RICE UNIVERSITY

FALL AP SEMINAR
AP CHEMISTRY

NOVEMBER 10, 2018

LISA MCGAW

2019 AP CHEMISTRY EXAM FORMAT
Thursday, May 9th (8:00 am)

TIME:
3 hours 15 minutes – 90 minutes MC; 105 minutes free-response

MULTIPLE CHOICE: (50% of exam grade)
60 questions (50 count towards the 50%)
- 4 choices
- No guessing penalty
- Discrete items
  - Much like "normal" multiple-choice
  - Probably not many (if any) tier-stemmed or EXCEPT items
  - No simple recall of factual information
- Sets
  - Not like "legacy" sets
  - Stimulus or data set with a series of related questions

No calculator allowed
Periodic table provided
Formula sheet provided

FREE-RESPONSE: (50% of exam grade)
(spend the first few minutes scanning through the exam before beginning)
7 questions total
- 3 long free-response
  - Similar to past free-response in length
  - More connections, analyzing, translating
  - Experimental design, analysis of lab data
  - Solve problems using a logical/analytical pathway
- 4 short free-response
  - Similar to above but shorter in length

Calculator allowed entire time
Periodic table provided
Formula sheet provided
No reduction potential chart

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)

Return to the Table of Contents

Appendix B: AP 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

Return to the Table of Contents

GASES, LIQUIDS, AND SOLUTIONS

$$PV = nRT$$

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

$$P_{total} = P_A + P_B + P_C + \ldots$$

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

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

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

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

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

$$A = abc$$

P = pressure
V = volume
T = temperature
n = number of moles
m = mass
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

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

Return to the Table of Contents

EQUATIONS NOT FOUND ON THE EQUATION SHEET FOR AP CHEMISTRY

Atomic Structure –

$1\text{ m} = 1 \times 10^9\text{ nm}$

Effective nuclear charge –

Zeff (which electron) = # protons – inner core electrons

relative weighted average atomic mass = Σ(isotopic mass · fractional abundance)

Equilibrium –

$K_{sp} = [A^+][B^-]$ where $AB(s) \rightleftharpoons A^+(aq) + B^-(aq)$

$$\%\text{ ionization} = \frac{[x]}{[acid\ or\ base]} \times 100$$

Kinetics –

Rate law = $k[A]^m[B]^n$

$k = Ae^{-Ea/RT}$ (qualitative understanding that E_a is independent of T)

Gases, Liquids, and Solutions –

Coulomb's Law – (all attractive forces)

Energy or force of attraction α charge/distance

Formal charge = # valence electrons – (#lone electrons + ½ shared electrons)

Dilution – $M_1V_1 = M_2V_2$

Thermodynamics and Electrochemistry –

$\Delta H^\circ_{rxn} = \Sigma_{\text{bonds broken}} - \Sigma_{\text{bonds formed}}$

$q_{\text{hot metal}} = -\,q_{\text{cold water}}$

$q_{\text{hot water}} = -\,q_{\text{cold water}}$

$q_{\text{dissolution}} = -(\,q_{\text{solution}} + q_{\text{calorimeter}})$

$q_{\text{reaction}} = -\,q_{\text{solution}}$

$E^\circ_{\text{cell}} = E^\circ_{\text{cathode}} - E^\circ_{\text{anode}}$

Amp = coulomb/s

Other –

$$\%\text{ yield} = \frac{actual}{theoretical} \times 100 \qquad \%\text{ error} = \frac{actual - theoretical}{theoretical} \times 100$$

equation for straight line – used for variety of plots – y = mx + b

$$\%\text{ mass} = \frac{g\ \ part}{total\ \ mass} \times 100$$

Learning Objectives

Learning objective 1.1 The student can justify the observation that the ratio of the masses of the constituent elements in any pure sample of that compound is always identical on the basis of the atomic molecular theory. [*See* **SP 6.1; Essential knowledge 1.A.1**]

Learning objective 1.2 The student is able to select and apply mathematical routines to mass data to identify or infer the composition of pure substances and/or mixtures. [*See* **SP 2.2; Essential knowledge 1.A.2**]

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. [*See* **SP 2.2, 6.1; Essential knowledge 1.A.2**]

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. [*See* **SP 7.1; Essential knowledge 1.A.3**]

Learning objective 1.5 The student is able to explain the distribution of electrons in an atom or ion based upon data. [*See* **SP 1.5, 6.2; Essential knowledge 1.B.1**]

Learning objective 1.6 The student is able to analyze data relating to electron energies for patterns and relationships. [*See* **SP 5.1; Essential knowledge 1.B.1**]

Learning objective 1.7 The student is able to describe the electronic structure of the atom, using PES data, ionization energy data, and/or Coulomb's law to construct explanations of how the energies of electrons within shells in atoms vary. [*See* **SP 5.1, 6.2; Essential knowledge 1.B.2**]

Learning objective 1.8 The student is able to explain the distribution of electrons using Coulomb's law to analyze measured energies. [*See* **SP 6.2; Essential knowledge 1.B.2**]

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. [*See* **SP 6.4; Essential knowledge 1.C.1**]

Learning objective 1.10 Students can justify with evidence the arrangement of the periodic table and can apply periodic properties to chemical reactivity. [*See* **SP 6.1; Essential knowledge 1.C.1**]

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. [*See* **SP 3.1, 5.1; Essential knowledge 1.C.1**]

Learning objective 1.12 The student is able to explain why a given set of data suggests, or does not suggest, the need to refine the atomic model from a classical shell model with the quantum mechanical model. [*See* **SP 6.3; Essential knowledge 1.C.2**]

Learning objective 1.13 Given information about a particular model of the atom, the student is able to determine if the model is consistent with specified evidence. [*See* **SP 5.3; Essential knowledge 1.D.1**]

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. [*See* **SP 1.4, 1.5; Essential knowledge 1.D.2**]

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. [*See* **SP 4.1, 6.4; Essential knowledge 1.D.3**]

Learning objective 1.16 The student can design and/or interpret the results of an experiment regarding the absorption of light to determine the concentration of an absorbing species in a solution. [*See* **SP 4.2, 5.1; Essential knowledge 1.D.3**]

Return to the Table of Contents

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. [*See* **SP 1.5; Essential knowledge 1.E.1**]

Learning objective 1.18 The student is able to apply conservation of atoms to the rearrangement of atoms in various processes. [*See* **SP 1.4; Essential knowledge 1.E.2**]

Learning objective 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. [*See* **SP 4.2, 5.1, 6.4; Essential knowledge 1.E.2**]

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. [*See* **SP 4.2, 5.1, 6.4; Essential knowledge 1.E.2**]

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. [*See* **SP 6.4, 7.1; Essential knowledge components of 2.A–2.D**]

Learning objective 2.2 The student is able to explain the relative strengths of acids and bases based on molecular structure, interparticle forces, and solution equilibrium. [*See* **SP 7.2,** *connects to* **Big Idea 5, Big Idea 6; Essential knowledge components of 2.A–2.D**]

Learning objective 2.3 The student is able to use aspects of particulate models (i.e., particle spacing, motion, and forces of attraction) to reason about observed differences between solid and liquid phases and among solid and liquid materials. [*See* **SP 6.4, 7.1; Essential knowledge 2.A.1**]

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. [*See* **SP 1.4, 6.4; Essential knowledge 2.A.2**]

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. [*See* **SP 1.3, 6.4, 7.2; Essential knowledge 2.A.2**]

Learning objective 2.6 The student can apply mathematical relationships or estimation to determine macroscopic variables for ideal gases. [*See* **SP 2.2, 2.3; Essential knowledge 2.A.2**]

Learning objective 2.7 The student is able to explain how solutes can be separated by chromatography based on intermolecular interactions. [*See* **SP 6.2; Essential knowledge 2.A.3**]

Learning objective 2.8 The student can draw and/or interpret representations of solutions that show the interactions between the solute and solvent. [*See* **SP 1.1, 1.2, 6.4; Essential knowledge 2.A.3**]

Learning objective 2.9 The student is able to create or interpret representations that link the concept of molarity with particle views of solutions. [*See* **SP 1.1, 1.4; Essential knowledge 2.A.3**]

Learning objective 2.10 The student can design and/or interpret the results of a separation experiment (filtration, paper chromatography, column chromatography, or distillation) in terms of the relative strength of interactions among and between the components. [*See* **SP 4.2, 5.1, 6.4; Essential knowledge 2.A.3**]

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. [*See* **SP 6.2, 6.4; Essential knowledge 2.B.1**]

Learning objective 2.12 The student can qualitatively analyze data regarding real gases to identify deviations from ideal behavior and relate these to molecular interactions. [*See* **SP 5.1, 6.5; Essential knowledge 2.B.2,** *connects to* **2.A.2**]

Return to the Table of Contents

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. [*See* **SP 1.4, 6.4; Essential knowledge 2.B.2**]

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. [*See* **SP 1.4, 6.4; Essential knowledge 2.B.2**]

Learning objective 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. [*See* **SP 1.4, 6.2; Essential knowledge 2.B.3,** *connects to* **5.E.1**]

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. [*See* **SP 6.2; Essential knowledge 2.B.3**]

Learning objective 2.17 The student can predict the type of bonding present between two atoms in a binary compound based on position in the periodic table and the electronegativity of the elements. [*See* **SP 6.4; Essential knowledge components of 2.C**]

Learning objective 2.18 The student is able to rank and justify the ranking of bond polarity on the basis of the locations of the bonded atoms in the periodic table. [*See* **SP 6.1; Essential knowledge 2.C.1**]

Learning objective 2.19 The student can create visual representations of ionic substances that connect the microscopic structure to macroscopic properties, and/or use representations to connect the microscopic structure to macroscopic properties (e.g., boiling point, solubility, hardness, brittleness, low volatility, lack of malleability, ductility, or conductivity). [*See* **SP 1.1, 1.4, 7.1; Essential knowledge 2.C.2,** *connects to* **2.D.1, 2.D.2**]

Learning objective 2.20 The student is able to explain how a bonding model involving delocalized electrons is consistent with macroscopic properties of metals (e.g., conductivity, malleability, ductility, and low volatility) and the shell model of the atom. [*See* **SP 6.2, 7.1; Essential knowledge 2.C.3,** *connects to* **2.D.2**]

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. [*See* **SP 1.4; Essential knowledge 2.C.4**]

Learning objective 2.22 The student is able to design or evaluate a plan to collect and/or interpret data needed to deduce the type of bonding in a sample of a solid. [*See* **SP 4.2, 6.4; Essential knowledge components of 2.D**]

Learning objective 2.23 The student can create a representation of an ionic solid that shows essential characteristics of the structure and interactions present in the substance. [*See* **SP 1.1; Essential knowledge 2.D.1**]

