Appendix

Study Guides

Analytical Chemistry (Prepared with the help of the ACS Division of Analytical Chemistry)
A sequence of courses designed to cover modern analytical chemistry at the undergraduate level should present an integrated view of the theories and methods for solving a variety of real problems in chemical analysis. Students should receive a coherent and progressive treatment of the various aspects of problem definition, physicochemical operations, and data evaluation. The problem-oriented role of chemical analysis should be emphasized throughout the student's experience.

In addition to a firm foundation in basic chemical reactions involving analytes and ordinary analytical reagents, adequate coverage of modern analytical chemistry should include:

- Distinction between qualitative and quantitative goals of determinations
- Choice of experimental designs
- Sampling methods for all states of matter
- Sample preparation and derivatization procedures
- Availability and evaluation of standards
- Standardization methodology
- Theory and methods of separation
- Physicochemical methods of measurement
- Fundamental characteristics of instruments, including recording devices and data acquisition options
- Comparison and critical selection of methods for both elemental and molecular determinations
- Optimization techniques for various aspects of analysis
- Methods of data evaluation

Individual topics should be presented in the framework as a systematic approach which emphasizes functional roles, facilitates comparison of performance characteristics, and provides a pattern the student can use to understand related topics not included in formal course work. The courses should integrate chemical and instrumental concepts; they should include examples from inorganic, organic and biological chemistry. They should emphasize the importance of kinetic and equilibrium aspects of both chemical and physical processes, and they should emphasize interactions and resulting interdependencies among different steps in the analytical process. The course should include discussion of methods used to optimize performance characteristics such as selectivity, sensitivity, uncertainty, and detection limits. They should examine the trade-offs that are made among these performance characteristics and practical considerations, such as time and cost, which are always associated with real problems (i.e., an industrial process, a clinical problem or an experiment performed in outer space).

Some topics in modern analytical chemistry may not require a thorough background in physics and/or certain areas of physical chemistry. Accordingly, these topics may be introduced in lower division chemistry courses. However, to achieve the desired depth and breadth in modern analytical chemistry at the undergraduate level, the more advanced topics in theory and methods should have as prerequisites including calculus-based physics, basic inorganic and organic chemistry, an upper-level treatment of structure/energy relationships, fundamentals of thermodynamics and electrochemistry, and basic chemical dynamics.

While all areas of chemistry utilize the concepts and techniques referred to above, it is the responsibility of the analytical chemist(s) to coordinate and reinforce their presentation. The student should emerge from an undergraduate program of studies in analytical chemistry with the following competencies:

A. Clearly define problems of chemical analysis. Is the information required of a qualitative or quantitative nature? If quantitative, what are the acceptable accuracy and precision limits? Is it an elemental or molecular determination? What are the chemical and physical properties unique to the analyte and what matrix effects should be considered in designing the experiments? How is data to be evaluated, interpreted, and optimized?

B. Wisely select a method, or methods, to achieve the goals discussed in A (above). This implies that the student should understand the chemical and instrumental options available for both elemental and molecular determinations, as well as equilibrium and kinetic processes. The student must understand the basic chemical reactions that will be involved in sample acquisition and preparation and chemical separations. The student must know how to eliminate or compensate for experimental interferences. The student must recognize the critical response parameters for each phase of the determination and be able to identify the sources of error.

C. Utilize the proper methods of statistical evaluation of data, including validation and optimization techniques. A thorough understanding of standardization methodology is prerequisite, as is knowledge of the sources of errors (instrumental and chemical).

D. Understand the theory and operational principles of the fundamental components of instrumentation including:

- Atomic spectroscopy (emission, absorption, x-ray), Molecular spectroscopy (UV-Vis, infrared, fluorescence), and Mass spectrometry

Biochemistry

The ACS examination in biochemistry is used as part of our Chemistry and Biochemistry Ph.D. qualifying exam (Part I). The exam covers material presented in a typical year-long advanced undergraduate curriculum in biochemistry as taught at most American Universities. Students are advised to prepare for the ACS biochemistry exam by studying from a biochemistry textbook and concentrating on basic biochemical principles, key structures, and metabolic intermediates. Since the ACS biochemistry exam is highly problem oriented, studying/working through problem sets at the end of the chapters in a biochemistry textbook is highly recommended.

