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Analytical Chemistry

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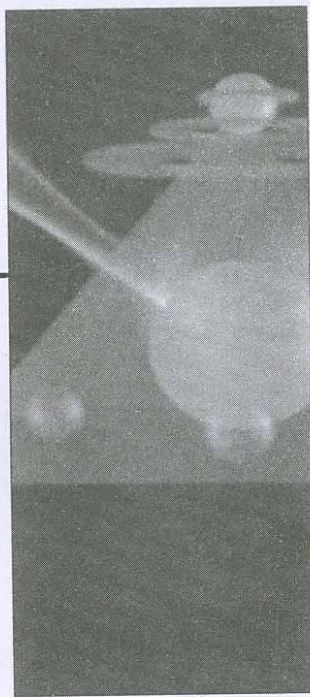
Gary D. Christian

ANALYTICAL CHEMISTRY

Sixth Edition

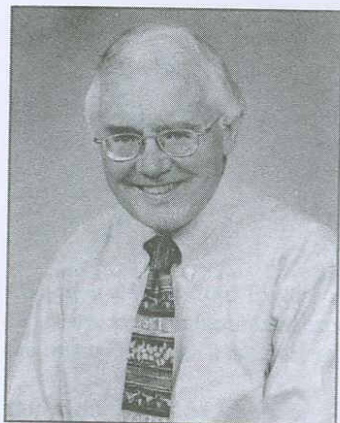
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About the Author



Gary Christian grew up in Oregon and has had a lifelong interest in teaching, inspired by a great high school science teacher in a rural school, Harald Platou. He received his B.S. degree from the University of Oregon and Ph.D. degree from the University of Maryland, where he gained an appreciation of the excitement of research from his mentor, Bill Purdy. He began his career as a research analytical chemist 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. He was Divisional Dean of Sciences during 1993–2001.

Gary wrote the first edition of this book in 1971. He is the author of over 300 research papers and has authored five other books, including *Instrumental Analysis*. His research interests include electroanalytical chemistry, atomic spectroscopy, process analysis, and flow injection analysis.

He was recipient of the American Chemical Society (ACS) Division of Analytical Chemistry Award for Excellence in Teaching and the ACS Fisher Award in Analytical Chemistry, a top recognition for contributions in analytical chemistry. He was a Fulbright Scholar and received the Talanta Gold Medal, Université Libre de Bruxelles Medal of Honor, Charles University Commemorative Medal, and University of Ghent Honorary Certificate of Research. He is joint editor-in-chief of *Talanta*, an international journal of analytical chemistry, and serves on the editorial boards of numerous other journals. He served as Chairman of the ACS Division of Analytical Chemistry.

Gary chaired preparation of the ACS Examination on Analytical Chemistry and was a preparer for the Chemistry Test for the GRE. He was a member of the team that prepared the exam for the International Chemistry Olympiad when it was held in the United States. He is a member of the American Chemical Society, Society for Applied Spectroscopy, Spectroscopy Society of Canada, and Society for Electroanalytical Chemistry.

Gary lives in Medina, Washington, with his wife of 41 years, Sue, and their wonderful granddaughters, Tanya and Taffy.

Preface

“Teachers open the door, but it is up to you to enter”—Anonymous

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. The late Charles N. Reilley said “analytical chemistry is what analytical chemists do.” You will learn in this text what they do.

This text is designed for college students majoring in chemistry and fields related to chemistry. It 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, 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. Chapters 24–26 illustrate applications of techniques you have learned to the fields of clinical chemistry, genomics and proteomics, and environmental sampling and analysis.

Examples of the use of analytical chemistry techniques are drawn from such areas as life sciences, clinical chemistry, air and water pollution, and industrial analyses. Analytical chemistry becomes meaningful when you realize that an incorrect blood analysis may endanger a patient’s life, or that an error in quality control analysis may result in serious financial loss for a manufacturer. Millions of dollars are saved in the chemical industry by performing on-line automated analyses of chemical processes, to assure maximum efficiency in chemical production.