Learning objective 2.24 The student is able to explain a representation that connects properties of an ionic solid to its structural attributes and to the interactions present at the atomic level. [*See* **SP 1.1, 6.2, 7.1; Essential knowledge 2.D.1**]

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. [*See* **SP 1.4, 7.2; Essential knowledge 2.D.2**]

Learning objective 2.26 Students can use the electron sea model of metallic bonding to predict or make claims about the macroscopic properties of metals or alloys. [*See* **SP 6.4, 7.1; Essential knowledge 2.D.2**]

Learning objective 2.27 The student can create a representation of a metallic solid that shows essential characteristics of the structure and interactions present in the substance. [*See* **SP 1.1; Essential knowledge 2.D.2**]

Return to the Table of Contents

Learning objective 2.28 The student is able to explain a representation that connects properties of a metallic solid to its structural attributes and to the interactions present at the atomic level. [*See* **SP 1.1, 6.2, 7.1; Essential knowledge 2.D.2**]

Learning objective 2.29 The student can create a representation of a covalent solid that shows essential characteristics of the structure and interactions present in the substance. [*See* **SP 1.1; Essential knowledge 2.D.3**]

Learning objective 2.30 The student is able to explain a representation that connects properties of a covalent solid to its structural attributes and to the interactions present at the atomic level. [*See* **SP 1.1, 6.2, 7.1; Essential knowledge 2.D.3**]

Learning objective 2.31 The student can create a representation of a molecular solid that shows essential characteristics of the structure and interactions present in the substance. [*See* **SP 1.1; Essential knowledge 2.D.4**]

Learning objective 2.32 The student is able to explain a representation that connects properties of a molecular solid to its structural attributes and to the interactions present at the atomic level. [*See* **SP 1.1, 6.2, 7.1; Essential knowledge 2.D.4**]

Learning objective 3.1 Students can translate among macroscopic observations of change, chemical equations, and particle views. [*See* **SP 1.5, 7.1; Essential knowledge components of 3.A–3.C**]

Learning objective 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. [*See* **SP 1.5, 7.1; Essential knowledge 3.A.1**]

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. [*See* **SP 2.2, 5.1; Essential knowledge 3.A.2**]

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. [*See* **SP 2.2, 5.1, 6.4; Essential knowledge 3.A.2**]

Learning objective 3.5 The student is able to design a plan in order to collect data on the synthesis or decomposition of a compound to confirm the conservation of matter and the law of definite proportions. [*See* **SP 2.1, 4.2, 6.4; Essential knowledge 3.B.1**]

Learning objective 3.6 The student is able to use data from synthesis or decomposition of a compound to confirm the conservation of matter and the law of definite proportions. [*See* **SP 2.2, 6.1; Essential knowledge 3.B.1**]

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. [*See* **SP 6.1; Essential knowledge 3.B.2**]

Learning objective 3.8 The student is able to identify redox reactions and justify the identification in terms of electron transfer. [*See* **SP 6.1; Essential knowledge 3.B.3**]

Learning objective 3.9 The student is able to design and/or interpret the results of an experiment involving a redox titration. [*See* **SP 4.2, 5.1; Essential knowledge 3.B.3**]

Learning objective 3.10 The student is able to evaluate the classification of a process as a physical change, chemical change, or ambiguous change based on both macroscopic observations and the distinction between rearrangement of covalent interactions and noncovalent interactions. [*See* **SP 1.4, 6.1; Essential knowledge 3.C.1,** *connects to* **5.D.2**]

Learning objective 3.11 The student is able to interpret observations regarding macroscopic energy changes associated with a reaction or process to generate a relevant symbolic and/or graphical representation of the energy changes. [*See* **SP 1.5, 4.4; Essential knowledge 3.C.2**]

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. [*See* **SP 2.2, 2.3, 6.4; Essential knowledge 3.C.3**]

Learning objective 3.13 The student can analyze data regarding galvanic or electrolytic cells to identify properties of the underlying redox reactions. [*See* **SP 5.1; Essential knowledge 3.C.3**]

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. [*See* **SP 4.2, 5.1; Essential knowledge 4.A.1**]

Learning objective 4.2 The student is able to analyze concentration vs. time data to determine the rate law for a zeroth-, first-, or second-order reaction. [*See* **SP 5.1, 6.4; Essential knowledge 4.A.2,** *connects to* **4.A.3]**

Learning objective 4.3 The student is able to connect the half-life of a reaction to the rate constant of a first-order reaction and justify the use of this relation in terms of the reaction being a first-order reaction. [*See* **SP 2.1, 2.2; Essential knowledge 4.A.3**]

Learning objective 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. [*See* **SP 7.1; Essential knowledge 4.B.1,** *connects to* **4.A.3, 4.B.2**]

Learning objective 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. [*See* **SP 6.2; Essential knowledge 4.B.2**]

Learning objective 4.6 The student is able to use representations of the energy profile for an elementary reaction (from the reactants, through the transition state, to the products) to make qualitative predictions regarding the relative temperature dependence of the reaction rate. [*See* **SP 1.4, 6.4; Essential knowledge 4.B.3**]

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. [*See* **SP 6.5;** *connects to* **Essential knowledge 4.C.1, 4.C.2, 4.C.3**]

Learning objective 4.8 The student can translate among reaction energy profile representations, particulate representations, and symbolic representations (chemical equations) of a chemical reaction occurring in the presence and absence of a catalyst. [*See* **SP 1.5; Essential knowledge 4.D.1**]

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. [*See* **SP 6.2, 7.2; Essential knowledge 4.D.2**]

Learning objective 5.1 The student is able to create or use graphical representations in order to connect the dependence of potential energy to the distance between atoms and factors, such as bond order (for covalent interactions) and polarity (for intermolecular interactions), which influence the interaction strength. [*See* **SP 1.1, 1.4, 7.2,** *connects to* **Big Idea 2; Essential knowledge components of 5.A–5.E**]

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. [*See* **SP 1.1, 1.4, 7.1; Essential knowledge 5.A.1**]

Return to the Table of Contents

Learning objective 5.3 The student can generate explanations or make predictions about the transfer of thermal energy between systems based on this transfer being due to a kinetic energy transfer between systems arising from molecular collisions. [*See* **SP 7.1; Essential knowledge 5.A.2**]

Learning objective 5.4 The student is able to use conservation of energy to relate the magnitudes of the energy changes occurring in two or more interacting systems, including identification of the systems, the type (heat versus work), or the direction of energy flow. [*See* **SP 1.4, 2.2,** *connects to* **Essential knowledge 5.B.1, 5.B.2**]

Learning objective 5.5 The student is able to use conservation of energy to relate the magnitudes of the energy changes when two nonreacting substances are mixed or brought into contact with one another. [*See* **SP 2.2,** *connects to* **Essential knowledge 5.B.1, 5.B.2**]

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. [*See* **SP 2.2, 2.3; Essential knowledge 5.B.3**]

Learning objective 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. [*See* **SP 4.2, 5.1, 6.4; Essential knowledge 5.B.4**]

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. [*See* **SP 2.3, 7.1, 7.2; Essential knowledge 5.C.2**]

Learning objective 5.9 The student is able to make claims and/or predictions regarding relative magnitudes of the forces acting within collections of interacting molecules based on the distribution of electrons within the molecules and the types of intermolecular forces through which the molecules interact. [*See* **SP 6.4; Essential knowledge 5.D.1**]

Learning objective 5.10 The student can support the claim about whether a process is a chemical or physical change (or may be classified as both) based on whether the process involves changes in intramolecular versus intermolecular interactions. [*See* **SP 5.1; Essential knowledge 5.D.2**]

Learning objective 5.11 The student is able to identify the noncovalent interactions within and between large molecules, and/or connect the shape and function of the large molecule to the presence and magnitude of these interactions. [*See* **SP 7.2; Essential knowledge 5.D.3**]

Learning objective 5.12 The student is able to use representations and models to predict the sign and relative magnitude of the entropy change associated with chemical or physical processes. [*See* **SP 1.4; Essential knowledge 5.E.1**]

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. [*See* **SP 2.2, 2.3, 6.4; Essential knowledge 5.E.2,** *connects to* **5.E.3**]

Learning objective 5.14 The student is able to determine whether a chemical or physical process is thermodynamically favorable by calculating the change in standard Gibbs free energy. [*See* **SP 2.2; Essential knowledge 5.E.3,** *connects to* **5.E.2**]

Learning objective 5.15 The student is able to explain how the application of external energy sources or the coupling of favorable with unfavorable reactions can be used to cause processes that are not thermodynamically favorable to become favorable. [*See* **SP 6.2; Essential knowledge 5.E.4**]

Learning objective 5.16 The student can use Le Chatelier's principle to make qualitative predictions for systems in which coupled reactions that share a common intermediate drive formation of a product. [*See* **SP 6.4; Essential knowledge 5.E.4,** *connects to* **6.B.1**]

Learning objective 5.17 The student can make quantitative predictions for systems involving coupled reactions that share a common intermediate, based on the equilibrium constant for the combined reaction. [*See* **SP 6.4; Essential knowledge 5.E.4,** *connects to* **6.A.2**]

Learning objective 5.18 The student can explain why a thermodynamically favored chemical reaction may not produce large amounts of product (based on consideration of both initial conditions and kinetic effects), or why a thermodynamically unfavored chemical reaction can produce large amounts of product for certain sets of initial conditions. [*See* **SP 1.3, 7.2; Essential knowledge 5.E.5,** *connects to* **6.D.1**]

Learning objective 6.1 The student is able to, given a set of experimental observations regarding physical, chemical, biological, or environmental processes that are reversible, construct an explanation that connects the observations to the reversibility of the underlying chemical reactions or processes. [*See* **SP 6.2; Essential knowledge 6.A.1**]

Learning objective 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. [*See* **SP 2.2; Essential knowledge 6.A.2**]

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. [*See* **SP 7.2; Essential knowledge 6.A.3**]

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. [*See* **SP 2.2, 6.4; Essential knowledge 6.A.3**]

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. [*See* **SP 2.2; Essential knowledge 6.A.3**]

Learning objective 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. [*See* **SP 2.2, 6.4; Essential knowledge 6.A.3**]

Learning objective 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. [*See* **SP 2.2, 2.3; Essential knowledge 6.A.4**]

Learning objective 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. [*See* **SP 1.4, 6.4; Essential knowledge 6.B.1**]

Learning objective 6.9 The student is able to use Le Chatelier's principle to design a set of conditions that will optimize a desired outcome, such as product yield. [*See* **SP 4.2; Essential knowledge 6.B.1**]

Learning objective 6.10 The student is able to connect Le Chatelier's principle to the comparison of Q to K by explaining the effects of the stress on Q and K. [*See* **SP 1.4, 7.2; Essential knowledge 6.B.2**]

Learning objective 6.11 The student can generate or use a particulate representation of an acid (strong or weak or polyprotic) and a strong base to explain the species that will have large versus small concentrations at equilibrium. [*See* **SP 1.1, 1.4, 2.3; Essential knowledge 6.C.1**]

