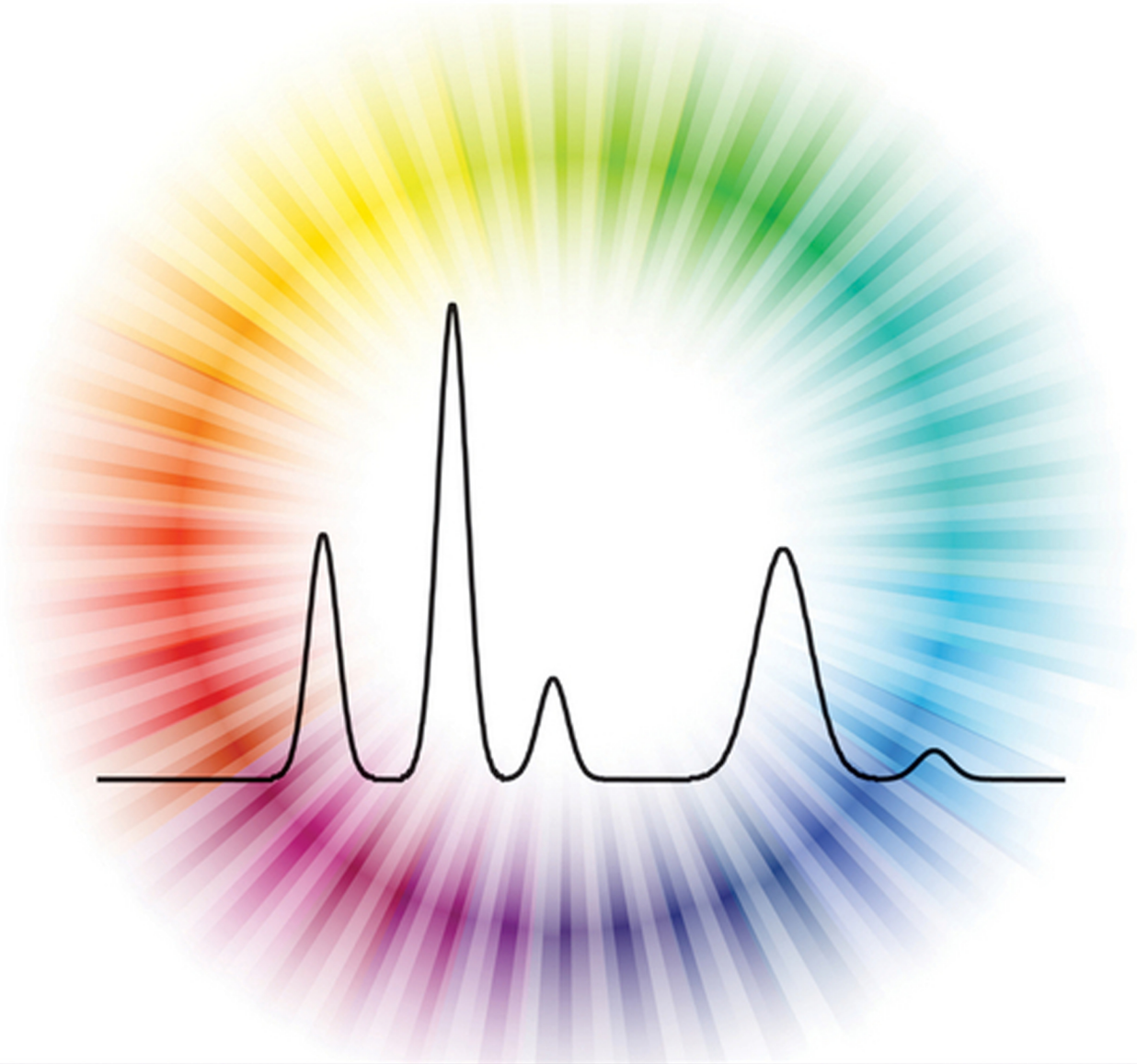
Seventh Edition

ANALYTICAL CHEMISTRY



Gary D. Christian • Purnendu K. Dasgupta • Kevin A. Schug

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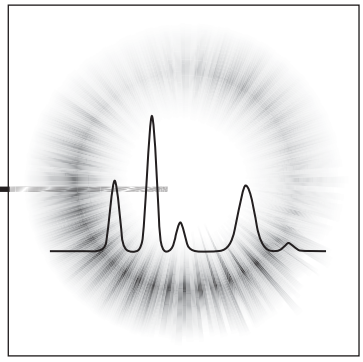
ANALYTICAL CHEMISTRY



SEVENTH EDITION

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WILEY

To

Nikola from Gary—for your interests in science. You have a bright future,wherever your interests and talents take you

Philip W. West from Sandy—wherever you are Phil, sipping your martini with 1 ppm vermouth, you know how it was: For he said, I will give you, A shelter from the storm. . . .

Dad from Kevin—well its not hardcore P. Chem., but it is still quite useful. Thanks for your love, support, and guidance through the years

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Preface

"Teachers open the door, but it is up to you to enter" —**Anonymous**

This edition has two new coauthors, Purnendu (Sandy) Dasgupta and Kevin Schug, both from the University of Texas at Arlington. So the authorship now spans three generations of analytical chemists who have each brought their considerable expertise in both teaching and research interests to this book. While all chapters have ultimately been revised and updated by all authors, the three authors have spearheaded different tasks. Among the most notable changes are the following: The addition of a dedicated chapter on mass spectrometry (Chapter 22) by Kevin. Sandy provided complete rewrites of the chapters on spectrochemical methods (Chapter 16) and atomic spectrometric methods (Chapter 17), and gas and liquid chromatography (Chapters 20 and 21), and added many new Excel problems and exercises. Gary compiled and organized all old and new supplementary materials for the textbook companion website and added QR codes for selected website materials, and he prepared the PowerPoint presentations of figures and tables.

WHO SHOULD USE THIS TEXT?

This text is designed for college students majoring in chemistry and in fields related to chemistry. It is written for an undergraduate **quantitative analysis course**. It necessarily contains more material than normally can be covered in a one-semester or one-quarter course, so that your instructor can select those topics deemed most important. Some of the remaining sections may serve as supplemental material. Depending on how a quantitative analysis and **instrumental analysis** sequence is designed, it may serve for **both courses**. In any event, we hope you will take time to read some sections that look interesting to you that are not formally covered. They can certainly serve as a reference for the future.

WHAT IS ANALYTICAL CHEMISTRY?

Analytical chemistry is concerned with the chemical characterization of matter, both qualitative and quantitative. It is important in nearly every aspect of our lives because chemicals make up everything we use.

This text deals with the principles and techniques of quantitative analysis, that is, how to determine how much of a specific substance is contained in a sample. You will learn how to design an analytical method, based on what information is needed or requested (*it is important to know what that is, and why!*), how to obtain a laboratory sample that is representative of the whole, how to prepare it for analysis, what measurement tools are available, and the statistical significance of the analysis.

Analytical chemistry becomes meaningful when you realize that a blood analysis may provide information that saves a patient's life, or that quality control analysis assures that a manufacturer does not lose money from a defective product.

WHAT'S NEW TO THIS EDITION?