Topics that can be covered on the ACS biochemistry exam include:

- *Buffers and pH* – ionization of amino acids

- *Protein structure and function* – chemistry of amino acids and peptides, protein structure hierarchy, equilibrium binding of ligands, enzyme catalysis (kinetics, regulation, inhibition), enzyme mechanisms, enzyme cofactors, protein structure determination, methods of analysis
- *Metabolic pathways and regulation* – glycolysis, TCA cycle, pentose phosphate pathway, fatty acid oxidation, gluconeogenesis, amino acid metabolism, nucleotide metabolism, oxidative phosphorylation, cofactor chemistry, feedback inhibition, key intermediates of photosynthesis
- *Thermodynamics* – free energy change, equilibrium concentrations of reactants and products, redox reactions, ATP-coupled reactions, solution properties of macromolecules
- *Carbohydrate structure and function* – common sugars, chemistry of carbohydrates (reducing/non-reducing), complex carbohydrates, glycoproteins, methods of analysis
- *Nucleic acid structure and function* – chemistry of nucleotides and nucleic acids, 3D structure of DNA and RNA
  DNA replication, RNA transcription and protein translation, regulation of expression of genetic information, methods of analysis, recombinant DNA technology, molecular genetics
- *Lipid and membrane structure and function* – chemistry of lipids, structure of biomembranes, function of plasma lipoproteins, hormones, receptors, molecule transport across membranes

Inorganic Chemistry

The ACS examination in inorganic chemistry is used as part of our Chemistry and Biochemistry Ph.D. qualifying exam (Part I). The exam covers material presented in a typical advanced inorganic chemistry undergraduate course as taught at most American Universities. Students preparing to write the ACS inorganic chemistry exam are advised to study a straight-forward text (i.e. "Basic Inorganic Chemistry" by Cotton, Wilkinson, and Gaus) and fully understand the basics of inorganic chemistry. Typically, the ACS inorganic chemistry exam focuses more on theory than on actual structures or inorganic chemical reactions.

Topics that can be covered on the ACS inorganic chemistry exam include:

- *Periodicity and atomic structure* – electron configurations, trends in various properties (and anomalies), electronegativity, term symbols for atomic ground states
- *Ionic properties* – radii, ionization energies, electron affinities, oxidation states, Born-Haber cycles, lattice energies, crystal packing
- *Systematic chemistry of the elements* – alkalis, alkali metals, alkaline earths, noble gases, halogens, chalcogens, pnictogens, carbon groups, boron groups, transition elements, lanthanides, actinides, polymeric oxides, boranes, sulfur ring systems, silicates, inorganic ring systems
- *Solvents and acid-base chemistry* – acid-base concepts, hard and soft acids, weak and strong acids, superacids, non-aqueous solvent systems, solvation energies
- *Bonding theories* – Lewis structures, hybridization, resonance, valence shell electron pair repulsion (VSEPR) theory, linear combination of atomic orbitals-molecular orbital (LCAO-MO) theory, valence bond theory, bond energies, covalent radii and symmetry
- *Coordination chemistry* – stereochemistry and isomerism, valence bond, ligand field, molecular orbital (MO) theories of bonding, ligand field splitting, ligand field stabilization effects, magnetic properties, absorption spectroscopy of transition metal ions (Tanabe-Sugano diagrams), synthesis, reaction mechanisms, kinetics, trans effect, redox reactions,

metal-metal bonds, metal clusters

- *Solid state chemistry* – simple metals (structures and theories of bonding), semiconductors, and band theory
- *Organometallic chemistry* – effective atomic number (EAN) rule, carbonyls and nitrosyls, olefin, acetylene, alkyl, arene complexes, metallocenes, clusters, homogeneous catalysis fluxionality, oxidative addition, reductive elimination

Organic Chemistry

The ACS examination in organic chemistry is used as part of our Chemistry and Biochemistry Ph.D. qualifying exam (Part I). The exam covers material presented in a typical year-long undergraduate curriculum in organic chemistry as taught at most American Universities. Students preparing to write the ACS inorganic chemistry exam are advised any introductory undergraduate organic chemistry textbook for study/review purposes. Since the ACS organic chemistry exam is highly problem oriented, studying/working through problem sets at the end of the chapters of an introductory organic chemistry textbook is highly recommended.

Topics that can be covered on the ACS organic chemistry exam include:

- *Introduction to organic chemistry and basic review* – "why carbon?", electronic orbitals, orbitals and geometry, molecular structure (representations, polarity and formal charges, acid-base definitions), percent composition analysis
- *Functional groups* – multiple bonds, heteroatom substitution, multiple atom fragments
- *Organic reactions* – polar (electrophilic and nucleophilic), radical (initiation, propagation, and termination), pericyclic reactions, rates of reaction, equilibria, energy diagrams, equilibrium constants, intermediates vs. transition states
- *Alkanes* – structure and nomenclature, alkyl groups and trivial names, carbon and hydrogen types, physical properties, conformation, cyclic alkanes (cis/trans isomers)
- *Alkenes* – structure and nomenclature (nature of the double bond, Z/E isomers, conjugation, stability), reactions (addition of HX – Markovnikov's rule and the Hammond postulate, addition of other electrophiles, addition of radicals, oxidation and reduction), synthesis (dehydrohalogenation, dehydration)
- *Alkynes* – structure and nomenclature, reactions (electrophilic additions, hydration, tautomerization, hydroboration, oxidation and reduction, acidity and carbon-based nucleophiles – terminal anion, dianion, synthesis), introduction to multistep syntheses
- *Stereochemistry* – the nature of optical activity, chirality and enantiomers, nomenclature and 3D representations (wedge and hashmark, Fischer projection, Cahn-Ingold-Prelog convention), multiple chiral centers and diastereomers, properties of enantiomers vs diastereomers, stereochemistry and reactions, chirality at sites other than carbon
- *Alkyl halides* – structure and nomenclature, synthesis (from alkanes and olefins, from alcohols), organometallic chemistry reactions (Grignard's, lithium reactions, cuprates), substitution reactions (SN^1 and SN^2), elimination reaction (E^1 and E^2)
- *Cyclic systems* – nomenclature, stability and ring strain, synthesis, cyclohexanes and conformation, polycyclics, stereochemistry
- *Conjugation* – preparation and stability of polyolefins, Hückel molecular orbital (MO) theory, reactions (allylic systems and conjugation addition, kinetic and thermodynamic control,

pericyclic reactions)

- *Benzene and aromaticity* – nomenclature, structure, stability, molecular orbital (MO) theory, heterocyclic aromatics, electrophilic and nucleophilic aromatic substitutions, mechanism and electronic control of regiochemistry (inductive effects and reaction rates, mesomeric effects and directing ability), halogenation, nitration, sulfonation, hydroxylation, elimination/addition reactions (the benzyne reaction)
- *Arenes: synthesis and reactions of substituted benzenes* – Friedel-Crafts alkylation and acylation (cation rearrangements, "ways around them"), aromatic side-chain reactions (benzylic activation, halogenation, oxidation), benzene ring reduction (catalytic hydrogenation, Birch reduction), poly-substituted benzenes
- *Alcohols and thiols* – nomenclature, general properties, synthesis (from halides, from olefins, from carbonyl compounds *via* reduction and addition, preparation of glycols), reactions of alcohols (as a leaving group – olefins and halides, as a nucleophile – ethers and esters, as a base, in oxidation reactions), synthesis and protecting groups, synthesis and properties of thiols,
- *Phenols* – nomenclature, properties and comparison to alcohols, synthesis, reactions (as nucleophiles to form an ether and/or ester, oxidation reactions, precursors for Claisen rearrangement)
- *Ethers, epoxides and their sulfur analogues* – nomenclature (as ethers, alkoxy substituents, cyclic ethers, epoxides, and thio analogues), physical properties, synthesis of ethers, synthesis of epoxides (from olefins, from halohydrins, from glycols, Darzens glycidic ester synthesis, from ketones), reactions of ethers (*via* acidolysis), reactions of epoxides (*via* ring openings), oxidations of thioethers (sulfoxides and sulfones)
- *Aldehydes and ketones: carbonyl compounds* – nature of the carbonyl group, general reactions (addition of nucleophiles, reduction, replacement of oxygen, nucleophilic substitutions, substitutions and condensations at the alpha site), nomenclature of aldehydes and ketones, synthesis of ketones and aldehydes (*via* oxidation of alcohols, reduction of acyl halides "aka Rosenmund reduction", ozonolysis of olefins, Friedel-Crafts acylation, hydration of alkynes, acyl halides and cuprates, hydrolysis of geminal dihalides, oxidation of glycols), oxidation of aldehydes (Fehling's and Tollen's tests), oxidation of ketones, cyanohydrin formation, addition of nitrogen (imines, enamines, oximes), acetal and ketal formation (protection groups), reduction (with hydride to give alcohols, Wolff-Kishner reduction to alkanes, reduction of thioacetals), phosphorus ylides (the Wittig reaction and olefin synthesis), conjugate addition (the Michael reaction)
- *Amines* – nomenclature, structure and properties, basicity and functionality, reaction with alkyl halides, reaction with sodium azide, Gabriel synthesis, reduction techniques (oxime reduction, nitrile reduction, amide reduction, reductive amination, reduction of nitro compounds), rearrangements of N-carbonyl compounds (Hofmann rearrangement, Curtius rearrangement), reactions of amines (quaternization and salts: optical resolution, Hofmann elimination, acylation, sulfonation – the Hinsberg test, diazotization – the Sandmeyer reaction)
- *Carboxylic acids* – nomenclature, structure and physical properties, synthesis (*via* oxidation, *via* hydrolysis, Grignard reagent), reactions (with salts, reduction, decarboxylation, decarboxylation of diacids)

