

AN ADVANCED COURSE OF INSTRUCTION  
IN  
CHEMICAL PRINCIPLES

---

ARTHUR A. NOYES

DIRECTOR OF THE GATES CHEMICAL LABORATORY  
CALIFORNIA INSTITUTE OF TECHNOLOGY

AND

MILES S. SHERRILL

ASSOCIATE PROFESSOR OF THEORETICAL CHEMISTRY  
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

---

NEW YORK  
THE MACMILLAN COMPANY

1922

AN ADVANCED COURSE OF INSTRUCTION

IN

CHEMICAL PRINCIPLES



THE MACMILLAN COMPANY  
NEW YORK • BOSTON • CHICAGO • DALLAS  
ATLANTA • SAN FRANCISCO

MACMILLAN & CO., LIMITED  
LONDON • BOMBAY • CALCUTTA  
MELBOURNE

THE MACMILLAN CO. OF CANADA, LTD.  
TORONTO

S312

## PREFACE

---

IN this book are presented the results of the authors' many years' experience with their own classes in the development of a thorough course of instruction in the laws and theories of chemistry from quantitative stand-points. The course is intended for junior, senior, or graduate students of physical chemistry in colleges, scientific schools, and universities, who have completed the usual freshman and sophomore courses in chemistry, physics, and mathematics.

The purpose of the course is to give such students an intimate knowledge of fundamental chemical principles and a training in logical, scientific thinking, such as will enable them to attack effectively the practical problems arising in their subsequent educational or professional work in any of the branches of chemistry or related sciences. Descriptive text-books of physical chemistry afford a general survey of chemical laws and theories which may suffice for the purposes of students who are not preparing for a professional career on the educational, research, or industrial sides of chemistry, but they do not give that intensive training which is essential for pursuing successfully more specialized courses of scientific study or for applying chemical principles to industrial problems. No one regards a course of lectures on the principles of mathematics as a suitable method of giving beginners the ability to handle that science, and with scarcely more reason can descriptive courses on physical chemistry be expected to afford a working knowledge of chemical principles in their quantitative aspects. Only by constantly applying the principles to concrete problems will the student acquire such a knowledge and the power to use it in new cases.

Accordingly, the course of instruction is so planned as to make the student think about the significance of the principles presented and work out for himself the method of treatment of special cases upon the basis of those principles. To this end, the text is interspersed with problems, which prevent the student from memorizing the principles or complacently believing that a formal knowledge constitutes a real understanding of them. These problems are for the most part not of the usual type, involving merely substitution in formulas and mathematical operations, but are such as require clear logical thinking in the application of the principles to the cases under consideration. They are not merely supplementary or incidental to the text, but they are the feature about which the whole presen-

tation centers. The aim striven for has been to make each problem serve a definite purpose, and to have it involve independent thought, yet in such measure as shall not be beyond the mental capacity of college students who have completed good general courses in mathematics, physics, and chemistry. The problems have been gradually developed as a result of many years' trial of the plan with large classes of such students. While the authors realize that the presentation is in its details still far from perfect, they have decided to defer publication of it no longer, in the hope that this educational method, novel in this subject, may be further developed through the experience of other teachers, from whom suggestions will be gratefully received.

In order to attain the purpose in view and yet keep the book within the limits of an undergraduate course, the subjects treated have been carefully selected from the point of view of their practical importance to the chemist; many topics being omitted that are commonly included in descriptive courses on physical chemistry or in complete treatises on the subject. The book consists mainly, as the table of contents shows, in a development of the atomic, kinetic, and ionic theories through a consideration of the physical properties directly related to them, and in a treatment, with the aid of these theories, from mass-action, phase, and thermodynamic view-points, of the principles relating to the rate and equilibrium of chemical reactions. The newer theories of atomic structure and of radiation have been reluctantly omitted; because, in spite of their transcendent interest and their importance to the future of chemistry, in their present stage of development they are appropriately treated in an advanced course of the research type, rather than in a fundamental undergraduate course of a systematic character. Lack of time has led also to the omission of those more specialized parts of the subject that treat of the physical properties of substances in the various states of aggregation, such as the metallic, crystalline, liquid, and dispersed states; for, important as are some of the generalizations already arrived at in these fields, their inclusion in this course would have involved sacrifice of an adequate and intensive treatment of the more fundamental principles. A systematic notation (summarized on page 297) has been employed throughout the book.