This seventh edition is extensively rewritten, offering new and updated material. The goal was to provide the student with a foundation of the analytical process, tools, and computational methods and resources, and to illustrate with problems that bring realism to the practice and importance of analytical chemistry. We take advantage of digital technologies to provide supplementary material, including videos, website materials, spreadsheet calculations, and so forth (more on these below). We introduce the chapters with examples of representative uses of a technique, what its unique capabilities may be, and indicate what techniques may be preferred or limited in scope. The beginning of each chapter lists key learning objectives for the chapter, with page numbers for specific objectives. This will help students focus on the core concepts as they read the chapter.

Here are some of the new things:

- **Professors Favorite Examples and Problems.** We asked professors and practicing analytical chemists from around the world to suggest new analytical examples and problems, especially as they relate to real world practice, that we could include in this new edition. It is with appreciation and pleasure that we thank the many that have generously provided interesting and valuable examples and problems. We call these **Professor's Favorite Examples**, and **Professor's Favorite Problems, and they are annotated within the text by a margin element**  . We have included these in the text where appropriate and as space allows, and have placed some on the text website. We hope you find these interesting and, as appropriate, are challenged by them.

  Our special thanks go to the following colleagues who have contributed problems, analytical examples, updates, and experiments:

  - Christine Blaine, Carthage College
  - Andre Campiglia, University of Central Florida
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  - Christa L. Colyer, Wake Forest University
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- Kris Varazo, Francis Marion University
- Akos Vertes, George Washington University
- Bin Wang, Marshall University
- George Wilson, University of Kansas
- Richard Zare, Stanford University

- **Mass spectrometry**, especially when used as a hyphenated technique with chromatography, is increasingly a routine and powerful analytical tool, and a new chapter (Chapter 22) is dedicated to this topic. Likewise, **liquid chromatography**, including **ion chromatography** for anion determinations, is one of the most widely used techniques today, even surpassing gas chromatography. There are a wide variety of options of systems, instruments, columns, and detectors available, making selection of a suitable system or instrument a challenge for different applications. The present liquid chromatography chapter (Chapter 21) uniquely provides comprehensive coverage within the scope of an undergraduate text that not only gives the fundamentals of various techniques, how they evolved, and their operation, but also what the capabilities of different systems are and guidance for selecting a suitable system for a specific application.
- **Revised chapters**. All chapters have been revised, several extensively, especially those dealing with instrumentation to include recent technological innovations, as done for the liquid chromatography chapter. These include the **spectrochemical chapter (16)**, the **atomic spectrometric chapter (17)**, and the **gas chromatography chapter (20)**. **State-of-the-art** technologies are covered. Some of this material and that of other chapters may be appropriate to use in an **Instrumental Analysis course**, as well as providing the basics for the quantitative analysis course; your instructor may assign selected sections for your course.
- **Historical information** is added throughout to put into perspective how the tools we have were developed and evolved. Some is this is included in **margin pictures** and notes, showing pioneers in development of our profession.
- **Videos of Excel Programs.** Major additions to the text and the text's website supplemental material include powerful Excel programs to perform complicated calculations, and to create plots of titration curves, alpha vs. pH, logC vs. pH, etc. We have included video tutorials created by students of Professor Dasgupta to illustrate the use of many of these. The following videos, by chapter and in order of page appearance, with page numbers listed, are available on the text website. We have also created QR Codes for these in each chapter (see below) for those who want to access them on their smartphones. You will find these useful as you experiment with Excel and its power.

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Thanks are due to the following students at the University of Texas as Arlington for their contributions: Barry Akhigbe, Jyoti Birjah, Rubi Gurung, Aisha Hegab, Akinde Kadjo, Karli Kirk, Heena Patel, Devika Shakya, and Mahesh Thakurathi.

OTHER MODIFICATIONS TO EXISTING CONTENT

It has been almost ten years since the last edition was published and since that time, much has changed! This seventh edition of *Analytical Chemistry* is extensively revised and updated, with new materials, new problems and examples, and new references.

- **Spreadsheets.** Detailed instructions are given on how to use and take advantage of spreadsheets in analytical calculations, plotting, and data processing. But the introductory material has been moved to the end of Chapter 3 as a separate unit, so that it can be assigned independently if desired, or treated as auxiliary material. The use of Excel Goal Seek and Excel Solver is introduced for solving complex problems and constructing titration curves (see below). Mastery of these powerful tools will allow students to tackle complex problems. Several useful programs introduced in the chapters are placed on the text website and instructions are given for applying these for plotting titration curves, derivative titrations, etc. by simply inputting equilibrium constant data, concentrations, and volumes.
- **References.** There are numerous recommended references given in each chapter, and we hope you will find them interesting reading. The late Tomas Hirschfeld said you should read the very old literature and the very new to know the field. We have deleted a number of outdated references, updating them with new ones. Many references are for classical, pioneering reports, forming the basis of current methodologies, and these remain.
- **Material moved to the text website.** As detailed elsewhere, we have moved certain parts to the text **website** as supplemental material and to make room for updating material on the techniques to be used. This includes:
  - The **single pan balance** (Chapter 2) and **normality calculations** (Chapter 5), which may still be used, but in a limited capacity.
  - The **experiments**.
  - Auxiliary spreadsheet calculations from different chapters are posted on the website.
  - Chapters dealing with specific applications of analytical chemistry are now on the text website for those interested in pursuing these topics. These are **Clinical Chemistry** (Chapter 25), and **Environmental Sampling and Analysis** (Chapter 26).
  - Analytical chemistry played a key role in the completion of the historic Human Genome Project, and the **Genomics and Proteomics chapter** documents how. This material is not mainstream in the quantitative analysis course, so it has been moved to the website as Chapter G. It is available there for the interested student or for professor assignment.

SPREADSHEETS

Spreadsheets (using **Excel**) are introduced and used throughout the text for performing computations, statistical analysis, and graphing. Many titration curves are derived using spreadsheets, as are the calculations of α-values and plots of α-pH curves, and of logarithm concentration diagrams. The spreadsheet presentations are given in a "user-friendly" fashion to make it easier for you to follow how they are set up.

We provide a **list of the different types of spreadsheets** that are used throughout the text, by topic, after the Table of Contents.

GOAL SEEK

We have introduced the use of Goal Seek, a powerful Excel tool, for solving complex problems. Goal Seek performs "trial and error" or successive approximation calculations to arrive at an answer. It is useful when one parameter needs to be varied in a calculation, as is the case for most equilibrium calculations. An introduction to Goal Seek is given in Section 6.11 in Chapter 6. Example applications are given on the text website, and we list these after the Table of Contents.

SOLVER

Excel Solver is an even more versatile tool. Goal Seek can only solve one parameter in a single equation, and does not allow for incorporating constraints in the parameter we want to solve. Solver, on the other hand, can solve for more than one parameter (or more than one equation) at a time. Example applications are given on the text website, with descriptions in the text. See the list after the Table of Contents. An introduction to its use is given in Example 7.21.

REGRESSION FUNCTION IN EXCEL DATA ANALYSIS

Possibly the most powerful tool to calculate all regression related parameters for a calibration plot is the "Regression" function in Data Analysis. It not only provides the results for r, r^2, intercept, and slope (which it lists as X variable 1), it also provides their standard errors and upper and lower limits at the 95% confidence level. It also provides an option for fitting the straight line through the origin (when you know for certain that the response at zero concentration is zero by checking a box "constant is zero"). A video illustrating its use is in the website of the book, Chapter 3, titled Data Analysis Regression. A description of how to use it is given in Chapter 16 at the end of Section 16.7, and example applications are given in Chapter 20, Section 20.5, and Chapter 23 for Examples 23.1 and Example 23.2.