Return to the Table of Contents

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. [*See* **SP 1.4, 6.4; Essential knowledge 6.C.1,** *connects to* **1.E.2**]

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. [*See* **SP 5.1, 6.4; Essential knowledge 6.C.1,** *connects to* **I.E.2**]

Learning objective 6.14 The student can, based on the dependence of K_w on temperature, reason that neutrality requires $[H^+] = [OH^-]$ as opposed to requiring $pH = 7$, including especially the applications to biological systems. [*See* **SP 2.2, 6.2; Essential knowledge 6.C.1**]

Learning objective 6.15 The student can identify a given solution as containing a mixture of strong acids and/or bases and calculate or estimate the pH (and concentrations of all chemical species) in the resulting solution. [*See* **SP 2.2, 2.3, 6.4; Essential knowledge 6.C.1**]

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), 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. [*See* **SP 2.2, 6.4; Essential knowledge 6.C.1**]

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. [*See* **SP 6.4; Essential knowledge 6.C.1**]

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. [*See* **SP 2.3, 4.2, 6.4; Essential knowledge 6.C.2**]

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. [*See* **SP 2.3, 5.1, 6.4; Essential knowledge 6.C.2**]

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. [*See* **SP 6.4; Essential knowledge 6.C.2**]

Learning objective 6.21 The student can predict the solubility of a salt, or rank the solubility of salts, given the relevant K_{sp} values. [*See* **SP 2.2, 2.3, 6.4; Essential knowledge 6.C.3**]

Learning objective 6.22 The student can interpret data regarding solubility of salts to determine, or rank, the relevant K_{sp} values. [*See* **SP 2.2, 2.3, 6.4; Essential knowledge 6.C.3**]

Learning objective 6.23 The student can interpret data regarding the relative solubility of salts in terms of factors (common ions, pH) that influence the solubility. [*See* **SP 5.1, 6.4; Essential knowledge 6.C.3**]

Learning objective 6.24 The student can analyze the enthalpic and entropic changes associated with the dissolution of a salt, using particulate level interactions and representations. [*See* **SP 1.4, 7.1; Essential knowledge 6.C.3,** *connects to* **5.E**]

Learning objective 6.25 The student is able to express the equilibrium constant in terms of $\Delta G°$ and RT and use this relationship to estimate the magnitude of K and, consequently, the thermodynamic favorability of the process. [*See* **SP 2.3; Essential knowledge 6.D.1**]

Science Practices for AP Chemistry

Science Practice 1: The student can use representations and models to communicate scientific phenomena and solve scientific problems.

The ability to use models and "pictures" to explain/represent what is happening at the particulate level is fundamental to understanding chemistry. The student must be able to draw representations of these particles (atoms, ions, molecules) whose behaviors we observe macroscopically in the laboratory. Students should be able to draw pictures that represent the particles we cannot observe but that match the accepted models for various phenomena, such as ionic solids vs. metallic solids (SP 1.1). The student should also be able to label representations of common chemical systems, such as the hydrogen bonding between ethanol molecules vs. the covalent bonding within the molecules (SP 1.2). It is expected that the student can use experimental evidence to refine a model, such as describing modifications to the Bohr model that are required by PES data (SP 1.3). The student needs to be able to use representations and models to make predictions, such as using VSEPR to draw molecules and predict their polarity (SP 1.4). The student also should be able to translate between various representations, such as reading photoelectron spectroscopy data and then writing an electron configuration consistent with the data, or using the periodic table to predict either the photoelectron spectrum or the electron configuration (SP 1.5).

1.1 The student can *create representations and models* of natural or man-made phenomena and systems in the domain.

1.2 The student can *describe representations and models* of natural or man-made phenomena and systems in the domain.

1.3 The student can *refine 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.

1.5 The student can *re-express key elements* of natural phenomena across multiple representations in the domain.

Science Practice 2: The student can use mathematics appropriately.

Mathematical reasoning skills are essential for success in chemistry. The student should be able to cite reasons for using a particular mathematical routine, such as graphical evidence for the inverse relationship between P and V to justify the use of inverse proportionality in mathematical problem solving, or justify the use of the ideal gas law based on the

Return to the Table of Contents

underlying assumptions of ideal gas behavior (SP 2.1). The student should also be able to use mathematics to solve problems that describe the physical world, such as predicting the empirical formula for a compound based on experimental data (SP 2.2). Sometimes students apply algorithms to solve problems, but have little conceptual understanding. An important skill for the student is the ability to estimate the approximate value rather than use routine application of an algorithm. For example, students should be able to predict the sign and approximate magnitude of the enthalpy change for a spontaneous reaction that has a negative entropy change (SP 2.3).

2.1 The student can *justify the selection of a mathematical routine* to solve problems.

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.

Science Practice 3: The student can engage in scientific questioning to extend thinking or to guide investigations within the context of the AP course.

Scientists ask questions about the natural world that will help them develop further understanding of how things work. The student in AP Chemistry should be encouraged to ask questions that can be answered with empirical data. The laboratory experience should include opportunities for the student to formulate hypotheses, such as in an inquiry lab in which the student decides what questions to investigate concerning the variables that determine the rate of a chemical reaction. Or, the student could formulate questions that must be answered to determine the identity of an unknown (SP 3.1). The student should be able to modify a hypothesis based on data collected, such as determining further questions that would need to be answered to determine the mechanism for a reaction, or completely identifying an unknown (SP 3.2). Additionally, the student should be able to examine evidence to determine if it supports the hypothesis; for instance, are PES data consistent with the Bohr model, or can Coulomb's law and the shell model be used to explain why the ionization energy of Na is higher than that of Rb (SP 3.3)?

3.1 The student can *pose scientific questions.*

3.2 The student can *refine scientific questions.*

3.3 The student can *evaluate scientific questions.*

Science Practice 4: The student can plan and implement data collection strategies in relation to a particular scientific question. [Note: Data can be collected from many different sources, e.g., investigations, scientific observations, the findings of others, historic reconstruction, and/or archived data.]

An important part of chemistry is the collection of data that can be used to answer a particular scientific question. Students should be able to justify why a particular kind of data is most useful for addressing a question, such as the use of mass spectra to support the existence of isotopes, or the trapping of a particular reaction intermediate to support a hypothesized reaction mechanism (SP 4.1). The student should also be able to design a plan that will generate useful data, such as a plan for measuring a reaction rate that controls the relevant variables (temperatures and concentrations), or a plan to determine homogeneity of a substance by collecting and analyzing small samples from different regions of a substance (SP 4.2). The student should also know which data should be collected to achieve a certain goal, such as monitoring concentrations versus time to measure a reaction rate (SP 4.3). Finally, the student should be able to evaluate sources of data to identify which are most useful for addressing a certain question, such as deciding which properties (melting point, boiling point, density) are most useful for determining the relative strength of intermolecular forces (SP 4.4).

4.1 The student can *justify the selection of the kind of data* needed to answer a particular scientific question.

4.2 The student can *design a plan* for collecting data to answer a particular scientific question.

4.3 The student can *collect data* to answer a particular scientific question.

4.4 The student can *evaluate sources of data* to answer a particular scientific question.

Science Practice 5: The student can perform data analysis and evaluation of evidence.

Critical analysis of data is an essential part of chemistry. Many of the most useful concepts in chemistry relate to patterns in the behavior of chemical systems, such as periodic trends in atomic and molecular properties, direct and inverse proportionalities in the properties of gases, and the coefficient-exponent relationships in a rate law derived from elementary processes. Students should be able to analyze data to identify these types of patterns and relationships (SP 5.1). Once such a pattern is identified, students should be able to use the pattern to refine observations and measurements, such as indicating whether sufficient data were collected to determine a reaction rate law, and suggesting additional data that may be needed (SP 5.2). Students should also be able to evaluate the degree to which a set of evidence can address a scientific question, such as evaluating the degree to which a particular set of observations indicates that a process is chemical versus physical, or indicates that a process is driven by entropy, enthalpy, or both (SP 5.3).

5.1 The student can *analyze data* to identify patterns or relationships.

5.2 The student can *refine observations and measurements* based on data analysis.

5.3 The student can *evaluate the evidence provided by data sets* in relation to a particular scientific question.

Science Practice 6: The student can work with scientific explanations and theories.

A goal of the AP course is to instill in students the ability to work with scientific explanations and theories. This higher level of the cognitive framework builds on the lower levels, and so the tasks will typically involve other portions of the framework, such as the generation and use of graphical representations (SP 1) or application of mathematical reasoning (SP 2). Students should be able to justify claims with evidence, such as justifying a reaction as being a redox reaction based on evidence regarding oxidation states, or justifying the relative strength of acids based on evidence regarding pH of various solutions (SP 6.1). Students should also be able to construct explanations based on evidence, such as constructing a reaction mechanism that is consistent with an observed rate law (SP 6.2). The student should also be able to articulate reasons why a theory is refined or replaced, such as citing specific evidence that led to revisions in the atomic theory, or explaining how free energy as criteria for spontaneity can be viewed as a refinement of the idea that all processes go downhill in energy (SP 6.3). The use of models and theories to generate predictions or claims occurs in nearly all facets of chemistry, including, for instance, the use of VSEPR theory to predict the structure of a molecule, or the use of Le Chatelier's principle to predict the response of a system to an external stress (SP 6.4). Evaluation of alternative explanations is an important aspect of scientific practice, and shows up particularly well in AP Chemistry with regard to using evidence to decide between various plausible mechanisms for a chemical reaction (SP 6.5).

6.1 The student can *justify claims with evidence.*

6.2 The student can *construct explanations of phenomena based on evidence* produced through scientific practices.

6.3 The student can *articulate the reasons that scientific explanations and theories are refined or replaced.*

6.4 The student can *make claims and predictions about natural phenomena* based on scientific theories and models.

6.5 The student can *evaluate alternative scientific explanations.*

Science Practice 7: The student is able to connect and relate knowledge across various scales, concepts, and representations in and across domains.

Students develop and demonstrate deep understanding of a subject by linking ideas both within a particular domain and across domains. A central aspect of chemistry is linking atomic level phenomena and models to macroscopic phenomena (SP 7.1). Such links occur, for instance, in relating the properties of gases to kinetic theory, connecting the properties of solids to the underlying atomic structure (covalent, molecular, metallic), and relating concentrations of species to the dynamic nature of chemical equilibrium. The conceptual structure of chemistry is also highly interconnected. For instance, the thermodynamics of a chemical reaction is connected both to the structural aspects of the reaction (i.e., which atomic-level interactions are being broken and formed), and to the macroscopic outcomes of the reaction (i.e., the concentrations at equilibrium, the rate at which it reaches equilibrium, and the energy released or absorbed as the reaction progresses). In addition to connecting concepts within chemistry, students should be able to draw connections to domains outside chemistry, such as the connection between protein structure (primary, secondary, and tertiary) in biology, and covalent versus non-covalent interactions in chemistry (SP 7.2).