The course of instruction, as carried out by the authors, consists of class-room exercises, mainly of the recitation type, given to sections of twenty to thirty students. At each exercise a number of problems are assigned which are to be solved and handed in at the beginning of the next exercise; the students being advised to use slide-rules so as to shorten the arithmetical work. The instructor then solves these problems on the blackboard, questioning members of the class as to how he shall proceed. He emphasizes the principles involved and the best way of looking at the problems under consideration. In the assignments it is customary not to

give out all at once the whole group of problems following a section of the text, but to assign only the first one or two of such a group, together with the last problems of the preceding group. This enables the instructor to discuss the principles relating to a new group of problems after the students have given some thought to them, but before they have passed to another topic; thereby insuring a better understanding of the general view-point from which it is best to attack the problems and removing difficulties which individual students may experience. Frequent written tests are given, consisting of review problems different from those already solved by the class, but involving the same principles.

In order that the student may better appreciate the principles he is studying, it is desirable that the class work be accompanied by a brief laboratory course, or if that is not practicable by lecture experiments, whose primary purpose should be to give concrete illustrations of the nature of the basic phenomena under consideration (such as vapor-pressure, ion-migration, reaction-rate); for the experimental methods by which the properties are determined are not described in this book, except in so far as these are essential to an understanding of the phenomena. Moreover, no attempt has been made to present the historical and research aspects of the topics, because of the impossibility of doing this at all adequately in a brief systematic treatment of the well-established principles of the subject. Many teachers will doubtless desire to supplement this systematic presentation by mentioning these historical and research aspects, and by suggesting the collateral reading of reviews and original articles that have appeared in chemical periodicals, or of text-books of physical chemistry in which these aspects are more fully discussed.

To cover satisfactorily the whole subject as here presented requires from 120 to 150 exercises; but, in order to make it readily adaptable to a one-year 90-hour course, certain articles and problems which are less important or more difficult are indicated by asterisks. It is also suggested that, when the subject must be completed in a one-year course, no attempt be made to include the thermodynamic treatment presented in Chapters X-XIII, but that, after taking up the chapter on thermochemistry, the course be completed by considering (without reference to its thermodynamic derivation) the applications of the important van't Hoff equation, as presented in Arts. 167-169. When the course extends through a year and a half, the second year work will naturally consist of Chapters IX-XIII, these constituting a systematic course on thermodynamic chemistry, which indeed may be pursued as a graduate subject by those who have not studied the earlier chapters of the book.

The authors desire to express their indebtedness to many of their colleagues for valuable suggestions, and especially to Professors S. J. Bates and E. B. Millard, and to Mr. Roger Williams, who have furnished detailed lists



of corrections and general criticisms. The authors desire also to thank Drs. G. N. Lewis and Merle Randall for the privilege of including, in advance of its publication in their book on Thermodynamics and the Free Energy of Chemical Substances, a table showing the values of the electrode-potentials recently derived by them.