READY TO USE PROGRAMS

As listed above, there are numerous supplemental materials on the text website, including Excel spreadsheets for different calculations. Many of these are for specific examples and are tutorial in nature. But several are suited to apply to different applications, simply by inputting data and not having to set up the calculation program. Examples include calculating titration curves and their derivatives, or for solving either quadratic or simultaneous equations. We list here a number that you should find useful. You can find them under the particular chapter on the website.

Chapter 2

- Glassware calibration, Table 2.4

Chapter 6
- Calculate activity coefficients, equations 6.19 and 6.20 (Auxiliary data)
- Quadratic equation solution (Example 6.1) (See also Goal Seek for solving quadratic equations)

Chapter 7
- Stig Johannson pH calculator. For calculating pH of complex mixtures. Easy to use.
- CurtiPotpH calculator (Ivano Gutz) for calculating pH of complex mixtures, as well as constructing pH related curves. Learning curve higher, but very powerful.
- logC-pH Master Spreadsheet. See Section 7.16 on how to use it.

Chapter 8
- Derivative titrations—Easy method (Section 8.11)
- Universal Acid Titrator—Alex Scheeline—Easy method (Section 8.11). For polyprotic acid titration curves.
- Master Spreadsheet for titrations of weak bases—Easy method

Chapter 10
- Solving simultaneous equations (Example 10.5)

Chapter 14
- Derivative titration plots (for near the endpoint)

Chapter 16
- Calculation of unknown from calibration curve plot
- Standard deviation of sample concentration
- Two component Beer's Law solution

Chapter 17
- Standard additions plot and unknown calculation

Chapter 20
- Internal standard calibration plot and unknown calculation (Section 20.5)

EXPERIMENTS

There are 46 experiments, grouped by topic, illustrating most of the measurement techniques presented in the text, and they can be downloaded from the text website. Each contains a description of the principles and chemical reactions involved, so the student gains an overview of what is being determined and how. Solutions and reagents to prepare in advance of the experiment are listed, so experiments can be performed efficiently. All experiments, particularly the volumetric ones, have been designed to minimize waste by preparing the minimum volumes of reagents, like titrants, required to complete the experiment.

Two **team experiments** are included (Experiments 45 and 46) to illustrate the principles presented in Chapter 4 on statistical validation. One is on method validation and quality control, in which different members of teams perform different parts of the validation for a chosen experiment. The other is on proficiency testing in which students calculate the z-values for all the student results of one or more class experiments and each student compares their z-value to see how well they have performed.

New experiments were contributed by users and colleagues. Included are three experiments from Professor Christopher Palmer, University of Montana using a **spectrophotometric microplate reader** (Experiments 3, 24, and 29).

Experiment Video Resource. Professor Christopher Harrison from San Diego State University has a YouTube "Channel" of videos of different types of experiments, some illustrating laboratory and titration techniques: http://www.youtube.com/user/crharrison.

We would recommend that students be encouraged to look at the ones dealing with buret rinsing, pipetting, and aliquoting a sample, before they begin experiments. Also, they will find useful the examples of acid-base titrations illustrating methyl red or phenolphthalein indicator change at end points. There are a few specific experiments that may be related to ones from the textbook, for example, EDTA titration of calcium or Fajan's titration of chloride. The video of glucose analysis gives a good illustration of the starch end point, which is used in iodometric titrations.

SUPPLEMENTARY MATERIALS FOR THE INSTRUCTOR AND THE STUDENT

WEBSITE URLs and QR CODES. There are some 200 website URLs, i.e., website addresses, given throughout the text for access to useful supplemental material. To efficiently access the websites, lists of all the URLs are posted on the text website for each chapter. These lists can be used to access the websites without typing the URLs.

The lists of URLs for each chapter are also added as QR codes at the beginning of each chapter, facilitating access on smartphones. QR codes for selected ones are also given on the text pages where they appear (see below). We list in the QR code here all the chapter URL lists.

QR codes are created for selected website materials in several chapters, as referred to in the chapter text. This will allow access to supplemental material using a smartphone, iPad, etc. So by accessing QR codes in a given chapter, one can browse for the videos and the selected URL links, alongside other valuable materials.

Complete URL list

TEXT COMPANION WEBSITE

John Wiley & Sons, Inc. maintains a companion website for your *Analytical Chemistry* textbook that contains additional valuable supplemental material.

The website may be accessed at: www.wiley.com/college/christian

Materials on the website include supplemental materials for different chapters that expand on abbreviated presentations in the text.

Following is a list of the types of materials on the website:

- Videos
- URLs
- Supplemental Material: WORD, PDFs, Excel, PowerPoint, JPEG

POWERPOINT SLIDES

All figures and tables in the text are posted on the text website as PowerPoint slides for each chapter, with notes on each for the instructor, and can be downloaded for preparation of PowerPoint presentations.

SOLUTIONS MANUAL

A comprehensive saleable solutions manual is available for use by instructors and students in which all problems are completely worked out and all questions are

answered, a total of 824. More information on the solutions manual can be found at www.wiley.com, including where/how to purchase it. Answers for spreadsheet problems, which include the spreadsheets, are given on the text website. Answers to all problems are given in Appendix F.

A WORD OF THANKS

The production of your text involved the assistance and expertise of numerous people. Special thanks go to the users of the text who have contributed comments and suggestions for changes and improvements; these are always welcome. A number of colleagues served as reviewers of the text and manuscript and have aided immeasurably in providing specific suggestions for revision. They, naturally, express opposing views sometimes on a subject or placement of a chapter or section, but collectively have assured a near optimum outcome that we hope you find easy and enjoyable to read and study.

First, Professors Louise Sowers, Stockton College; Gloria McGee, Xavier University; and Craig Taylor, Oakland University; and Lecturer Michelle Brooks, University of Maryland and Senior Lecturer Jill Robinson, Indiana University offered advice for revision and improvements of the 6th edition. Second, Professors Neil Barnett, Deakin University, Australia; Carlos Garcia, The University of Texas at San Antonio; Amanda Grannas, Villanova University; Gary Long, Virginia Tech; Alexander Scheeline, University of Illinois; and Mathew Wise, Condordia University, proofed the draft chapter manuscripts of this edition and offered further suggestions for enhancing the text. Dr. Ronald Majors, a leading chromatography expert from Agilent Technologies, offered advice on the liquid chromatography chapter.

The professionals at John Wiley & Sons have been responsible for producing a high quality book. Petra Recter, Vice President, Publisher, Chemistry and Physics, Global Education, shepherded the whole process from beginning to end. Her Editorial Assistants Lauren Stauber, Ashley Gayle, and Katherine Bull were key in taking care of many details, with efficiency and accuracy. Joyce Poh was the production editor, arranging copyediting to printing, attending to many details, and assuring a quality final product. Laserwords Pvt Ltd was responsible for artwork in your text. We appreciate the efforts of Marketing Manager, Kristy Ruff, in making sure the text is available to all potential users. It has been a real pleasure for all of us working with this team of professionals and others in a long but rewarding process.

We each owe special thanks to our families for their patience during our long hours of attention to this undertaking. Gary's wife, Sue, his companion for over 50 years, has been through seven editions, and remains his strong supporter, even now. Purnendu owes his wife, Kajori, and his students, much for essentially taking off from all but the absolute essentials for the last three years. He also thanks Akinde Kadjo in particular for doing many of the drawings. Kevin's wife, Dani, put up with yet another "interesting project" and lent her support in the form of keeping the kids at bay and making sure her husband was well fed while working on the text.