WHO SHOULD USE THIS TEXT?

The text 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 could serve for both courses. In any event, I 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 in the future.

WHAT IS THE SAME?

This sixth edition of *Analytical Chemistry* is extensively revised and updated (more on that below), but many features from previous editions remain. Each chapter is

introduced with a summary paragraph that lists the topics to be covered, giving you a broad overview of each subject. **Boldface type** is used for key terms, and important equations are boxed to aid in review. *Margin notes* are generously used to further emphasize important concepts and aid in review.

Dimensional analysis is emphasized throughout to give you a better feel for the proper setting up of problems. SI units or symbols (e.g., L, mL, mol, and s) are used throughout. The concept of normality and equivalents is introduced, but emphasis remains on the use of molarity and moles. The presentation of normality is done in a way that allows it to be ignored if your instructor chooses not to assign it.

Problems and Recommended References are grouped by topic, for ease in assignment. References have been extensively updated, and numerous new problems added. There are 673 questions and problems for you to practice answering (there is Solutions Manual for these—see below).

A number of new topics were introduced in the prior edition, and most remain as important features of the text. Some are:

- Statistics of small sets of data
- Statistics of sampling
- Systematic approach to equilibrium calculations (mass and charge balance)
- Heterogeneous equilibria
- Logarithmic diagrams for describing multiple equilibria species (the preparation of these using spreadsheets is now introduced)
- Diode array spectrometers
- Fourier transform infrared spectroscopy
- Near-IR spectroscopy
- Fiber-optic sensors
- Gas chromatography–mass spectrometry

WHAT IS CHANGED?

Some chapters have been reordered to better tie together related topics. The chapter on basic tools and operations in analytical chemistry has been moved to the front of the text (Chapter 2), at the suggestion of a number of users. Different sections of it can be assigned by your instructor as needed for the laboratory. The chapter on gravimetric analysis and precipitation equilibria (Chapter 10) has been moved to just before the one on precipitation reactions and titrations, which better aligns these related topics.

Chromatography, a major analytical tool for analyzing mixtures of analytes, has undergone significant growth in recent years, with improved capabilities, and so the coverage of chromatographic techniques has been expanded and updated, comprising three chapters on principles of chromatography, gas chromatography, and liquid chromatography (Chapters 19–21). Older techniques such as paper chromatography have been deleted.

WHAT IS NEW?

This revision follows publication of the fifth edition of *Analytical Chemistry* by nearly a decade, a result of being a dean too long! Much has changed in that time. This sixth edition presents a number of new topics, new chapters, and changes in presentation. Major additions include:

- **Color** added to the text, for a more pleasing layout
- Spreadsheets (using Excel) 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. The way in which spreadsheet calculations are performed is by entering formulas in specific cells, e.g., cell B11 may contain a formula to calculate the ratio of numbers entered in cells A2 and A3, and the formula is (=A2/A3). The answer appears in cell B11 where the formula is entered. Cells that have formulas entered in them are **boldfaced**. Usually, you have to “reverse engineer” the cell entries to determine the equations from which they were derived, for example, the equation dividing one number by another to obtain the fraction. This is very awkward for complicated equations. To avoid this, the actual equations used for deriving the cell formulas are given in the documentation section below the spreadsheet setups; the formula to be entered in the identified cell number is given just below the equation. You will better understand and appreciate this when you begin studying the use of spreadsheets.