*Pasadena and Cambridge, March, 1922.*

PRINTED IN THE UNITED STATES OF AMERICA

PRELIMINARY EDITIONS  
COPYRIGHT, 1917 AND 1920,  
BY ARTHUR A. NOYES

COMPLETE REVISION  
COPYRIGHT, 1922,  
BY ARTHUR A. NOYES AND MILES S. SHERRILL

Set up and electrotyped. Published May, 1922

Press of J. J. Little & Ives Co.  
New York



# CONTENTS

## PART I

### THE ATOMIC, MOLECULAR, AND IONIC THEORIES AND THE PROPERTIES OF SUBSTANCES DIRECTLY RELATED TO THESE THEORIES

#### CHAPTER I: THE COMPOSITION OF SUBSTANCES AND THE ATOMIC THEORY

	PAGE
1. The Field of Chemistry. Its General Principles the Subject of this Course . . . . .	3
2. Pure Substances and Mixtures, Elementary and Compound Substances, the Elements, and the Law of Definite Proportions . . . . .	3
3. The Law of Combining Weights . . . . .	4
4. The Atomic Theory . . . . .	5
5. Determination of Combining and Atomic Weights . . . . .	6
6. Values of the Atomic Weights . . . . .	8
7. Chemical Formulas, Formula-Weights, and Equivalent-Weights . . . . .	8

#### CHAPTER II: THE MOLAL PROPERTIES OF GASES AND THE MOLECULAR AND KINETIC THEORIES

1. THE VOLUME OF GASES IN RELATION TO PRESSURE, TEMPERATURE, AND MOLAL COMPOSITION	
8. The Volume of Perfect Gases in Relation to Pressure and Temperature . . . . .	10
9. Law of Combining Volumes and the Principle of Avogadro . . . . .	12
10. Empirical Definition of Molecular Weight and of Mol . . . . .	12
11. General Expression of the Laws of Perfect Gases . . . . .	13
12. Dalton's Law of Partial Pressures . . . . .	14
13. Determination of Molecular Weights . . . . .	16
14. Derivation of the Atomic Weights of Elements and of the Molecular Composition of Compounds . . . . .	17
15. Deviations from the Perfect-Gas Laws at Moderate Pressures . . . . .	19
16. Pressure-Volume Relations of Gases at High Pressures . . . . .	19

II. THE KINETIC THEORY		PAGE
17.	The Fundamental Kinetic Hypotheses . . . . .	22
18.	The Kinetic Equation for Perfect Gases . . . . .	22
19.	The Kinetic Energy of the Molecules and the Avogadro Number . . . . .	24
20.	The Kinetic Equation for Imperfect Gases . . . . .	25
21.	The Characteristics of the Molecules . . . . .	29
22.	Distribution of the Velocities and Kinetic Energies of the Molecules of a Gas . . . . .	31
III. THE ENERGY RELATIONS OF GASES		
23.	Energy in General and the Law of its Conservation . . . . .	35
24.	Work Attending Volume Changes in General . . . . .	37
25.	The Energy-Content of Systems in General in Relation to Temperature and Heat-Capacity . . . . .	39
26.	The Energy-Content and Heat-Capacity of Perfect Gases . . . . .	40
27.	The Heat-Capacity of Perfect Gases in Relation to their Molecular Composition . . . . .	41
28.	The Energy-Content and Heat-Capacity of Perfect Gases in Relation to the Kinetic Theory . . . . .	42
29.	The Energy-Content of Imperfect Gases in Relation to Volume and Pressure . . . . .	44
30.	The Energy-Content of Imperfect Gases at Constant Temperature in Relation to the Kinetic Theory . . . . .	45

### CHAPTER III: THE MOLAL PROPERTIES OF SOLUTIONS AND THE MOLECULAR THEORY

I. VAPOR-PRESSURE AND BOILING-POINT IN GENERAL		
31.	Vapor-Pressure . . . . .	47
32.	Relation of Boiling-Point to Vapor-Pressure . . . . .	48
33.	Change of Vapor-Pressure with Temperature. The Clapeyron Equation . . . . .	48
34.	Vaporization in Relation to the Kinetic Theory . . . . .	51
II. SOLUTIONS IN GENERAL		
35.	The Nature and Composition of Solutions . . . . .	55
III. VAPOR-PRESSURE AND BOILING-POINT OF PERFECT SOLUTIONS WITH ONE VOLATILE COMPONENT		
36.	Raoult's Law of Vapor-Pressure Lowering . . . . .	57
37.	Relation of Boiling-Point Raising to Vapor-Pressure Lowering and Molal Composition . . . . .	59
38.	Determination of Molecular Weights . . . . .	62
39.	Partial Vapor-Pressure of Volatile Solutes. Henry's Law . . . . .	63