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.

Return to the Table of Contents

Appendix A: Preparing Students for Success in AP Chemistry

In order to provide teachers with the information they need to incorporate the science practices and required course concepts into the AP Chemistry classroom, this section includes a description of **desired performance** (what students should know and be able to do) for high achievement in an introductory college-level chemistry course (which is comparable to an AP Chemistry course).

	Competence ⟶ Mastery		
Big Idea 1: Atomic Structure			
Periodicity	Uses the shell structure of the atom to determine electron configurations and relates these to the structure of the periodic table. Communicates the form and basic consequences of Coulomb's law. Recounts the shape of the *s* and *p* atomic orbitals.	Portrays the properties of atoms and/or binary compounds by recounting periodic trends. Analyzes elementary atomic data/ properties through the context of the shell model of the atom. States what evidence regarding the atom requires shifts between different models of the atom.	Given a set of data, delineates periodic trends, or deviations from periodicity, using Coulomb's law, including electron shielding and the concept of effective nuclear charge. Uses the concept of periodicity in predicting reactivity and properties of binary compounds. Explains the agreement between data and various models of the atom, and explains how this influences the utility of a particular model.
Spectroscopy	States the types of molecular motions that are related to the different spectral ranges. Applies Beer's law to determine the concentration of an absorbing species in a solution. Uses Planck's equation to calculate energy of a photon. Uses conservation of energy to connect energy of the photon to the energies involved in the processes induced by the photon.	Justifies the choice of a particular type of spectroscopy to probe a target aspect of a molecule. Analyzes data from a spectroscopy experiment using Beer's law. Communicates the basic structure of a spectroscopy experiment (i.e., electromagnetic radiation [light] of different wavelengths is passed through a system, and the amount absorbed or emitted is measured). Relates mass spectra to abundances of the relevant chemical species.	Designs an experiment involving spectroscopy to quantify the concentration/ amount of a substance. Interprets data in which spectroscopy is used for qualitative analysis (e.g., connecting the data to symbolic representations, such as electron configurations, or affirming that spectral patterns often indicate the presence of a particular functional group).
Stoichiometry	Uses the mole concept to connect quantities between the macroscopic and particulate levels, both quantitatively and qualitatively. Performs routine stoichiometric computations of reactants to products, including balancing an equation. Successfully communicates and flexibly uses different measures of a substance (e.g., volume, mass, concentration, density). Recognizes connections between macroscopic-level and particulate-level representations.	States the utility of the mole to connect measurements made at the macroscopic level to the particulate level. Applies conservation of number of atoms to analyze systems both quantitatively and qualitatively. Interprets experiments designed to determine concentration and composition, such as gravimetric analysis, titrations, and Beer's law. Compares isotopic distributions to the average atomic mass, both qualitatively and quantitatively. Translates between different representations related to amounts and concentrations, including macroscopic-level data and particulate-level views.	Uses stoichiometric reasoning in situations that involve impure substances. Designs experiments to determine concentration, composition, and identity of a substance. Generates appropriate representations of chemical mixtures, including macroscopic-level and particulate-level views.

Return to the Table of Contents

	Competence ⟶ **Mastery**		
Big Idea 2: Structure–Property Relations			
Classification of Substances	Communicates and visually represents the basic structural features of different classes of solids — metallic, ionic, network covalent, and molecular. Relates the gross features of different solids (e.g., conductivity, boiling point, etc.) to the types of forces between atoms. Predicts trends in macroscopic properties based on recollection of general trends.	Predicts trends in macroscopic properties, based on predicted structure and strength of atomic-level interactions for cases in which the properties reported are familiar, the data is unambiguous, and the materials clearly fall within one of the familiar types: metals, alloys, ionic solids, network covalent solids, molecular solids, gases, or liquids.	Predicts trends in macroscopic properties, based on predicted structure and strength of atomic-level interactions for cases in which the properties reported are unfamiliar, the data is ambiguous, and/or the materials lie within the boundaries between material types. Draws clear connections between the atomic-level forces and Coulomb's law.
Molecules	Uses Lewis dot structures and VSEPR to predict the bond orders, 3-D structure, and polarity of a molecule. Communicates why these models are useful for determining which compounds are likely to be stable.	Based on molecular structure, predicts the types and strengths of intermolecular forces. Based on molecular structure, predicts molecular properties such as relative strengths of acids. Interprets separation experiments based on predictions regarding intermolecular forces.	Relates multiple factors influencing molecular structure, such as resonance and formal charge. Designs separation experiments based on predictions regarding intermolecular forces. Relates solute–solvent interactions based on intermolecular forces. Recounts the properties of polymers based on intermolecular forces.
Solutions	Uses and applies solution stoichiometry in a variety of contexts. Selects appropriate particulate-level representations of a solution, showing interactions between solute and solvent.	Interprets particulate-level representations of a solution. Relates the factors that influence solubility of a salt in water.	Generates and translates between various particulate-level representations of a solution. Relates the distinction between homogeneous and heterogeneous solutions. Explains relative solubilities (including solubilities in non-aqueous solvents) in terms of intermolecular interactions.
Phases of Matter	Generates representations of the different phases of matter. Uses the ideal gas law to interrelate gas properties. States the basic elements of the kinetic molecular theory. Describes with some inaccuracy the relationship of pressure to a particulate-level view. Distinguishes constant pressure from constant volume conditions.	Predicts or analyzes data regarding melting and boiling points in terms of the arrangement of particles in the different phases and estimated magnitudes of intermolecular forces. Accurately states the particulate-level nature of pressure and its relation to the volume and temperature. Describes the properties of ideal gases based on kinetic molecular theory.	Predicts or analyzes data regarding deviations from ideal gas behavior based on kinetic molecular theory and estimated strengths of intermolecular forces. Explains, on a particulate level, why the ideal gas model applies over a broad range. Accurately explains the relation between temperature and kinetic energy, including the distribution of kinetic energies and meaning of absolute zero temperature.

	Competence ——————→		Mastery
Big Idea 3: Transformations			
Physical and Chemical Processes	Given a reaction, predicts the effects of this reaction on a collection of molecules and identifies whether the process corresponds to a precipitation, acid–base, or redox reaction. From data, determines expected amount and product yield for a reaction. Distinguishes between exothermic and endothermic reactions using data.	From data regarding a chemical process, generates an appropriate reaction and identifies the process as being a precipitation, acid–base, or redox reaction. Translates between symbolic, macroscopic, and particulate-level views of a chemical process.	Identifies connections between symbolic representations of reactions and energies associated with change and equilibrium (e.g., recounting that not all reactions go to completion). Classifies evidence as suggesting a physical versus chemical change, for ambiguous cases (e.g., dissolution of a salt).
Electro-chemistry	Writes a redox reaction in terms of its half-cell reactions. Uses half-cell potentials to predict whether a redox reaction will or will not occur between a solid metal and an aqueous ion. Identifies the connection between the standard cell potential and $\Delta G°$ of the reaction.	Relates the structure of an electrochemical cell to the processes occurring at electrodes, the transport of ions in the salt bridge, and the flow of electrons through the circuit. Distinguishes electrolytic from galvanic cells and the different processes occurring in each. Predicts the extent of a reaction using Faraday's law. Interprets data from a redox titration.	Predicts products of an electrolysis reaction depending on the redox potentials of the solute species and solvent. Designs a redox titration experiment.

	Competence ⟶ Mastery		
Big Idea 4: Kinetics			
Rate and Collision Theory	Provides a basic definition of *reaction rate* and explains that reaction rate is influenced by factors such as temperature, surface area, and concentration. Accurately identifies the rate law for reactions of various orders and uses this to compute the rate. Connects half-life with rate constant for a first-order reaction. Explains that the rate is influenced by the number of collisions and the energy and orientation of those collisions.	Identifies the connection between the influence of concentration on the reaction rate, a particulate-level view, and collision theory, with not all collisions being successful.	Identifies the connection between the influence of temperature on the reaction rate, a particulate-level view, and a reaction energy profile (e.g., Boltzmann distributions and activation energy). Explains why the rate of the reaction changes as the reaction progresses. Explains when half-life is concentration independent.
Mechanism	Distinguishes between a mechanism and an overall reaction. Relates that catalysts increase the rate of a reaction and are not consumed by the reaction.	Given a simple mechanism, predicts the rate law. Identifies reaction intermediates and catalysts.	Predicts the rate for mechanisms in which the first step is not rate limiting. Uses experimental data to distinguish between various proposed mechanisms, including affirming that multiple mechanisms may be consistent with the observations. Relates catalysis to mechanistic steps and to a particulate-level view of a reaction.
Observations (Measurement)	Identifies the connection between direct measures of concentration and the rate of the underlying reaction. Qualitatively distinguishes fast from slow reactions.	Identifies the connection between less direct observations (intensity of color, color changes) made at the macroscopic level and the rate law of an underlying reaction.	Designs an experiment to determine the rate law of a reaction. Articulates the distinction and relation between the rate law and integrated rates, and uses these to determine rate laws from experimental data regarding either initial rates or changes in concentration versus time.

Return to the Table of Contents

	Competence ——→ Mastery		
Big Idea 5: Thermodynamics			
Nature of Heat and Transfer	Identifies subsystems involved in a heat transfer process and the type of process occurring in each subsystem, for simple cases (e.g., a metal bar in water). Articulates that temperature is a measure of average kinetic energy, and heat transfer is kinetic energy transfer. Solves simple heat transfer problems (e.g., those involving heat transfer in which no phase changes or reactions occur).	Identifies subsystems for more complex situations, such as situations involving work or reactions occurring in solution. Solves heat transfer problems that involve phase transitions. Relates average particle velocities to temperature and mass (e.g., less massive particles move faster at a given temperature), including connections to particulate representations.	Solves heat transfer problems that involve chemical reactions. Delineates the distribution of kinetic energies present at a given temperature, including connections to particulate representations.
Nature of Chemical Energy	States that breaking a bond requires energy. Uses mathematical relations that relate heat to heat capacity, for simple situations. Generates and interprets graphical representations, capturing the relative state energies of chemical substances.	Connects the bond energies of reactants and products to the heat of reaction. Delineates qualitatively the origins and consequences of substances that have different heat capacities and recognizes the distinction between heat and temperature. Explains relative magnitudes of thermodynamic properties in terms of molecular structure of materials and the strength and nature of chemical bonds and intermolecular forces. Interprets a graph of energy versus interparticle separation. Analyzes energy transformations for complex, multicomponent, or multistep processes.	Generates and interprets diagrams showing the relationship between energy and interparticle separation. Reasons accurately about heat and energy in complex systems, such as those arising in biological systems.
Free Energy and Work	States a form of the second law of thermodynamics. Qualitatively ranks the entropy changes associated with various chemical processes. Calculates free energy for a process given the change in enthalpy and entropy, and identifies the sign of the result as indicating favorability. Communicates that both enthalpy and entropy must be considered to determine spontaneity.	Estimates the magnitude of the entropy change associated with a process, using particulate-level reasoning. From information about the occurrence of an endothermic process, identifies that the entropy must be increasing. Explains the use of coupled processes to drive unfavorable thermodynamic processes, such as the use of a battery to drive an electrolytic cell.	Describes how heat is connected to PV work and explains that the second law limits the ability to convert heat to work. Relates the consequences of positive versus negative ΔG°; for instance, articulates that processes with $\Delta G^\circ > 0$ may still occur, depending on initial conditions. Explains the distinction between processes that are thermodynamically unfavorable versus reactions that are too kinetically slow to be observed.

