and **Course Descriptions** may be downloaded free of charge from AP Central; printed copies may be purchased through the College Board Store (store.collegeboard.org).

Course Audit Resources. For those looking for information on developing syllabi, the AP Course Audit website offers a host of valuable resources. Each subject has a syllabus development guide that includes the guidelines reviewers use to evaluate syllabi as well as multiple samples of evidence for each requirement. Four sample syllabi written by AP teachers and college faculty who teach the equivalent course at colleges and universities are also available. Along with a syllabus self-evaluation checklist and an example textbook list, a set of curricular/resource requirements is provided for each course that outlines the expectations that college faculty nationwide have established for college-level courses. Visit www.collegeboard.org/apcourseaudit for more information and to download these free resources.

Released Exams. Periodically the AP Program releases a complete copy of each exam. In addition to providing the multiple-choice questions and answers, the publication describes the process of scoring the free-response questions and includes examples of students' actual responses, the scoring standards, and commentaries that explain why the responses received the scores they did. Released Exams are available at the College Board Store (store.collegeboard.org).

Additional, **free AP resources** are available to help students, parents, AP Coordinators, and high school and college faculty learn more about the AP Program and its courses and exams. Visit www.collegeboard.org/apfreepubs for details.

Contact Us

National Office
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New York, NY 10023-6992
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