# CONTENTS

xi

## IV. VAPOR-PRESSURE AND BOILING-POINT OF CONCENTRATED SOLUTIONS WITH TWO VOLATILE COMPONENTS

	PAGE
40. The Vapor-Pressure of Concentrated Solutions . . . . .	67
41. Vapor-Pressure and Boiling-Point of Concentrated Perfect Solutions in Relation to their Molal Composition . . . . .	67
42. Vapor-Pressure of Concentrated Solutions in General in Relation to their Composition . . . . .	69
43. Boiling-Point of Concentrated Solutions in General in Relation to their Composition . . . . .	72

## V. DISTRIBUTION BETWEEN PARTIALLY MISCIBLE SOLVENTS

44. Determination of Equilibrium-Conditions by the Perpetual-Motion Principle . . . . .	76
45. Distribution of a Solute between Two Non-Miscible Solvents . . . . .	76
46. The Lowering by Solutes of the Solubility of One Solvent in Another Solvent . . . . .	78
47. The Vapor-Pressure Relations of Partially Miscible Liquids . . . . .	79

## VI. THE FREEZING-POINT OF SOLUTIONS

48. Freezing-Point and Its Relation to Vapor-Pressure and Molal Composition . . . . .	80
49. Determination of Molecular Weights . . . . .	83

## VII. OSMOTIC PRESSURE OF SOLUTIONS

50. Osmotic Pressure . . . . .	84
51. Relation of Osmotic Pressure to Vapor-Pressure . . . . .	85
52. Relation between Osmotic Pressure and Molal Composition . . . . .	87

## VIII. REVIEW OF THE PRINCIPLES RELATING TO THE MOLAL PROPERTIES

53. Review Problems . . . . .	89
-------------------------------	----

## CHAPTER IV: THE ATOMIC PROPERTIES OF SOLID SUBSTANCES

### I. HEAT-CAPACITIES OF SOLID SUBSTANCES

54. Properties in the Solid State . . . . .	91
55. The Heat-Capacity of Solid Elementary Substances . . . . .	91
56. The Heat-Capacity of Solid Compound Substances . . . . .	93
57. Determination of Atomic Weights . . . . .	94

### II. GENERALIZATIONS RELATING TO ATOMIC WEIGHTS

58. Methods of Atomic Weight Determination and the Periodic Law . . . . .	95
---	----

## CHAPTER V: THE ELECTROLYTIC BEHAVIOR OF SOLUTIONS AND THE IONIC THEORY

### I. THE MOLAL PROPERTIES OF SOLUTIONS OF IONIZED SUBSTANCES

	PAGE
59. Effects of Salts on the Molal Properties of Aqueous Solutions and their Explanation by the Ionic Theory . . . . .	96

### II. ELECTROLYSIS AND FARADAY'S LAW

60. Electrolytic Conduction . . . . .	98
61. Chemical Changes at the Electrodes . . . . .	98
62. Faraday's Law . . . . .	99
63. The Mechanism of Conduction between Electrodes and Solutions	100

### III. ELECTRICAL TRANSFERENCE

64. The Phenomenon of Electrical Transference . . . . .	104
65. The Law of Transference . . . . .	105
66. Transference-Numbers . . . . .	105
67. The Mechanism of Conduction in Solutions . . . . .	106
68. Transference in Relation to the Mobility of the Ions . . . . .	107
69. The Moving-Boundary Method of Determining Transference . . . . .	108
70. Change of Transference-Numbers with the Concentration . . . . .	109
71. The Composition of Ions Determined by Transference Experiments . . . . .	110