Return to the Table of Contents

Big Idea 5: Thermodynamics *(continued)*			
Calorimetry	States the connection between calorimetry and the law of conservation of energy. Interprets data from a calorimetry experiment to determine the heat liberated by a chemical process. Explains that the value of ΔH is tied to a particular equation and when coefficients are multiplied, the value of ΔH is also multiplied and when the equation is reversed, the sign of ΔH changes.	Interprets data from a calorimetry experiment to determine heat capacity or heat of fusion. Uses Hess's law to add together steps of a chemical process to determine overall reaction enthalpy or establish a reaction as endothermic or exothermic.	Interprets data from a calorimetry experiment to determine heat of reaction or dissolution. Designs a calorimetry experiment.

Return to the Table of Contents

	Competence ⟶		Mastery
Big Idea 6: Equilibrium			
Equilibrium	Generates the equilibrium expression for a given reaction and manipulates it for reaction reversal, etc. Uses Le Chatelier's principle for simple situations (e.g., simple stress applied to a single reaction). Given a set of concentrations, computes Q and compares it to K to determine direction of a reaction. Solves equilibrium problems involving a single reaction. Communicates that at equilibrium reactions continue to occur.	Maps real systems (e.g., solubility of salts and molecules, vapor pressures) onto equilibrium processes. Given data, identifies the point at which a system reaches equilibrium and relates this to a balance of forward and reverse rates. Clearly recognizes the distinction between initial and equilibrium and relates this to a balance of forward and reverse rates. Clearly recognizes the distinction between initial and equilibrium and conditions and how these are related via the equilibrium expression. Understands that there are many different sets of concentrations that satisfy the equilibrium expression and that Le Chatelier's principle predicts a shift from one equilibrium state to another equilibrium state in response to a stress.	Can use Le Chatelier's principle and stoichiometry to reason about complex situations, such as liquid–vapor equilibria in systems with different volumes or addition of an inert gas at constant volume. Understands the connection between equilibrium constants and forward/reverse rate constants for single-step reactions. Can use equilibrium reasoning to design conditions that optimize a desired result, such as product yield. Can connect reasoning based on Le Chatelier's principle to reasoning based on a comparison of Q and K.
Acid–Base	When discussing acids and bases, affirms the definitions of *strong/weak* versus *concentrated/dilute*. Determines pH of a strong acid solution. Determines pH of a strong base. Interprets titration curves for simple situations, such as titration of a monoprotic acid with a strong base. Presents the components of a buffer.	Interrelates pH, K_a, and K_b for solutions of a single strong or weak acid or base. Articulates and justifies, and generates representations of, which species will be present in large versus small concentrations in simple solutions, such as a single component acid solution. Identifies the ionization state of a weak acid, given the pH and pK_a. Identifies a particular mixture as being a buffer solution, estimates the pH, and identifies the reactions occurring upon addition of an acid or base. Describes and/or interprets changes in a titration curve for acids of different strengths or different concentrations of the same acid. Generates particulate representations of buffer solutions.	Articulates and justifies, both through computation and estimation, which species will be present in large versus small concentrations in equilibrium systems containing mixtures of acids, bases, salts, etc. Interprets titration curves for unfamiliar situations, including identifying the majority species at any point. Designs buffers with a target pH and buffer capacity. Explains the consequences of the temperature dependence of K_w.

Big Idea 6: Equilibrium *(continued)*			
Solubility	Accurately relates solubility to K_{sp} for 1:1 salts. Ranks solubilities based on K_{sp} for salts with identical numbers of ions.	Accurately relates solubility to K_{sp} for arbitrary salts. Explains the meaning of *saturated solution* and the relation to solubility and K_{sp}. Uses Le Chatelier's principle to reason qualitatively about the common ion effect and pH-sensitive solubility.	Articulates when the ranking of solubility does and does not follow the ranking of K_{sp}.
Equilibrium and Thermodynamics	Uses the mathematical relation connecting free energy to the equilibrium constant. States that there is a connection between the heat of dissolution and the nature of the interparticle forces.	Explains qualitatively the consequences of the relations between free energy and the equilibrium constant.	Articulates and cites inferences about the relation between the magnitude of K and the thermodynamic notion of $\Delta G°$, indicating favorability. Articulates and cites inferences about the conditions ($\Delta G°$ and RT) under which K is close to 1. Identifies and explains free energy in complex systems, such as biological systems. Relates at the particulate level the enthalpic and entropic effects accompanying dissolution of a salt.

Return to the Table of Contents

	Competence ⟶		Mastery
Investigative and Communication Skills			
Experimental Design	Identifies the variable being changed in an experiment. Recounts the types of information gathered by familiar experiments. Correctly selects and uses tools to measure desired quantities.	Clearly articulates which variables are being varied and which are being controlled in an experiment. Identifies likely sources of error.	Portrays principled design in experiments that vary a desired variable and control other relevant variables. Describes the impact of errors on the experimental results and refines experiments to reduce the impact of such errors.
Data Analysis	Presents data in the format most familiarly used for a particular class of experiments. Calculates the target quantities from experimental data. Handles units correctly.	Reports data to the appropriate level of precision. Translates between various representations of the data, e.g., graphical or tabular.	Estimates the uncertainty of the target quantity based on uncertainties in the measured quantities, e.g., uses a computational tool to estimate error in a linear regression and/or rejects outliers.
Terminology	Identifies domain-specific terms, with occasional errors in use of terms that have similar meanings.	Consistently and accurately uses domain-specific terms.	Consistently and accurately uses domain-specific terms.
Modeling	Identifies what a model is and recounts that model-building is central to science. Articulates that models are derived from observations and are attempts to explain data; but do not replace reality (i.e., that models are a human invention). Recounts models that were experienced previously and applies those models to simple, but unfamiliar, situations.	Selects appropriate models to address a given situation. States that the best models have predictive value. Affirms that models have limitations.	Applies multiple models to a complex situation. Identifies when a model is insufficient to explain a certain phenomenon.

KINETICS QUESTIONS
RICE FALL 2018

1. The following initial rate data were collected for the reaction
$BrO_3^-(aq) + 5Br^-(aq) + 6H^+(aq) \rightarrow 3Br_2(aq) + 3H_2O(l)$
at 25 °C.

Exp. #	$[BrO_3^-]$	$[Br^-]$	$[H^+]$	rate of disappearance of BrO_3^- $\left(\frac{M}{s}\right)$
1	0.200 M	0.100 M	6.31×10^{-3}	6.37×10^{-6}
2	0.300 M	0.100 M	6.31×10^{-3}	9.56×10^{-6}
3	0.500 M	0.200 M	6.31×10^{-3}	3.18×10^{-5}
4	0.500 M	0.200 M	1.00×10^{-2}	8.00×10^{-5}

a) Determine the reaction order for
  i. BrO_3^-

  ii. Br^-

  iii. H^+

b) Write the specific rate law for the reaction.

c) Determine the rate constant for the reaction (include units).

d) When a 5th run used $[BrO_3^-] = 0.500$ M and the $[Br^-] = 0.400$ M the rate of disappearance of BrO_3^- was 8.00×10^{-6} M s^{-1}. Calculate the pH of the solution for this run.

2. The following data is for the decomposition of NOBr to Br_2 and NO at a particular temperature.

Time (seconds)	0	2.0	4.0	6	8	10
[NOBr] M	0.0100	0.0071	0.0055	0.0045	0.0038	0.0033

Describe a graphical method that could be used to determine the order of the reaction and the rate constant for the reaction.

3. The following data was collected at a specific temperature for the reaction

$$2NO(g) + Cl_2(g) \rightarrow 2NOCl(g);$$

Experiment	[NO]	$[Cl_2]$	Initial Rate ($M\ s^{-1}$)
1	0.115 M	0.263 M	6.74×10^{-2}
2	0.200 M	0.264 M	1.17×10^{-1}
3	0.065 M	0.389 M	5.63×10^{-2}

a) Determine the order of the reaction with respect to NO and Cl_2. (Show your work clearly)

b) Write the differential rate law for this reaction.

c) What is the magnitude and the units of the rate constant?

d) The initial rate listed in the table is in terms of the disappearance of Cl_2. For Experiment 1 calculate the initial rate of appearance of NOCl.

e) Suggest a 2-step mechanism that is supported by the rate law you determined.

f) List two factors that are important for collisions between reactant molecules to be effective. Briefly, explain why all collisions between reactant molecules do not lead to a chemical reaction.