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September, 2013

"*To teach is to learn twice.*" —**Joseph Joubert**

List of Spreadsheets Used Throughout the Text

The use of spreadsheets for plotting curves and performing calculations is introduced in different chapters. Listed in the Preface are several that are ready to use for different applications. Following is a list of the various other applications of Microsoft Excel, by category, for easy reference for different uses. All spreadsheets are given in the text website. The Problem spreadsheets are only in the website; others are in the text but also in the website. You should always practice preparing assigned spreadsheets before referring to the website. You can save the spreadsheets in your website to your desktop for use.

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LINEST for Additional Statistics (Section 3.23, Figure 3.11)

Ten functions: slope, std. devn., R^2, F, sum sq. regr., intercept, std. devn., std. error of estimate, d.f., sum sq. resid.

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Chapter 7, Problem 73 (H_3PO_4, H_3A)

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Chapter 10, Problem 41

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Chapter 10, Problem 42

Van Deemter Plot: Chapter 19, Problem 13

EXCEL SOLVER FOR PROBLEM SOLVING

This program can be used to solve several parameters or equations at a time. An introduction is given in Example 7.21.

Chapter 3 video Solver (solving quadratic equation, Example 6.1)

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GOAL SEEK FOR PROBLEM SOLVING

The spreadsheets listed below are on the text website for the particular chapter. The page numbers refer to corresponding discussions on setting up the programs. See Section 6.11 for introduction to and application of Goal Seek. It can be used to solve one parameter in an equation, as in most equilibrium problems.

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Example 11.2 Goal Seek (charge balance, solubility of MA in 0.1M HCl)

Example 11.5 Goal Seek (solubility of MX in presence of complexing ligand L)

REGRESSION FUNCTION IN EXCEL DATA ANALYSIS

This Excel tool calculates all regression related parameters for a calibration plot. It provides the results for r, r^2, intercept, and slope, and also provides their standard errors and upper and lower limits at the 95% confidence level.

Chapter 3 video Data Analysis Regression; 87, 120

Chapter 16, end of Section 16.7, Excel Exercise. Describes the use of the Excel Regression function in Data Analysis to readily calculate a calibration curve and its uncertainty, and then apply this to calculate an unknown concentration and its uncertainty from its absorbance; 502

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Chapter 20, Problem 11. GC internal standard determination

Example 23.1, Lineweaver-Burk K_m determination

Example 23.2, Calculating unknown concentration from reaction rate

Problem 23.17, Lineweaver-Burk K_m determination

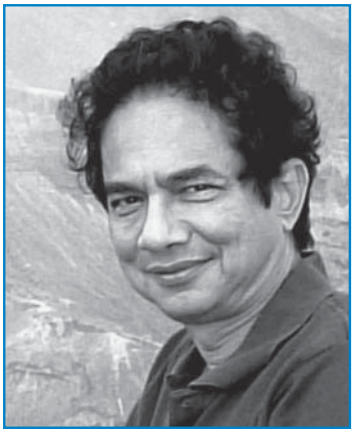
About the Authors

Gary Christian grew up Oregon, and has had a lifelong interest in teaching and research, inspired by great teachers throughout his education. He received his B.S. degree from the University of Oregon and Ph. D. degree from the University of Maryland. He began his career at Walter Reed Army Institute of Research, where he developed an interest in clinical and bioanalytical chemistry. He joined the University of Kentucky in 1967, and in 1972 moved to the University of Washington, where he is Emeritus Professor, and Divisional Dean of Sciences Emeritus.

Gary wrote the first edition of this text in 1971. He is pleased that Professors Dasgupta and Schug have joined him in this new edition. They bring expertise and experience that markedly enhance and update the book in many ways.

Gary is the recipient of numerous national and international awards in recognition of his teaching and research activities, including the American Chemical Society (ACS) Division of Analytical Chemistry Award for Excellence in Teaching and the ACS Fisher Award in Analytical Chemistry, and received an Honorary Doctorate Degree from Chiang Mai University. The University of Maryland inducted him into their distinguished alumni Circle of Discovery.

He has authored five other books, including *Instrumental Analysis*, and over 300 research papers, and has been Editor-in-Chief of the international analytical chemistry journal, *Talanta*, since 1989.



Purnendu K. (Sandy) Dasgupta is a native of India and was educated in a college founded by Irish missionaries and graduated with honors in Chemistry in 1968. After a MSc in Inorganic Chemistry in 1970 from the University of Burdwan and a brief stint as a researcher at the Indian Association for the Cultivation of Science (where Raman made his celebrated discovery), he came as a graduate student to Louisiana State University at Baton Rouge in 1973. Sandy received his PhD in Analytical Chemistry with a minor in Electrical Engineering from LSU in 1977 and managed to get a diploma as a TV mechanic while a graduate student. He joined the California Primate Research Center at the University of California at Davis as an Aerosol research Chemist in 1979 to be part of a research team studying inhalation toxicology of air pollutants. In his mother tongue, Bengali, he was once a well-published poet and a fledgling novelist but seemingly finally found his love of analytical chemistry as salvation. He joined Texas Tech in 1981 and was designated a Horn Professor in 1992, named after the first president of the University, the youngest person to be so honored at the time. He remained at Texas Tech for 25 years, joining the University of Texas at Arlington in 2007 as the Department Chair. He has stepped down as Chair, and currently holds the Jenkins Garrett Professorship.

Sandy has written more than 400 papers/book chapters, and holds 23 US patents, many of which have been commercialized. His work has been recognized by the Dow Chemical Traylor Creativity Award, the Ion Chromatography Symposium

Outstanding Achievement Award (twice), the Benedetti-Pichler Memorial Award in Microchemistry, American Chemical Society Award in Chromatography, Dal Nogare Award in the Separation Sciences, Honor Proclamation of the State of Texas Senate and so on. He is the one of the Editors of *Analytica Chimica Acta*, a major international journal in analytical chemistry. He is best known for his work in atmospheric measurements, ion chromatography, the environmental occurrence of perchlorate and its effect on iodine nutrition, and complete instrumentation systems. He is a big champion of the role of spreadsheet programs in teaching analytical chemistry.

Kevin Schug was born and raised in Blacksburg, Virginia. The son of a physical chemistry Professor at Virginia Tech, he grew up running around the halls of a chemistry building and looking over his father's shoulder at chemistry texts. He pursued and received his B.S. degree in Chemistry from the College of William & Mary in 1998, and his Ph.D. degree in Chemistry under the direction of Professor Harold McNair at Virginia Tech in 2002. Following two years as a post-doctoral fellow with Professor Wolfgang Lindner at the University of Vienna (Austria), he joined the faculty in the Department of Chemistry & Biochemistry at The University of Texas at Arlington in 2005, where he is currently the Shimadzu Distinguished Professor of Analytical Chemistry.

The research in Kevin's group spans fundamental and applied aspects of sample preparation, separation science, and mass spectrometry. He also manages a second group, which focuses their efforts on chemical education research. He has been the recipient of several awards, including the Eli Lilly ACACC Young Investigator in Analytical Chemistry award, the LCGC Emerging Leader in Separation Science award, and the American Chemical Society Division of Analytical Chemistry Award for Young Investigators in Separation Science.