- New chapter on Good Laboratory Practice: Quality Assurance of Analytical Measurements

This aspect of the practice of analytical chemistry has become increasingly important as government agencies have established rather complex and stringent guidelines to assure that analytical measurements are accurate, for establishing or enforcing policy. Any budding analytical chemist will find that knowledge of these guidelines will be viewed favorably by an employer. This chapter serves as an introduction and reference to current practices, and includes:

- Validation of analytical methods
- Quality assurance
- Laboratory accreditation
- Electronic records and electronic signatures (the new 21 CFR, Part 11 regulations)
- New chapter on Genomics and Proteomics

Analytical chemistry played a key role in the completion of the historic Human Genome Project. You should know what that is. The technologies have become routine for DNA sequencing of complex organisms, for forensic science, and so forth. We now move into the realm of protein profiling (proteomics), an even more challenging analytical endeavor, and an introduction to this emerging field is given. This chapter discusses:

- The Human Genome Project
- How genes are sequenced
- The polymerase chain reaction (PCR)
- DNA chips
- 2-D PAGE and MALDI-TOF for protein profiling

A number of new topics throughout the text include:

- Calibration of glassware
- Accelerated and microwave extraction and digestion
- Solid-state ISFET electrodes
- Spectral databases—web-based: commercial and free
- Solid-phase extraction (SPE) expanded; solid-phase microextraction (SPME)
- Chromatography nomenclature: IUPAC-recommended terms and symbols used
- Theory of chromatography column efficiency expanded
- Chromatography simulation software for method development
- Capillary gas chromatography (GC) columns: updated and expanded
- Headspace, thermal desorption, and purge and trap GC analysis
- Fast gas and liquid chromatography
- High performance liquid chromatography-mass spectrometry (HPLC-MS)
- Mass analyzers for GC-MS and LC-MS
- HPLC stationary phases updated; narrowbore columns for high sensitivity
- Capillary electrophoresis expanded; capillary electrochromatography

EXPERIMENTS

There are 40 experiments illustrating most of the measurement techniques presented in your text. Experiments are grouped by topic. Each contains a description of the principles and chemical reactions involved, so you gain an overview of what is being analyzed and how. Solutions and reagents to prepare in advance of the experiment are listed, so experiments can be performed efficiently; your instructor will have prepared many of these. Experiments are designed where possible to avoid the use of asbestos, chloroform, carbon tetrachloride, or benzene, consistent with occupational health and safety. All experiments, particularly the volumetric ones, have been designed to minimize chemical waste by preparing the minimum volumes of reagents, like titrants, required to complete the experiment.

Deleted. Three experiments that use mercury have been deleted. The paper chromatography experiment is deleted because thin-layer chromatography is predominantly used in its place today. For space reasons, the presentation of catalytic methods and the corresponding experiment are deleted from the text in favor of enzymatic kinetic methods. Also, the anion chromatography separation of cobalt and nickel is omitted.

New. A new microscale titration experiment is included, provided by Professor John Richardson from Shippensburg State University, for the analysis of hard-water samples (Experiment 18). The tools and techniques used for that experiment could be used to design similar experiments for other titrations if desired. (If your instructor tries this with you, I may include your experiment in the next edition!) Two **team experiments** are added (Experiments 39 and 40) 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 you calculate the z -values for all the student results of one or more class experiments and you compare your z -value to see how well you have performed.

Spreadsheets. You are encouraged (actually instructed) to use spreadsheets in your experiments to prepare calibration curves and to perform statistical analysis on your experimental results.

CD-ROM

Your textbook includes a CD-ROM that contains useful supplemental material to complement the text. When opening the CD-ROM, click first on “Read me” for details of the contents. There are files on chapter auxiliary data, chapter spreadsheet figures, chapter text spreadsheets, laboratory apparatus, spreadsheet problem solutions, and website URLs. There are useful hints for using the spreadsheets.

A WORD ABOUT WEBSITES

There are over 100 websites given throughout the text for access to useful supplemental material. I have heavy fingers when typing URLs, and the Web is unforgiving of typos. To efficiently access the websites, a list of all the URLs is provided on your CD, by chapter in order of appearance, including margin notes. It is also posted on the Wiley website for your text. You can use this list to access the websites without typing the URLs.