### IV. ELECTRICAL CONDUCTANCE

72. Conductance, Specific Conductance, and Equivalent Conductance	112
73. Conductance in Relation to the Mobility of the Ion-Constituents	113
74. Change of Equivalent Conductance with the Concentration . . . . .	114
75. Conductance in Relation to the Concentration and Mobility of the Ions . . . . .	116
76. Conductance of the Separate Ion-Constituents . . . . .	119
77. Determination of the Concentration of Ions and of Largely Ionized Substances by Conductance Measurements . . . . .	121

### V. THE IONIZATION OF SUBSTANCES

78. Ionization of Substances Not Largely Ionized . . . . .	123
79. Ionization of Largely Ionized Substances . . . . .	123

### VI. APPLICATIONS OF THE LAWS OF CONDUCTANCE AND TRANSFERENCE

80. Review Problems . . . . .	127
-------------------------------	-----

## PART II

THE RATE AND EQUILIBRIUM OF CHEMICAL CHANGES  
FROM MASS-ACTION AND PHASE VIEW-POINTS

## CHAPTER VI: THE RATE OF CHEMICAL CHANGES

I. THE EFFECT OF CONCENTRATION ON REACTIONS  
BETWEEN SOLUTES OR GASEOUS SUBSTANCES

	PAGE
81. Concept of Reaction-Rate . . . . .	131
82. The Mass-Action Law of Reaction-Rate between Solutes . . .	131
83. First-Order Reactions . . . . .	132
84. Second-Order and Third-Order Reactions . . . . .	133
85. The Mechanism of Reactions and the General Mass-Action Law of Reaction-Rate . . . . .	134
86. The Mass-Action Law of Reaction-Rate between Gaseous Sub- stances . . . . .	135
87. Simultaneous Reactions . . . . .	136

II. THE EFFECT OF CONCENTRATION AND SURFACE ON REACTIONS  
BETWEEN SOLUTES AND SOLID SUBSTANCES

88. Rate of Reaction between Solutes and Solid Substances . . .	139
89. Solid Substances Dissolving in their Own Solutions . . . .	139

## III. THE EFFECT OF CATALYSTS

90. Catalysis . . . . .	140
91. Carriers . . . . .	140
92. Contact Agents . . . . .	141
93. Hydrogen-Ion and Hydroxide-Ion as Catalysts . . . . .	142
94. Enzymes . . . . .	143
95. Water as a Catalyst . . . . .	143

## IV. THE EFFECT OF TEMPERATURE

96. Principles Relating to the Effect of Temperature . . . . .	144
--	-----

CHAPTER VII: THE EQUILIBRIUM OF CHEMICAL CHANGES  
AT CONSTANT TEMPERATURE

## I. THE LAW OF MASS-ACTION

97. The Equilibrium of Chemical Reactions . . . . .	145
98. The Mass-Action Law of Chemical Equilibrium . . . . .	146

II. THE MASS-ACTION LAW FOR REACTIONS BETWEEN GASES		PAGE
99.	The Mass-Action Law in Terms of Partial Pressures . . . . .	148
100.	Gaseous Dissociation . . . . .	148
101.	Metathetical Gas Reactions . . . . .	150
III. THE MASS-ACTION LAW FOR REACTIONS BETWEEN SOLUTES		
102.	Ionization of Slightly Ionized Univalent Acids and Bases . . . . .	152
103.	Ionization of Largely Ionized Substances . . . . .	153
104.	The Ionization of Water . . . . .	154
105.	The Hydrolysis of Salts . . . . .	154
106.	Ionization of Dibasic Acids and their Acid Salts . . . . .	157
107.	Displacement of One Acid or Base from its Salt by Another . . . . .	159
108.	Neutralization-Indicators . . . . .	161
IV. THE MASS-ACTION LAW FOR REACTIONS INVOLVING SOLID PHASES		
109.	Form of the Mass-Action Expression . . . . .	165
110.	Reactions Involving Solid and Gaseous Substances . . . . .	165
111.	Solubility of Unionized and Slightly Ionized Substances . . . . .	166
112.	Solubility of Largely Ionized Substances . . . . .	167
113.	The Mass-Action of Imperfect Solutes. The Concept of Activity . . . . .	169
CHAPTER VIII: EQUILIBRIUM OF CHEMICAL SYSTEMS IN RELATION TO THE PHASES PRESENT		
I. GENERAL CONSIDERATIONS		
114.	General Considerations . . . . .	174
II. ONE-COMPONENT SYSTEMS		
115.	Representation of the Equilibrium-Conditions by Diagrams . . . . .	176
III. THE PHASE RULE		
116.	The Concept of Variance and Inductive Derivation of the Phase Rule . . . . .	180
117.	Discussion of the Concept of Components . . . . .	181
118.	Derivation of the Phase Rule from the Perpetual-Motion Principle . . . . .	183
IV. TWO-COMPONENT SYSTEMS		
119.	Systems with Solid and Gaseous Phases . . . . .	187
120.	Systems with Solid, Liquid, and Gaseous Phases. Pressure- Temperature Diagrams . . . . .	188
121.	Systems with Solid and Liquid Phases. Temperature-Compo- sition Diagrams . . . . .	190