At present, he has authored or coauthored 65 scientific peer-reviewed manuscripts. Kevin is a member of the Editorial Advisory Boards for *Analytica Chimica Acta* and *LCGC* Magazine, and is a regular contributor to *LCGC* on-line articles. He is also Associate Editor of the *Journal of Separation Science*.

Chapter One
ANALYTICAL OBJECTIVES, OR: WHAT ANALYTICAL CHEMISTS DO

"Unless our knowledge is measured and expressed in numbers, it does not amount to much."
—Lord Kelvin

Chapter 1 URLs

Learning Objectives

WHAT ARE SOME OF THE KEY THINGS WE WILL LEARN FROM THIS CHAPTER?

- Analytical science deals with the chemical characterization of matter—what, how much?, p. 2
- The analyst must know what information is really needed, and obtain a representative sample, pp. 6, 9
- Few measurements are specific, so operations are performed to achieve high selectivity, p. 11
- You must select the appropriate method for measurement, p. 12
- Validation is important, p. 15
- There are many useful websites dealing with analytical chemistry, p. 16

Analytical chemistry is concerned with the chemical characterization of matter and the answer to two important questions: what is it (qualitative analysis) and how much is it (quantitative analysis). Chemicals make up everything we use or consume, and knowledge of the chemical composition of many substances is important in our daily lives. Analytical chemistry plays an important role in nearly all aspects of chemistry, for example, agricultural, clinical, environmental, forensic, manufacturing, metallurgical, and pharmaceutical chemistry. The nitrogen content of a fertilizer determines its value. Foods must be analyzed for contaminants (e.g., pesticide residues) and for essential nutrients (e.g., vitamin content). The air we breathe must be analyzed for toxic gases (e.g., carbon monoxide). Blood glucose must be monitored in diabetics (and, in fact, most diseases are diagnosed by chemical analysis). The presence of trace elements from gun powder on a perpetrator's hand will prove a gun was fired by that hand. The quality of manufactured products often depends on proper chemical proportions, and measurement of the constituents is a necessary part of **quality assurance**. The carbon content of steel will influence its quality. The purity of drugs will influence their efficacy.

In this text, we will describe the tools and techniques for performing these different types of analyses. There is much useful supplemental material on the text website, including Excel programs that you can use, and videos to illustrate their use. **You should first read the Preface to learn what is available to you, and then take advantage of some of the tools**.

Lord Kelvin (William Thomson, 1824–1907)

Everything is made of chemicals. Analytical chemists determine what and how much.

1.1 What Is Analytical Science?

The above description of analytical chemistry provides an overview of the discipline of analytical chemistry. There have been various attempts to more specifically define the discipline. The late Charles N. Reilley said: "Analytical chemistry is what analytical chemists do" (Reference 2). The discipline has expanded beyond the bounds of just chemistry, and many have advocated using the name *analytical science* to describe the field. This term is used in a National Science Foundation report from workshops on "Curricular Developments in the Analytical Sciences." Even this term falls short of recognition of the role of instrumentation development and application. One suggestion is that we use the term *analytical science and technology* (Reference 3).

The Federation of European Chemical Societies held a contest in 1992 to define analytical chemistry, and the following suggestion by K. Cammann was selected [*Fresenius' J. Anal. Chem.*, **343** (1992) 812–813].

> **Analytical Chemistry provides the methods and tools needed for insight into our material world . . . for answering four basic questions about a material sample:**
>
> - **What?**
> - **Where?**
> - **How much?**
> - **What arrangement, structure or form?**

These cover qualitative, spatial, quantitative, and speciation aspects of analytical science. The Division of Analytical Chemistry of the American Chemical Society developed a definition of analytical chemistry, reproduced in part here:

> **Analytical Chemistry seeks ever improved means of measuring the chemical composition of natural and artificial materials. The techniques of this science are used to identify the substances which may be present in a material and to determine the exact amounts of the identified substance.**
>
> **Analytical chemists serve the needs of many fields:**
>
> - **In *medicine*, analytical chemistry is the basis for clinical laboratory tests which help physicians diagnose disease and chart progress in recovery.**
> - **In *industry*, analytical chemistry provides the means of testing raw materials and for assuring the quality of finished products whose chemical composition is critical. Many household products, fuels, paints, pharmaceuticals, etc. are analyzed by the procedures developed by analytical chemists before being sold to the consumer.**
> - ***Environmental quality* is often evaluated by testing for suspected contaminants using the techniques of analytical chemistry.**
> - **The nutritional value of *food* is determined by chemical analysis for major components such as protein and carbohydrates and trace components such as vitamins and minerals. Indeed, even the calories in food are often calculated from its chemical analysis.**
>
> **Analytical chemists also make important contributions to fields as diverse as forensics, archaeology, and space science.**

An interesting article published by a leading analytical chemist, G. E. F. Lundell, from the National Bureau of Standards in 1935 entitled "The Analysis of Things As They Are", describes why we do analyses and the analytical process *(Industrial and Engineering Chemistry, Analytical Edition,* **5**(4) (1933) 221–225). The article is posted on the text **website**.

A brief overview of the importance of analytical chemistry in society, with examples that affect our lives, and the tools and capabilities, is given in the article, "What Analytical Chemists Do: A Personal Perspective," by Gary Christian, *Chiang Mai Journal of Science,* **32**(2) (2005) 81–92: http://it.science.cmu.ac.th/ejournal/journalDetail.php?journal_id=202

Reading this before beginning this course will help place in context what you are learning. A reprint of the article is posted on the text website.

What Analytical Chemists Do

1.2 Qualitative and Quantitative Analysis: What Does Each Tell Us?

The discipline of analytical chemistry consists of **qualitative analysis** and **quantitative analysis**. The former deals with the identification of elements, ions, or compounds present in a sample (we may be interested in whether only a given substance is present), while the latter deals with the determination of how much of one or more constituents is present. The sample may be solid, liquid, gas, or a mixture. The presence of gunpowder residue on a hand generally requires only qualitative knowledge, not of how much is there, but the price of coal will be determined by the percent of undesired sulfur impurity present.

Qualitative analysis tells us what chemicals are present.
Quantitative analysis tells us how much.

How Did Analytical Chemistry Originate?

That is a very good question. Actually, some tools and basic chemical measurements date back to the earliest recorded history. Fire assays for gold are referred to in Zechariah 13:9, and the King of Babylon complained to the Egyptian Pharoah, Ammenophis the Fourth (1375–1350 BC), that gold he had received from the pharaoh was "less than its weight" after putting it in a furnace. The perceived value of gold, in fact, was probably a major incentive for acquiring analytical knowledge. Archimedes (287–212 BC) did nondestructive testing of the golden wreath of King Hieron II. He placed lumps of gold and silver equal in weight to the wreath in a jar full of water and measured the amount of water displaced by all three. The wreath displaced an amount between the gold and silver, proving it was not pure gold!

The balance is of such early origin that it was ascribed to the gods in the earliest documents found. The Babylonians created standard weights in 2600 BC and considered them so important that their use was supervised by the priests.

The alchemists accumulated the chemical knowledge that formed the basis for quantitative analysis as we know it today. Robert Boyle coined the term *analyst* in his 1661 book, *The Sceptical Chymist*. Antoine Lavoisier has been considered the "father of analytical chemistry" because of the careful quantitative experiments he performed on conservation of mass (using the analytical balance). (Lavoisier was actually a tax collector and dabbled in science on the side. He was guillotined on May 8, 1793, during the French Revolution because of his activities as a tax collector.)