- *Carboxylic acid derivatives* – nomenclature, acid halide synthesis, acid halide reactions (nucleophilic substitutions, Friedel-Crafts acylation, Grignard addition, reduction), acid anhydride synthesis, acid anhydride reactions, ester properties, ester synthesis (Fischer esterification, from acid halides and anhydrides), ester reactions (substitution/transesterification, reduction, pyrolysis, Grignard addition, polyesters), amide synthesis, amide reactions, nitriles
- *Reaction of an α-carbon to a Carbonyl Group* – keto-enol equilibrium, halogenation of aldehydes and ketones, Hell-Volhard-Zelinsky reaction, alkylation type reactions (enolate formation, bromoform reaction, selenation, alkyl halide reaction, reaction of enamines, malonic and acetoacetic ester reactions), reaction of an α-carbon to a nitrile
- *Carbonyl condensation reactions* – aldol condensation, Cannizzaro reaction, Claisen condensation (not rearrangement), Dieckmann cyclization, Michael additions, Robinson annulation, acyloin condensation, Thorpe condensation
- *Spectroscopy* – methods and spectral analysis (infrared, UV-Vis, mass spectrometry, ^{1}H and ^{13}C NMR spectroscopy)

Physical Chemistry

The ACS examination in physical chemistry is used as part of our Chemistry and Biochemistry Ph.D. qualifying exam (Part I). The exam covers material presented in a typical year-long advanced undergraduate curriculum in physical chemistry as taught at most American Universities. Students are advised to prepare for the ACS physical chemistry exam by studying from a physical chemistry textbook (and studying/working through problem sets at the end of the chapters.

Topics that are typically covered on the ACS physical chemistry exam include:

- *Properties of gases* – properties of an ideal gas and mixtures, the barometric distribution law, the van der Waals equation, isotherms of real gases, critical state, the law of corresponding states, the Maxwell velocity distribution law
- *First law of thermodynamics* – temperature, heat and work, exact and inexact differentials, the Einstein function, heat capacities, internal energy, enthalpy, expansion and compression of gasses, thermochemistry
- *Second and third laws of thermodynamics* – Carnot heat engines, entropy, calculation of entropy changes, free energy, partial derivatives, equations of thermodynamics, entropy of real substances, thermodynamics of rubber elasticity
- *Equilibrium in pure substances* – chemical potential, phase equilibrium, surface tension, equilibria of condensed phases, phase diagrams, glass phase transition
- *Chemical reactions* – heats of reaction, adiabatic flame temperature, reversible reactions, calculation of equilibrium constants, fugacity of real gases, extent of reaction, heterogeneous reactions
- *Solutions* – partial molar quantities, Gibbs' phase rule, Raoult's law, Henry's law, colligative properties, equilibrium in solution, solution of macromolecules, phase diagrams, ionic solutions, Debye-Hückel theory, electrochemistry
- *Transport properties* – molecular collisions, random walks, diffusion, convection, chromatographic separation, viscosity, sedimentation

- *Chemical kinetics* – rate laws, effect of temperature on rate constants, theories of reaction rates, multistep reactions, chain reactions, reaction mechanisms, molecular beams, polymerization, surface catalysis, enzyme catalysis
- *Quantum theory* – particles and waves, Bohr's atomic theory, postulates of quantum theory, “the particle in a box”, the harmonic oscillator, angular momentum
- *Atoms* – hydrogen atom, electron spin, helium atom, Pauli exclusion principle, vector model of the atom, many-electron atoms, spin-orbit coupling, atomic spectroscopy, photoelectron spectroscopy
- *Diatomic molecules* – molecular vibrations, rotations, orbital theory, electronic spectroscopy, ionic bonding, dipole moments
- *Polyatomic molecules* – symmetry operations, groups, degenerate representations, bonding theory, symmetry orbitals, selection rules, molecular vibrations, Raman spectroscopy, molecular rotations
- *Structure of condensed phases* – crystallography, diffraction, crystalline solids, synthetic polymers, biopolymers, liquid crystals
- *Magnetic resonance spectroscopy* – principles of magnetic resonance, electron spin resonance (ESR), hyperfine coupling, ESR applications, high resolution NMR spectrometry, chemical shift, spin-spin splitting, second-order effects, ^{13}C NMR spectroscopy, relaxation processes, magnetic resonance imaging

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