# CONTENTS

XV

	PAGE
122. Systems with Liquid and Gaseous Phases . . . . .	197
123. Systems Involving Solid Solutions . . . . .	197

## V. THREE-COMPONENT SYSTEMS

124. Systems with Liquid and Solid Phases. Temperature-Composition Diagrams . . . . .	201
125. Systems with Gaseous, Liquid, and Solid Phases in Relation to the Phase Rule and Mass-Action Law . . . . .	203

## PART III

### THE ENERGY EFFECTS ATTENDING CHEMICAL CHANGES, AND THE EQUILIBRIUM OF CHEMICAL CHANGES IN RELATION TO THESE EFFECTS

#### CHAPTER IX: THE PRODUCTION OF HEAT BY CHEMICAL CHANGES

##### I. THE FUNDAMENTAL PRINCIPLES OF THERMOCHEMISTRY

126. The First Law of Thermodynamics . . . . .	207
127. Heat-Effects Attending Isothermal Changes in State . . . . .	208
128. Change in Energy-Content and in Heat-Content . . . . .	209
129. Expression of Changes in Heat-Content by Thermochemical Equations . . . . .	211
130. Indirect Determination of the Heat-Effects of Chemical Changes . . . . .	214
131. Influence of Temperature on the Heat-Effects Attending Chemical Changes . . . . .	215

##### II. GENERAL RESULTS OF THERMOCHEMICAL INVESTIGATIONS

132. Heat-Effects Attending Changes in the State of Aggregation of Substances . . . . .	217
133. Heats of Reaction in Aqueous Solution . . . . .	218
134. Applications of Thermochemical Principles . . . . .	221

#### CHAPTER X: THE PRODUCTION OF WORK BY ISOTHERMAL CHEMICAL CHANGES IN RELATION TO THEIR EQUILIBRIUM CONDITIONS

##### I. THE SECOND LAW OF THERMODYNAMICS AND THE CONCEPT OF FREE-ENERGY

135. The Second Law of Thermodynamics and its Application to Isothermal Changes in State . . . . .	223
136. The Concepts of Work-Content and Free-Energy . . . . .	226