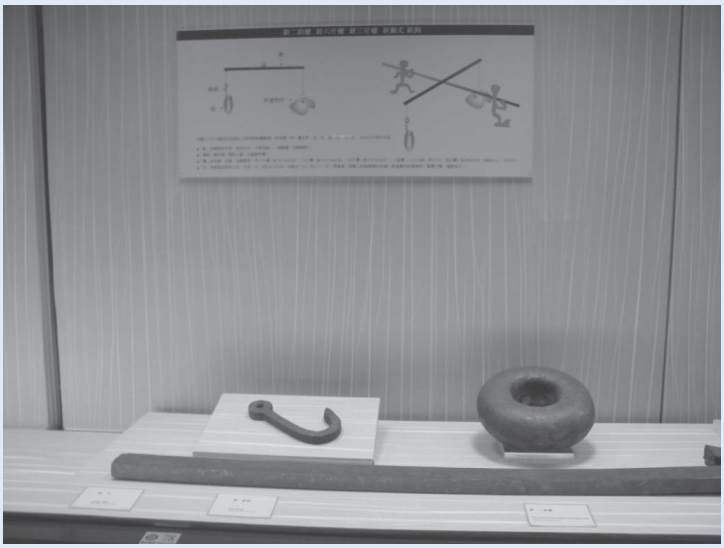
Gravimetry was developed in the seventeenth century, and titrimetry in the eighteenth and nineteenth centuries. The origin of titrimetry goes back to Geoffroy in 1729; he evaluated the quality of vinegar by noting the quantity of solid K_2CO_3 that could be added before effervescence ceased (Reference 4). Gay-Lussac, in 1829, assayed silver by titration with 0.05% relative accuracy and precision!

Robert Boyle coined the term "analyst" in his book *The Sceptical Chymist* in 1661

Antoine Lavoisier used a precision balance for quantitative experiments on the conservation of mass. He is considered the "father of quantitative analysis."

Karl Remigius Fresenius (1818–1897) published a textbook on quantitative analysis in 1846, which went through six editions and became a standard in the field. He also founded the first journal in analytical chemistry, *Zeitschrift Fur Analytische Chemie* in 1862.

Wilhelm Ostwald (1853–1932) published the influential text, *Die Wissenschaflichen Grundlagen Der Analytischem Chemie* (*The scientific fundamentals of analytical chemistry*) in 1894. He introduced theoretical explanations of analytical phenomena and equilibrium constants.



A 2000-year-old balance. Han Dynasty 10 AD. Taiwan National Museum, Taipei. From collection of G. D. Christian.

Textbooks of analytical chemistry began appearing in the 1800s. Karl Fresenius published *Anleitung zur Quantitaven Chemischen Analyse* in Germany in 1845. Wilhelm Ostwald published an influential text on the scientific fundamentals of analytical chemistry in 1894 entitled *Die wissenschaflichen Grundagen der analytischen Chemie*, and this book introduced theoretical explanations of analytical phenomena using equilibrium constants (thank him for Chapter 6 and applications in other chapters).

The twentieth century saw the evolution of instrumental techniques. Steven Popoff's second edition of *Quantitative Analysis* in 1927 included electroanalysis, conductimetric titrations, and colorimetric methods. Today, of course, analytical technology has progressed to include sophisticated and powerful computer-controlled instrumentation and the ability to perform highly complex analyses and measurements at extremely low concentrations.

This text will teach you the fundamentals and give you the tools to tackle most analytical problems. Happy journey. For more on the evolution of the field, see Reference 8.

Qualitative tests may be performed by selective chemical reactions or with the use of instrumentation. The formation of a white precipitate when adding a solution of silver nitrate in dilute nitric acid to a dissolved sample indicates the presence of a halide. Certain chemical reactions will produce colors to indicate the presence of classes of organic compounds, for example, ketones. Infrared spectra will give "fingerprints" of organic compounds or their functional groups.

A clear distinction should be made between the terms **selective** and **specific**:

Few analyses are specific. Selectivity may be achieved through proper preparation and measurement.

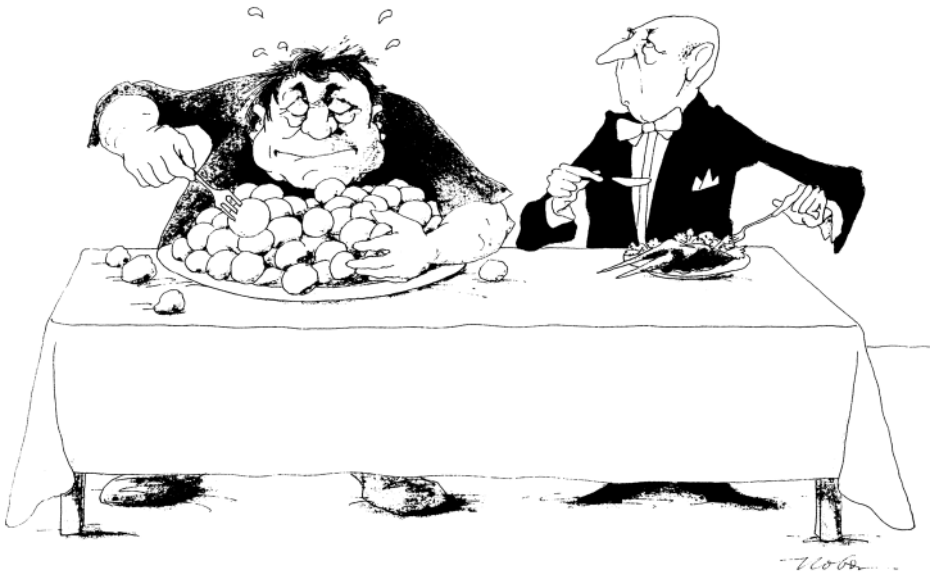
- A *selective* reaction or test is one that can occur with other substances but exhibits a degree of preference for the substance of interest.
- A *specific* reaction or test is one that occurs *only* with the substance of interest.

Unfortunately, very few reactions are truly specific but many exhibit selectivity. Selectivity may be also achieved by a number of strategies. Some examples are:

- Sample preparation (e.g., extractions, precipitation)
- Instrumentation (selective detectors)
- Target analyte derivatization (e.g., derivatize specific functional groups)
- Chromatography, which separates the sample constituents

For quantitative analysis, the typical sample composition will often be known (we know that blood contains glucose), or else the analyst will need to perform a qualitative test prior to performing the more difficult quantitative analysis. Modern chemical measurement systems often exhibit sufficient selectivity that a quantitative measurement can also serve as a qualitative measurement. However, simple qualitative tests are usually more rapid and less expensive than quantitative procedures. Qualitative analysis has historically been composed of two fields: inorganic and organic. The former is usually covered in introductory chemistry courses, whereas the latter is best left until after the student has had a course in organic chemistry.