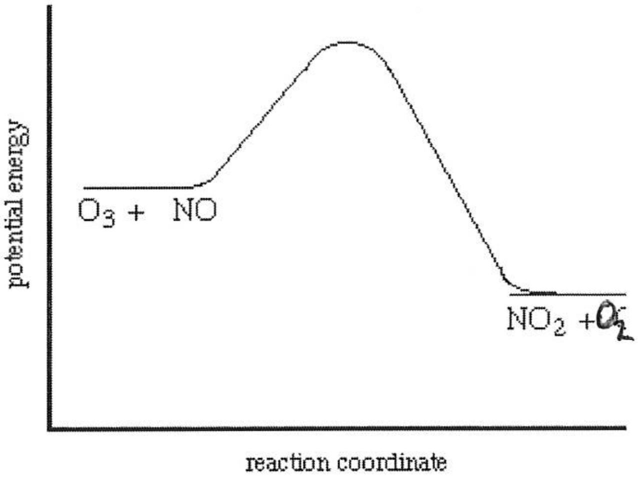
4. a) The diagram to the right shows the energy pathway for the reaction

$$O_3(g) + NO(g) \rightarrow NO_2(g) + O_2(g)$$

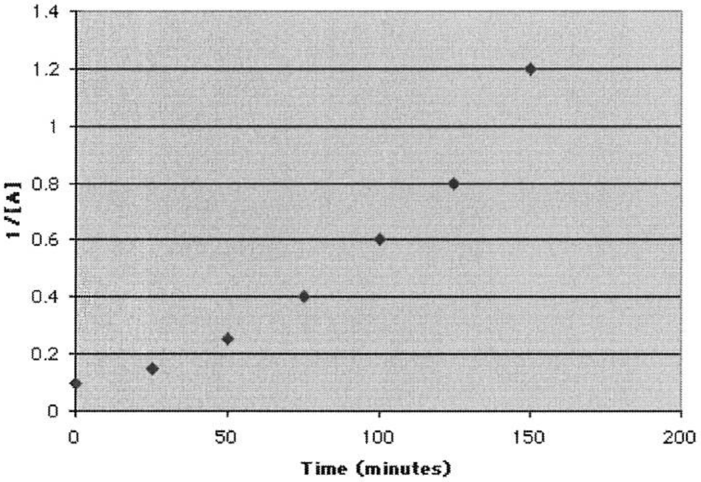
Clearly label the following directly on the diagram

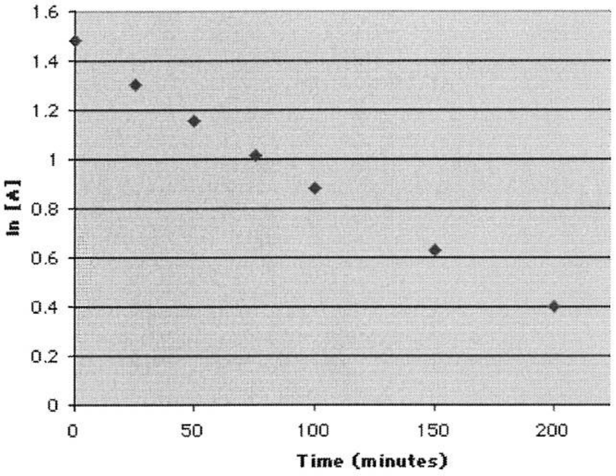
i) The activation energy, E_a, for the forward reaction;

ii) The enthalpy change, ΔH, for the reaction



5. a) Data for the chemical reaction 2A → B + C were collected by measuring the concentration of A over time. The following graphs were generated from analysis of the data.





Using the information in the graphs above, answer the following questions.

(i) Write the rate law expression (differential form) for the reaction. Justify your answer.

(ii) Describe how to determine the value of the rate constant for the reaction.

6. The following initial rate data were collected for the reaction

$$2NO_{(g)} + O_{2(g)} \rightarrow 2NO_{2(g)}$$

at 25 °C.

Exp. #	[NO]	$[O_2]$	rate of disappearance of O_2 $\left(\frac{M}{s}\right)$
1	3.6×10^{-4} M	5.2×10^{-3} M	3.4×10^{-8}
2	3.6×10^{-4} M	1.02×10^{-2} M	6.75×10^{-8}
3	1.8×10^{-4} M	6.2×10^{-3} M	1.01×10^{-8}
4	?	0.101 M	1.07×10^{-6}

a) Determine the reaction order for NO and O_2.

b) Write the specific rate law for the reaction.

c) Determine the rate constant for the reaction (include units).

d) Calculate the initial concentration of NO in Experiment 4 above.

Last modified: Thu 09/19/2013 01:28:17 pm

Oklahoma State University

It is OK to use your textbook or lecture notes from class, but if you can answers the questions without it that is OK too.

Do not press the RETURN or ENTER key while you are answering these questions. Your browser will interpret either the same as clicking on the Submit key.

Answer all of the questions below. If you do not know an answer enter CNA. However, it will help me the most if you answer each question with your best intuition/idea about what would be a reasonable answer.

First Name: ☐

Last Name: ☐

Laboratory Section: ☐

A simple reaction follows first order kinetics. Complete the following table;

[Reactant]	0.600 M	0.400 M	0.300 M	0.250 M	Q1
Time (sec)	0	Q2	137	Q3	274

1. Determine the concentration of the reactant after 274 seconds.

☐ **M**

2. How long does it take for the concentration of the reactant to fall to 0.400 M?

☐ **seconds**

3. How long does it take for the concentration of the reactant to fall to 0.250 M?

☐ **seconds**

When the first order integrate rate law is written in the following form;

$$\ln[A]_t = -kt + \ln[A]_o$$

The equation has the form of the equation for a straight line.

4. If the data in the table at the top of the page were plotted according to the equation,$\ln[A]_t = -kt + \ln[A]_o$, what would would be plotted on the y-axis and what would be plotted on the x-axis?

5. What does the slope of the line tell us and what is the y-intercept?

6. For a simple reaction that follows second order kinetics when the initial concentration is 0.0300 M the time required for the concentration to fall to 0.0150 m is 28 seconds. How long will it take for the concentration to fall to 0.0125 M? to 0.00625M?

seconds (to 0.0125 M) **seconds (to 0.00625 M)**

7. Is there anything about the reaction or the questions that you feel you do not understand? List your concerns/questions.

8. If there is one question you would like to have answered in lecture, what would that question be?

REACTION MECHANISMS

NAME

SECTION

1. Given the chemical equation

$$R + BG \rightarrow RG + B$$

Describe the interaction between reactant particles that must occur to convert them to products. You may draw one or more pictures as part of your description.

2. Write the general differential form of the rate law for the reaction above.

3. The following table summarizes several experiments where the concentrations of R and BG were varied to determine the effect on the initial rate of the reaction.

Experiment Number	R (M)	BG (M)	Initial Rate ($\frac{M}{s}$)
1	0.240	0.125	1.85×10^1
2	0.480	0.124	3.68×10^1
3	0.479	0.249	7.37×10^1

Determine the rate law for the reaction.

4. How do the exponents in the rate law that was obtained in Question 3 compare to the coefficients in the balanced chemical equation in Question 1?

5. Define the term *reaction mechanism*.

6. a. Optional: Look at the simulation (http://introchem.chem.okstate.edu/DCICLA/K2GBM.htm) for the reaction:

$$2G + B \rightarrow G_2B$$

The rate law is known to be rate = $k[G]^2$. Suggest a possible mechanism for this reaction.

b. Why is B not part of the rate law? (Hint: do all of the steps in a mechanism contribute to the overall rate? Why or why not?)

7. The rate law for the following reaction

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

was experimentally determined to be

$$\text{rate} = k[NO_2]^1[F_2]^1$$

Which of the following mechanisms is the most reasonable? Explain your reasoning for making the choice you did.

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

b. $NO_2(g) + F_2(g) \rightarrow NO_2F(g) + F(g)$ (fast)

$NO_2(g) + F(g) \rightarrow NO_2F(g)$ (slow)

c. $NO_2(g) + F_2(g) \rightarrow NO_2F(g) + F(g)$ (slow)

$NO_2(g) + F(g) \rightarrow NO_2F(g)$ (fast)

8. Suggest a mechanism for the reaction

$$CH_3NC(g) \rightarrow CH_3CN(g)$$

if the experimental rate law is rate = $k[CH_3NC]^1$.

9. Suggest a possible mechanism for the reaction

$$OH^- + CH_3Br \rightarrow CH_3OH + Br^-$$

if the experimental rate law is rate = $k[CH_3Br]^1[OH^-]^1$.

10. Suggest a possible mechanism for the reaction

$$NO_2(g) + CO(g) \rightarrow NO(g) + CO_2(g)$$

if the experimental rate law is rate = $k[NO_2]^2$.

11. Consider the following set of equations

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

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

$O_3(g) \rightarrow O(g) + O_2(g)$

Describe the process illustrated by the above set of equations and the role each of the species plays in the process. Use words like mechanism, elementary steps, overall reaction, reactants, products, intermediate, and catalyst in your description.

EQUILIBRIUM PROBLEMS
RICE FALL 2018

1. A flask containing 1.00 atm of NO_2 and 1.50 atm of N_2O_4 is allowed to proceed to equilibrium at a given temperature.

$$2NO_2(g) \rightleftharpoons N_2O_4(g)$$

When equilibrium is established the partial pressure of NO_2 is 0.500 atm.

a) Calculate the magnitude of the equilibrium constant for this reaction at this temperature.

b) After the reaction mixture has established equilibrium, 0.250 atm of N_2O_4 are added to the reaction flask. Which direction (left to right; right to left; or no change) will the reaction proceed to re-establish equilibrium? Explain in terms of Q and Kp.

c) Does the position of equilibrium favor the products side or the reactants side? Explain.

2. The equilibrium constant for the reaction

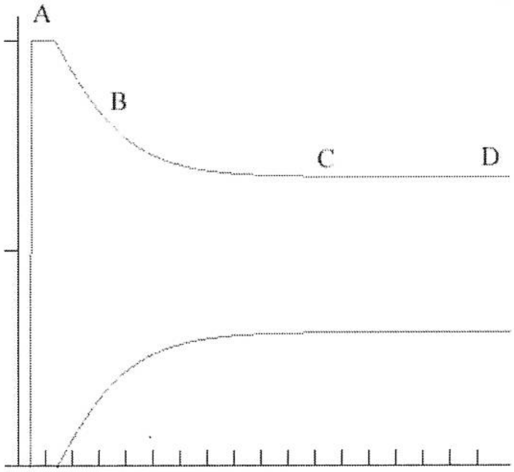
$$2NO(g) + O_2(g) \rightleftharpoons 2NO_2(g)$$

At a certain temperature is 1.48×10^4. The equilibrium constant for the reaction

$$NO_2(g) \rightleftharpoons \frac{1}{2}O_2(g) + NO(g)$$

What is the equilibrium constant for this reaction at the same temperature?

3. In the graph below the endothermic reaction BR*(g)* $\rightleftharpoons$ B*(g)* + R*(g)* is represented. Initially only BR*(g)* is present in the reaction vessel. The marks along the *x*-axis are in 1 minute increments. The initial [BR] (*y-axis)* is 2.0 M. The reaction begins about 1.5 minutes in this case.

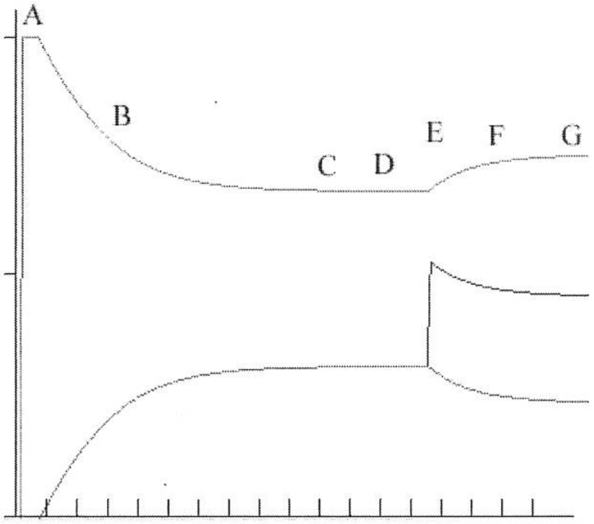


a) At what point (indicate a letter) does the reaction attain equilibrium? NOTE: You can also label the graph if your prefer.

b) Indicate whether K for the reaction is greater than 1, less than 1 or equal to1. Explain.