II. FREE-ENERGY CHANGES ATTENDING PHYSICAL CHANGES		PAGE
137.	Free-Energy Changes Attending Changes in Volume and Pressure . . . . .	230
138.	Free-Energy Changes Attending the Transfer of Substances between Solutions of Different Concentrations . . . . .	231
139.	Free-Energy Changes Attending the Transfer of Substances between Different Phases . . . . .	234
III. FREE-ENERGY CHANGES ATTENDING CHEMICAL CHANGES		
140.	The Free-Energy Equation for Chemical Changes between Perfect Gases . . . . .	238
141.	The Free-Energy Equation for Chemical Changes between Perfect Solutes . . . . .	240
142.	The Free-Energy Equations for Chemical Changes between Solid Substances and Perfect Gases or Perfect Solutes . . . . .	242
CHAPTER XI: THE PRODUCTION OF WORK FROM ISOTHERMAL CHANGES BY ELECTROCHEMICAL PROCESSES		
I. CHANGES IN STATE AND IN FREE ENERGY IN VOLTAIC CELLS		
143.	Introduction . . . . .	243
144.	Changes in State in Voltaic Cells . . . . .	243
145.	The Production of Work and the Corresponding Decrease of Free Energy in Voltaic Cells . . . . .	247
II. THE ELECTROMOTIVE FORCE OF CELLS UNDERGOING ONLY CHANGES IN CONCENTRATION OR PRESSURE		
146.	Change of the Electromotive Force of Voltaic Cells with the Concentration of the Solutions . . . . .	249
147.	The Electromotive Force of Concentration-Cells . . . . .	250
III. THE ELECTROMOTIVE FORCE OF CELLS UNDERGOING CHEMICAL CHANGES AND ITS RELATION TO THEIR EQUILIBRIUM CONDITIONS		
148.	Chemical Changes in Voltaic Cells . . . . .	252
149.	The Electromotive Force of Cells in Relation to the Equilibrium Conditions of the Chemical Reactions . . . . .	252
IV. ELECTRODE-POTENTIALS AND LIQUID-POTENTIALS		
150.	The Nature of Electrode-Potentials . . . . .	254
151.	The Expression of Electrode-Potentials . . . . .	255
152.	Change of Electrode-Potentials with the Ion-Concentrations, and the Concept of Molal Electrode-Potentials . . . . .	256

# CONTENTS

xvii

	PAGE
153. Values of the Molal Electrode-Potentials . . . . .	259
154. Derivation of Related Molal Electrode-Potentials from One Another . . . . .	260
155. The Electromotive Force of Cells with Dilute Solutions in Relation to the Molal Electrode-Potentials . . . . .	260
156. The Electromotive Force of Cells with Concentrated Solutions . . . . .	261
157. The Nature of Liquid-Potentials and Expressions for their Approximate Evaluation . . . . .	262
158. Derivation of the Liquid-Potential Equations . . . . .	264
159. Determination of Ion-Concentrations and of Equilibrium-Constants by Means of Electromotive-Force Measurements . . . . .	266
V. THE EQUILIBRIUM OF OXIDATION REACTIONS IN RELATION TO THE ELECTRODE-POTENTIALS	
160. Derivation of the Equilibrium-Constants of Oxidation Reactions from the Molal Electrode-Potentials . . . . .	269
VI. VOLTAIC ACTION, ELECTROLYSIS, AND POLARIZATION	
161. Concentration-Changes Attending Voltaic Action and the Resulting Polarization . . . . .	271
162. Electrolysis in Relation to Minimum Decomposition-Potential . . . . .	272
163. Electrolysis in Relation to Polarization . . . . .	273
CHAPTER XII: THE EFFECT OF TEMPERATURE ON THE WORK PRODUCIBLE BY ISOTHERMAL CHEMICAL CHANGES AND ON THEIR EQUILIBRIUM CONDITIONS	
I. THE FUNDAMENTAL SECOND-LAW EQUATION	
164. The Quantity of Work Produisible from a Quantity of Heat that Passes from One Temperature to Another . . . . .	277
II. THE EFFECT OF TEMPERATURE ON THE EQUILIBRIUM OF UNIVARIANT SYSTEMS	
165. The Effect of Temperature on the Pressure at which the Phases of Univariant Systems are in Equilibrium . . . . .	280
III. THE EFFECT OF TEMPERATURE ON THE EQUILIBRIUM OF CHEMICAL REACTIONS IN GENERAL	
166. The Effect of Temperature on the Free-Energy Decrease Attending Any Isothermal Change in State . . . . .	284
167. The Effect of Temperature on the Equilibrium of Chemical Changes Involving Perfect Gases . . . . .	285
168. The Effect of Temperature on the Equilibrium of Chemical Changes Involving Perfect Solutes . . . . .	288