In comparing qualitative versus quantitative analysis, consider, for example, the sequence of analytical procedures followed in testing for banned substances at the Olympic Games. The list of prohibited substances includes about 500 different active constituents: stimulants, steroids, beta-blockers, diuretics, narcotics, analgesics, local anesthetics, and sedatives. Some are detectable only as their metabolites. Many athletes must be tested rapidly, and it is not practical to perform a detailed quantitative analysis on each. There are three phases in the analysis: the fast-screening phase, the identification phase, and possible quantification. In the fast-screening phase, urine samples are rapidly tested for the presence of classes of compounds that will differentiate them from "normal" samples. Techniques used include immunoassays, gas chromatography–mass spectrometry, and liquid chromatography–mass spectrometry. About 5% of the samples may indicate the presence of unknown compounds that may or may not be prohibited but need to be identified. Samples showing a suspicious profile during the screening undergo a new preparation cycle (possible hydrolysis, extraction, derivatization), depending on the nature of the compounds that have been detected. The compounds are then identified using the highly selective combination of



(Courtesy of Merck KGaA. Reproduced by permission.)

gas chromatography/mass spectrometry (GC/MS). In this technique, complex mixtures are separated by gas chromatography, and they are then detected by mass spectrometry, which provides molecular structural data on the compounds. The MS data, combined with the time of elution from the gas chromatograph, provide a high probability of the presence of a given detected compound. GC/MS is expensive and time consuming, and so it is used only when necessary. Following the identification phase, some compounds must be precisely quantified since they may normally be present at low levels, for example, from food, pharmaceutical preparations, or endogenous steroids, and elevated levels must be confirmed. This is done using quantitative techniques such as spectrophotometry or gas chromatography.

This text deals principally with quantitative analysis. In the consideration of applications of different techniques, examples are drawn from the life sciences, clinical chemistry, environmental chemistry, occupational health and safety applications, and industrial analysis.

We describe briefly in this chapter the analytical process. More details are provided in subsequent chapters.

See the text **website** for useful chapters from *The Encyclopedia of Analytical Chemistry* (Reference 9 at the end of the chapter) on literature searching and selection of analytical methods.

1.3 Getting Started: The Analytical Process

The general analytical process is shown in Figure 1.1. The analytical chemist should be involved in every step. The analyst is really a problem solver, a critical part of the team deciding what, why, and how. The unit operations of analytical chemistry that are common to most types of analyses are considered in more detail below.

DEFINING THE PROBLEM—WHAT DO WE REALLY NEED TO KNOW? (NOT NECESSARILY EVERYTHING)

"To many . . . , the object of chemical analysis is to obtain the composition of a sample . . . . It may seem a small point . . . that the analysis of the sample is *not* the true aim of analytical chemistry . . . . the real purpose of the analysis is to solve a problem . . . " H. A. Laitinen, Editorial: The Aim of Analysis, *Anal. Chem.*, **38** (1966) 1441.

Before the analyst can design an analysis procedure, he or she must know what information is needed, by whom, for what purpose, and what type of sample is to be analyzed. As the analyst, you must have good communication with the client. This stage of an analysis is perhaps the most critical. The client may be the Environmental Protection Agency (EPA), an industrial chemist, an engineer, or your grandmother—each of which will have different criteria or needs, and each having their own understanding of what a chemical analysis involves or means. It is important to communicate in language that is understandable by both sides. If someone puts a bottle on your desk and asks, "What is in here?" or "Is this safe?", you may have to explain that there are 10 million known compounds and substances. A client who says, "I want to know what elements are in here" needs to understand that at perhaps $20 per analysis for 85 elements it will cost $1700 to test for them all, when perhaps only a few elements are of interest.

The way an analysis is performed depends on the information needed.

Laypersons might come to analytical chemists with cosmetics they wish to "reverse engineer" so they can market them and make a fortune. When they realize it may cost a small fortune to determine the ingredients, requiring a number of sophisticated analyses, they always rethink their goals. On the other hand, a mother may come to you with a white pill that her teenage son insists is vitamin C and she fears is an illicit drug. While it is not trivial to determine what it is, it is rather straightforward to determine if it undergoes the same reactions that ascorbic acid (vitamin C) does. You may be able to greatly alleviate the concerns of an anxious mother.

The concept of "safe" or "zero/nothing" is one that many find hard to define or understand. Telling someone their water is safe is not for the analyst to say. All you

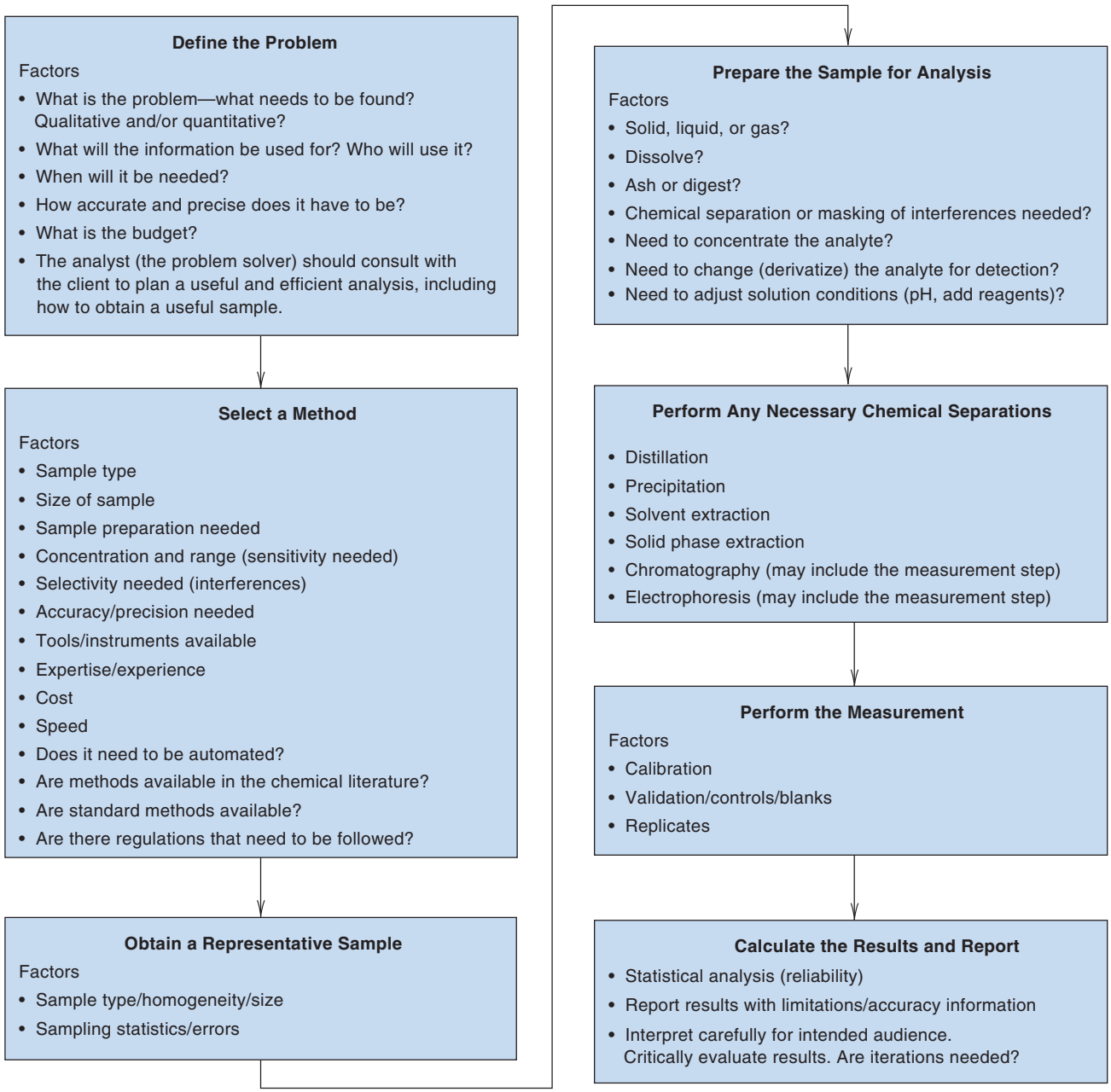


Fig. 1.1. Steps in an analysis.

can do is present the analytical data (and give an indication of its range of accuracy). The client must decide whether it is safe to drink, perhaps relying on other experts. Also, never report an answer as "zero," but as less than the detection limit, which is based on the measurement device/instrument. We are limited by our methodology and equipment, and that is all that can be reported. Some modern instruments, though, can measure extremely small amounts or concentrations, for example, parts per trillion. This presents a dilemma for policy makers (often political in nature). A law may be passed that there should be zero concentration of a chemical effluent in water. In practice, the acceptable level is defined by how low a concentration can be detected; and the very low detectability may be far below the natural occurrence of the chemical

or below the levels to which it can be reasonably reduced. We analysts and chemists need to be effective communicators of what our measurements represent.