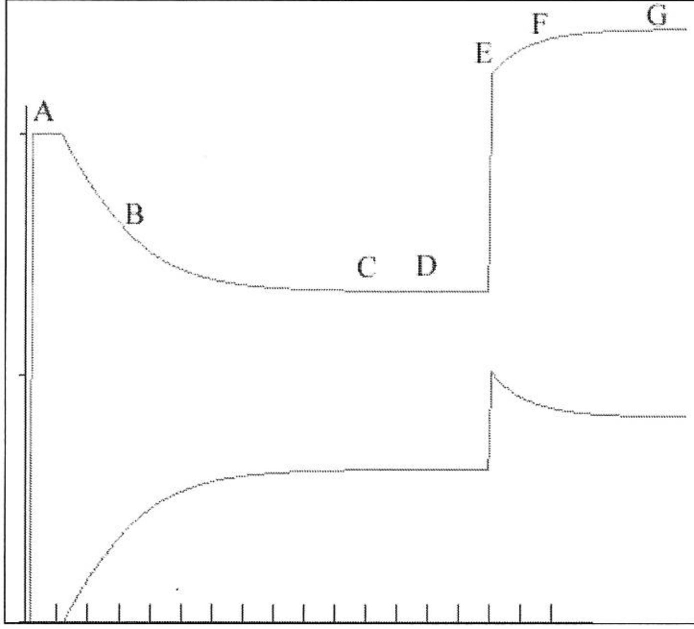
c) At point 'B' indicate how Q compares to K. Explain.

d) In this new view the same reaction has occurred. Indicate the stress (at point E) that was imposed on the system, and explain how the system changed as a response to the stress.



Explain:

e) In this new view the same reaction has occurred. Indicate the stress (at E) that was imposed on the system, and explain how the system changed as a response to the stress.



Explain:

4. a) The following reversible reaction occurs at 25. °C.

$$2HOCl(g) \rightleftharpoons H_2O\ g) + Cl_2O(g)$$

A reaction vessel that contains 0.500 atm of HOCl initially is allowed to attain equilibrium at 25 °C. Analysis indicates 0.0650 atm of HOCl are present at equilibrium. Calculate K_p for the reaction as written.

b) After the reaction in 4a attains equilibrium, some HOCl is added so the new partial pressure of HOCl is 0.200 atm. Calculate the new equilibrium amounts of the system when equilibrium is re-established.

5. In the reaction.

$$HNO_3(aq) + KOH(aq) \rightarrow KNO_3(aq) + H_2O(l)$$

a) Write the net ionic equation and determine the value of K for the neutralization reaction between nitric acid and potassium hydroxide?

b) In the neutralization reaction between $H_2PO_4^-(aq)$ and $HF(aq)$

$$H_2PO_4^-(aq) + HF(aq) \rightarrow H_3PO_4(aq) + F^-(aq)$$

i) Identify a conjugate acid-base pair in the equation above.

ii) Determine *K* for the reaction above. Show your work.

iii) Which acid in the above reaction is the strongest? What evidence did you use to make the claim?

6. a) Given that NaH_2PO_4 is soluble in water identify the two ions present when NaH_2PO_4 dissolves in water.

b) Of the two ions in the NaH_2PO_4 solution, identify the ion that can act as a Brønsted-Lowry base?

c) If the weak acid, $HC_2H_3O_2$, is added to the solution of NaH_2PO_4. Write a Brønsted-Lowry acid-base balanced chemical equation between $HC_2H_3O_2$ and the ion in the solution that will behave as a base and label all species as an acid, base, conjugate acid or conjugate base.

d) The K for the above reaction has a value of 1.33×10^{-3}. Which of the two acids is the strongest?

7. In aqueous solution, trimethylamine, $(CH_3)_3N$, acts as a weak base. The pH of 0.250 M $(CH_3)_3N$ is 11.60

a) Write the balanced chemical equation that describes how $(CH_3)_3N$ acts as a weak base.

b) Write the equilibrium constant expression, K_b, for trimethylamine. (3)

c) Calculate the value of the $[OH^-]$ in 0.250 M $(CH_3)_3N$.

d) Calculate the value of K_b for the reaction.

Dimethylamine, $(CH_3)_2NH$ is also a weak base. A 25.0 mL sample of 0.350 M $(CH_3)_2NH$ is titrated with 0.500 M HCl. The value of K_b for $(CH_3)_2NH$ is 5.4×10^{-4}.

e) Calculate the volume of 0.500 M HCl that must be added to reach the equivalence point of the titration.

f) A student claims the [OH$^-$] = K_b at the half-equivalence point of the titration. Provide evidence that supports the claim.

g) The pH at the equivalence point of the titration is 5.71. Show the calculation that produces this pH.

h) Which of the two bases, trimethylamine or dimethylamine is the stronger base? Explain.

8. Calculate the pH of each of the following,

a) 0.300 *M* $HC_3H_5O_2$ (propionic acid)

b) 0.400 *M* $CH_3NH_3NO_3$

c) 250. mLs of a solution that is 0.450 *M* CH_3NH_2 and 0.400 *M* $CH_3NH_3NO_3$.

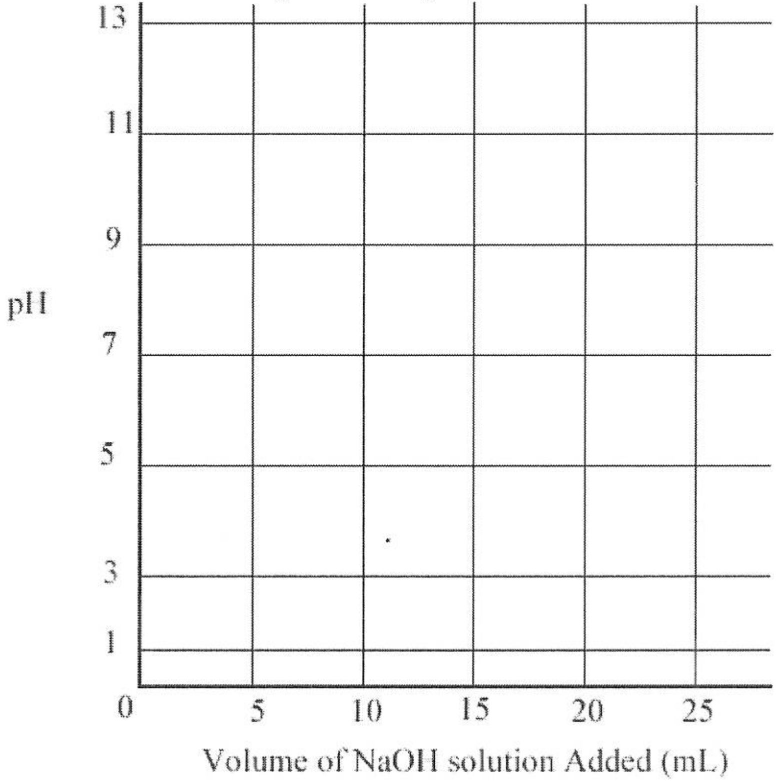
d) after adding 0.0025 mol HNO_3 to the solution in part 2c.

9. A solution of NaOH with an approximate concentration of 0.1 *M* is to be standardized by titration. Assume that the following materials are available.

Clean, dry 25 mL buret 125 mL Erlenmeyer flask Wash bottle filled with distilled water	Analytical balance Phenolphthalein indicator solution Potassium hydrogen phthalate, KHP (*MM* = 204 g mol^{-1}), solid monoprotic acid (to be used as a primary standard)

a) Briefly describe the steps you would take, using the materials listed above, to standardize the NaOH solution. Indicate the data you must collect, and how the data is used to calculate the concentration of the NaOH solution.

b) After the NaOH is standardized (to 3 significant figures) it is used to titrate a weak monoprotic acid, HX. The equivalence point is reached after adding 15.0 mL of the NaOH solution. In the space below sketch a titration curve, showing the pH changes that occur as the volume of NaOH solution added increases from 0 to 25 mL. Clearly label the equivalence point on the curve.



c) Describe how the value of the acid dissociation equilibrium constant, K_a, for the weak acid, HX, could be determined from the titration curve you drew in part b.

10. In aqueous solution, lactic acid, $HC_3H_5O_3$, behaves as a weak acid. In 0.0247 *M* $HC_3H_5O_3$ at 25 °C, the hydrogen ion concentration, $[H^+]$ is 1.79×10^{-3} M. In answering the following questions assume that the temperature is constant at 25 °C and that volumes are additive.

a) Write the weak acid dissociation chemical equation for lactic acid, $HC_3H_5O_3$.

b) write the equilibrium-constant expression for the reaction in part a).

c) Determine the pH of 0.0247 *M* $HC_3H_5O_3(aq)$.

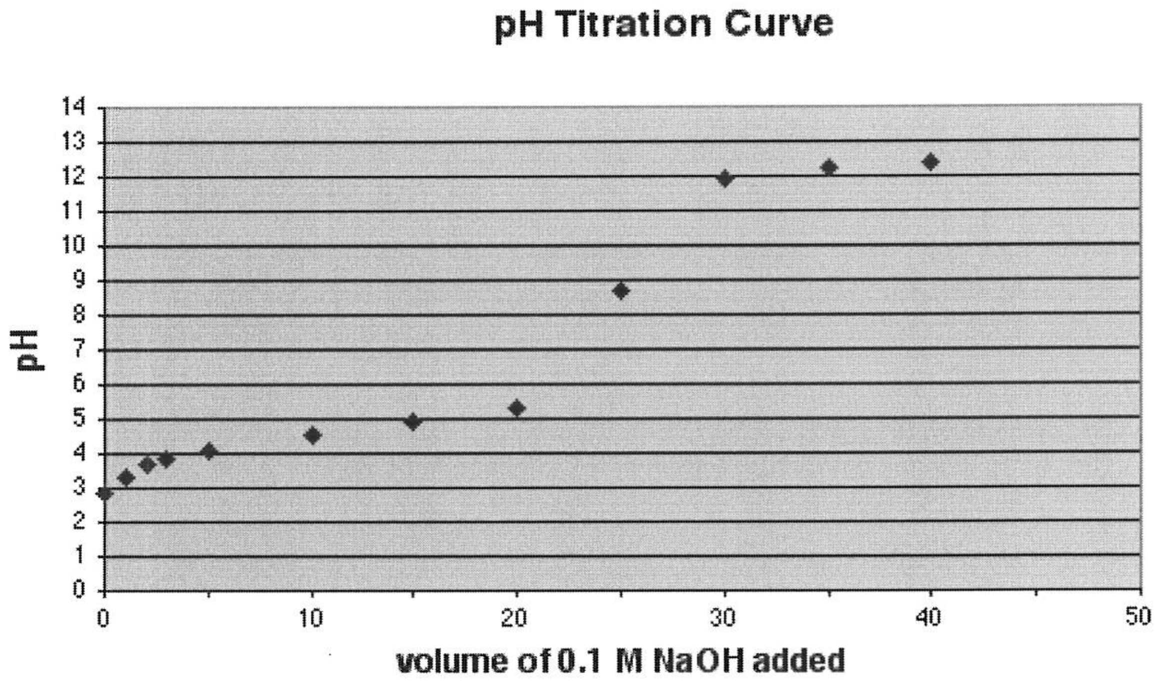
d) Determine the value of the acid ionization constant, K_a, for $HC_3H_5O_3(aq)$.

e) In an experiment a 20.0 mL sample of 0.0247 *M* $HC_3H_5O_3(aq)$ was placed in a flask and titrated to the equivalence point and beyond using 0.0450 *M* KOH.

i) Determine the volume of 0.0450 *M* KOH that was added to reach the equivalence point.

ii) Is the pH of the mixture at the equivalence point, greater than, less than or equal to 7? Explain. (Do <u>not</u> do a calculation.)