Once the problem is defined this will dictate how the sample is to be obtained, how much is needed, how sensitive the method must be, how accurate and precise[1] it must be, and what separations may be required to eliminate interferences. The determination of trace constituents will generally not have to be as precise as for major constituents, but greater care will be required to eliminate trace contamination during the analysis.

The way you perform an analysis will depend on your experience, the equipment available, the cost, and the time involved.

Once the required measurement is known, the analytical method to be used will depend on a number of factors, including the analyst's skills and training in different techniques and instruments; the facilities, equipment, and instrumentation available; the sensitivity and precision required; the cost and the budget available; and the time for analysis and how soon results are needed. There are often one or more standard procedures available in reference books for the determination of an **analyte** (constituent to be determined) in a given **sample type**. This does not mean that the method will necessarily be applicable to other sample types. For example, a standard EPA method for groundwater samples may yield erroneous results when applied to the analysis of sewage water. The chemical literature (journals) contains many specific descriptions of analyses. *Chemical Abstracts* (http://info.cas.org), published by the American Chemical Society, is a good place to begin a literature search. It contains abstracts of all articles appearing in the major chemical journals of the world. Yearly and cumulative indices are available, and many libraries have computer search facilities. If your library subscribes to Scifinder from Chemical Abstracts Service, this is the best place to start your search (www.cas.org/products/scifindr/index.html). The Web of Science, a part of the Web of Knowledge (www.isiwebofknowledge.com) is an excellent place to search the literature and provides also the information as to where a particular article has been cited and by whom. Another excellent source, available to anyone, is Google Scholar, which allows you to search articles, authors, etc. (http://scholar.google.com). The major analytical chemistry journals may be consulted separately. Some of these are: *Analytica Chimica Acta, Analytical Chemistry, Analytical and Bioanalytical Chemistry, Analytical Letters, Analyst, Applied Spectroscopy, Clinica Chimica Acta, Clinical Chemistry, Journal of the Association of Official Analytical Chemists, Journal of Chromatography, Journal of Separation Science, Spectrochimica Acta*, and *Talanta*. While the specific analysis of interest may not be described, the analyst can often use literature information on a given analyte to devise an appropriate analytical scheme. Finally, the analyst may have to rely upon experience and knowledge to develop an analytical method for a given sample. The literature references in Appendix A describe various procedures for the analysis of different substances.

The *analyte* is the substance *analyzed* for. Its concentration is *determined*.

Chemical Abstracts is a good source of literature.

Examples of the manner in which the analysis of particular types of samples are made are given in application Chapters 25 and 26 on the text's website. These chapters describe commonly performed clinical, biochemical, and environmental analyses. The various techniques described in this text are utilized for the specific analyses. Hence, it will be useful for you to read through these applications chapters both now and after completing the majority of this course to gain an appreciation of what goes into analyzing real samples and why the analyses are made.

Once the problem has been defined, the following steps can be started.

---

[1] Accuracy is the degree of agreement between a measured value and a true value. Precision is the degree of agreement between replicate measurements of the same quantity and does not necessarily imply accuracy. These terms are discussed in more detail in Chapter 3.

OBTAINING A REPRESENTATIVE SAMPLE—WE CAN'T ANALYZE THE WHOLE THING

A chemical analysis is usually performed on only a small portion of the material to be characterized. If the amount of material is very small and it is not needed for future use, then the entire sample may be used for analysis. The gunshot residue on a hand may be an example. More often, though, the characterized material is of value and must be altered as little as possible in sample collection. For example, sampling of a Rembrandt painting for authenticity would need to be done with utmost care for sample quantity, so as not to deface the artwork.

The material to be sampled may be solid, liquid, or gas. It may be homogeneous or heterogeneous in composition. In the former case, a simple "grab sample" taken at random will suffice for the analysis. In the latter, we may be interested in the variation throughout the sample, in which case several individual samples will be required. If the gross composition is needed, then special sampling techniques will be required to obtain a representative sample. For example, in analyzing for the average protein content of a shipment of grain, a small sample may be taken from each bag, or tenth bag for a large shipment, and combined to obtain a **gross sample**. Sampling is best done when the material is being moved, if it is large, in order to gain access. The larger the particle size, the larger should be the gross sample. The gross sample must be reduced in size to obtain a **laboratory sample** of several grams, from which a few grams to milligrams will be taken to be analyzed (**analysis sample**). The size reduction may require taking portions (e.g., two quarters) and mixing, in several steps, as well as crushing and sieving to obtain a uniform powder for analysis. Methods of sampling solids, liquids, and gases are discussed in Chapter 2. If one is interested in spatial structure, then homogenization must not be carried out, but spatially resolved sampling must be done.

The *gross sample* consists of several portions of the material to be tested. The *laboratory sample* is a small portion of this, taken after homogenization. The *analysis sample* is that actually analyzed. See Chapter 2 for methods of sampling.

In the case of biological fluids, the conditions under which the sample is collected can be important, for example, whether a patient has just eaten. The composition of blood varies considerably before and after meals, and for many analyses a sample is collected after the patient has fasted for a number of hours. Persons who have their blood checked for cholesterol levels are asked to fast for up to twelve hours prior to sampling. Preservatives such as sodium fluoride for glucose preservation and anticoagulants for blood samples may be added when samples are collected; these may affect a particular analysis.

Blood samples may be analyzed as whole blood, or they may be separated to yield plasma or serum according to the requirements of the particular analysis. Most commonly, the concentration of the substance external to the red cells (the extracellular concentration) will be a significant indication of physiological condition, and so serum or plasma is taken for analysis.

If whole blood is collected and allowed to stand for several minutes, the soluble protein **fibrinogen** will be converted by a complex series of chemical reactions (involving calcium ion) into the insoluble protein **fibrin**, which forms the basis of a gel, or **clot**. The red and white cells of the blood become caught in the meshes of the fibrin network and contribute to the clot, although they are not necessary for the clotting process. After the clot forms, it shrinks and squeezes out a straw-colored fluid, **serum**, which does not clot but remains fluid indefinitely. The clotting process can be prevented by adding a small amount of an **anticoagulant**, such as heparin or a citrate salt (i.e., a calcium complexor). Blood collection vials are often color-coded to provide a clear indication of the additives they contain. An aliquot of the unclotted whole blood can be taken for analysis, or the red cells can be centrifuged to the bottom, and the light pinkish-colored

Serum is the fluid separated from clotted blood. *Plasma* is the fluid separated from unclotted blood. It is the same as serum, but contains fibrinogen, the clotting protein.