11. The graph below shows the result of the titration of a sample of a 0.10 M solution of a weak acid, HA, with a strong base, 0.10 M NaOH.



i) What are two features of the graph above that identify the acid as a weak acid?

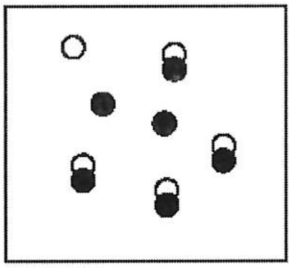
ii) without doing calculations, describe one method by which the acid ionization constant for the unknown substance can be determined.

iii) Using the graph above, sketch the titration curve the would be obtained if an equal amount of 0.10 M HCl were used instead of the 0.10 M HA

iv) If 0.20 M NaOH were used to titrate the same volume of the 0.10 M HA, what would be the volume of base added at the equivalence point? Would the pH at the equivalence point be equal to, greater than, or less than the pH at the equivalence point using 0.10 M NaOH? Explain.

MULTIPLE CHOICE:

1. The following diagram represents a reaction chamber



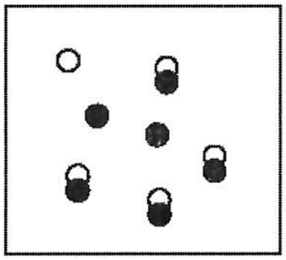
where the chemical reaction,

is at equilibrium

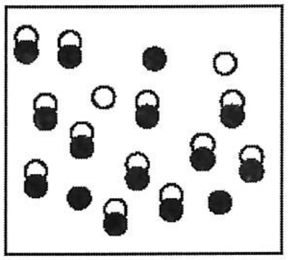
If nine units of

are added to the reaction chamber, which of the following best represents the system when it reestablishes equilibrium?

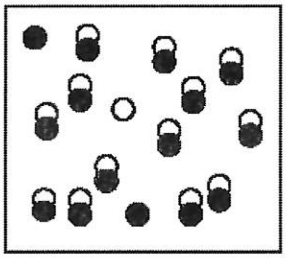
A.



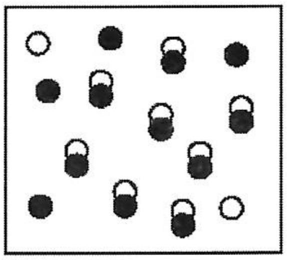
B.



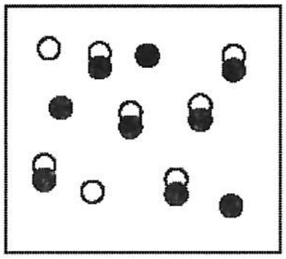
C.



D.



E.

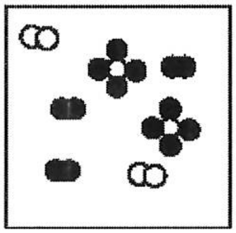


2. Consider the following hypothetical reaction:

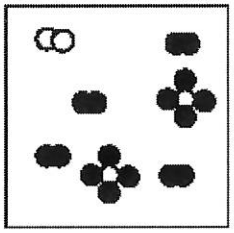
$$A_2(g) + 4B_2(g) \rightleftharpoons 2AB_4(g)$$

Initially 3 molecules of A_2 and 7 molecules of B_2 are placed in a reaction vessel. After a period of time 2 molecules of AB_4 are found in the vessel. Which of the following diagrams represents this final state?

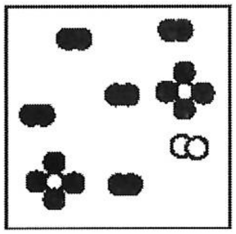
A.



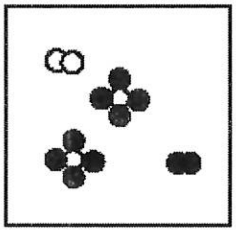
B.



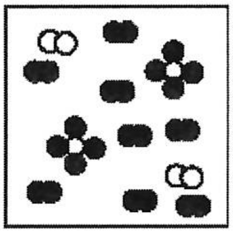
C.



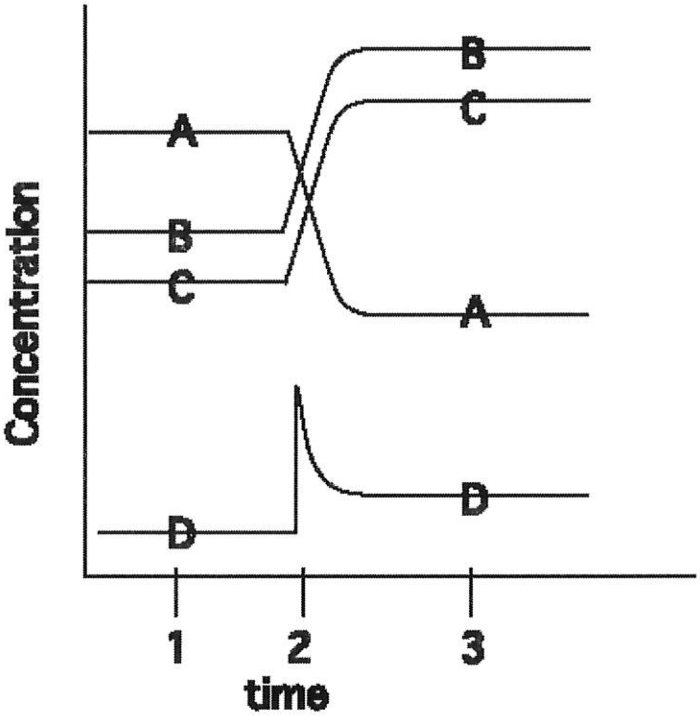
D.



E.



3. The following diagram represents a hypothetical chemical reaction



At time 2 a change takes place in the reaction. Which of the following statements about this chemical system is false?

A) At time 3 the system is at equilibrium.
B) At time 2 the concentration of D was increased
C) The change at time 2 caused more C to be formed.
D) The diagram is an illustration of the effect that changing the concentration has on a reaction at equilibrium
E) D and A are on opposite sides of the equation representing the reaction

Name	Formula	K_{a1}	K_{a2}	K_{a3}
Acetic	$HC_2H_3O_2$	1.8×10^{-5}		
Ascorbic	$HC_6H_7O_6$	8.0×10^{-3}		
Arsenic	H_3AsO_4	5.6×10^{-3}	1.0×10^{-7}	3.0×10^{-12}
Arsenous	H_3AsO_3	6.0×10^{-10}		
Benzoic	$HC_7H_5O_2$	6.5×10^{-5}		
Boric	H_3BO_3	5.8×10^{-10}		
Butyric acid	$HC_4H_7O_2$	1.5×10^{-5}		
Carbonic	H_2CO_3	4.3×10^{-7}	5.6×10^{-11}	
Cyanic	$HCNO$	3.5×10^{-4}		
Citric	$H_3C_6H_5O_7$	7.4×10^{-4}	1.7×10^{-5}	4.0×10^{-7}
Formic	$HCHO_2$	1.8×10^{-4}		
Hydroazoic	HN_3	1.9×10^{-5}		
Hydrocyanic	HCN	4.9×10^{-10}		
Hydrofluoric	HF	7.2×10^{-4}		
Hydrogen chromate ion	$HCrO_4^-$	3.0×10^{-7}		
Hydrogen peroxide	H_2O_2	2.4×10^{-12}		
Hydrogen selenate ion	$HSeO_4^-$	2.2×10^{-2}		
Hydrogen sulfate ion	HSO_4^-	1.2×10^{-2}		
Hydrogen sulfide	H_2S	5.7×10^{-8}	1.3×10^{-13}	
Hypobromous	$HBrO$	2.0×10^{-9}		
Hypochlorous	$HClO$	3.0×10^{-8}		
Hypoiodus	HIO	2.0×10^{-11}		
Iodic	HIO_3	1.7×10^{-1}		
Lactic	$HC_3H_5O_3$	1.4×10^{-4}		
Malonic	$H_2C_3H_2O_4$	1.5×10^{-3}	2.0×10^{-6}	
Oxalic	$H_2C_2O_4$	5.9×10^{-2}	6.4×10^{-5}	
Nitrous	HNO_2	4.5×10^{-4}		
Phenol	HC_6H_5O	1.3×10^{-10}		
Phosphoric	H_3PO_4	7.5×10^{-3}	6.2×10^{-8}	4.2×10^{-13}
Paraperiodic	H_5IO_6	2.8×10^{-2}	5.3×10^{-9}	
Propionic	$HC_3H_5O_2$	1.3×10^{-5}		
Pyrophosphoric	H_4P_2O	3.0×10^{-2}	4.4×10^{-3}	
Selenous	H_2SeO_3	2.3×10^{-3}	5.3×10^{-9}	
Sulfuric	H_2SO_4	strong acid	1.2×10^{-2}	
Sulfurous	H_2SO_3	1.7×10^{-2}	6.4×10^{-8}	
Tartaric	$H_2C_4H_4O_6$	1.0×10^{-3}	4.6×10^{-5}	

E.2 DISSOCIATION CONSTANTS FOR BASES AT 25°C

Name	Formula	K_b	Name	Formula	K_b
Ammonia	NH_3	1.8×10^{-5}	Hydroxylamine	$HONH_2$	1.1×10^{-8}
Aniline	$C_6H_5NH_2$	4.3×10^{-10}	Methylamine	CH_3NH_2	4.4×10^{-4}
Dimethylamine	$(CH_3)_2NH$	5.4×10^{-4}	Pyridine	C_5H_5N	1.7×10^{-9}
Ethylamine	$C_2H_5NH_2$	6.4×10^{-4}			
Hydrazine	H_2NNH_2	1.3×10^{-6}			