Click on the URL to open the site. If this does not work, copy it to your clipboard and then paste into your browser **Address** and then click on **Go** (or **Enter** on your keyboard). Sometimes a linked site won't open, but if you input just the homepage portion of the URL, you can open this and then link to the final URL. For company homepages, you may need to go the the Product link. Or try the site's search engine. Some URLs will change or be deleted with time. If you have trouble getting a website to open, or if it is changed, try going to a search engine, such as Google, and search for the company or topic.

TEXT WEBSITE

John Wiley & Sons, Inc. maintains a website for *Analytical Chemistry* that contains additional supplemental material, which may be updated or added to from time to time. Any text errors that are noted will be posted on this site. Materials on the website include supplemental materials for different chapters that expand on abbreviated presentations in the text. Chapters from *The Encyclopedia of Analytical Chemistry* on “Literature Searching Methodology” and “Analytical Problem Solving: Selection of Analytical Methods” are included. The website URLs in the text are also listed on this site and may be updated. **All figures and tables in the text are posted on the website and can be downloaded for preparation of transparencies.** You may access the website at: www.wiley.com/college/christian.

THANKS

The production of your text involved the assistance and expertise of numerous people. Special thanks go first 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 I hope you find easy and enjoyable to read and study. Special mention goes to Professors Dennis Anjo (California State University at Long Beach), Kevin Chambliss (Baylor University),

Michael DeGrandpre (University of Montana), Jinmo Huang (The College of New Jersey), Ira Krull (Northeastern University), Gary Long and Harold McNair (Virginia Tech), Jody Redpenning (University of Nebraska), John Richardson and Thomas Schroeder (Shippensburg State University), Benjamin Rusiloski (Delaware State University), James Rybarczyk (Ball State University), Cheryl Klein Stevens (Xavier University of Louisiana), and Phillip Voegel (Midwestern State University). Professor Norman Dorichi (University of Washington) provided valuable input on Chapter 25 on genomes and proteomics. And thanks to Mack Carter for his computer wizardry, and Sheila Parker for helping keep my head above water.

The professionals at John Wiley & Sons have been responsible for producing a high-quality book. David Harris and Deborah Brennan, Acquisitions Editors, shepherded the process from beginning to end. Their assistant, Cathy Donovan, handled the whole review process and attended to many details. Elizabeth Swain was the production editor, arranging copyediting to printing. Sandra Rigby was the illustration editor responsible for the artwork in your text. Ernestine Franco at Pern Editorial Services was a real professional in copyediting the manuscript for a smooth printing. It has been a real pleasure working with this team and others in a long but rewarding process.

My wife and best friend, Sue, has been my strongest supporter during this two-year exercise. She kept the process on schedule by her efficient translation and typing of my scribbled handwritten pages. Thanks, thanks, thanks!

SOLUTIONS MANUAL

A comprehensive solutions manual is available for use by instructors and students in which all problems are completely worked out and all questions are answered. Answers for spreadsheet problems, which include the spreadsheets, are given in your CD-ROM. Answers to even-numbered problems are given in Appendix F.

GARY D. CHRISTIAN

January, 2003

Seattle

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

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List of Spreadsheets Used throughout the Text

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

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Analytical chemistry is concerned with the chemical characterization of matter and the answer to two important questions: what is it (qualitative) and how much is it (quantitative). 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, medical, environmental, forensic, manufacturing, metallurgical, and pharmaceutical chemistry. The nitrogen content of a fertilizer determines its value. Foods must be analyzed for contaminants (e.g., pesticides, residues) and for essential nutrients (e.g., vitamin content). The acid in urine must be analyzed for certain drug side. Blood glucose must be measured in diabetics (and, in fact, most diabetics are diagnosed by chemical analysis). The presence of trace elements from gun powder on a murder suspect's hand will have a gun was fired. The quality of manufactured products often depends on proper chemical proportions, and measurement of the composition is a necessary part of quality control. The carbon content of steel will determine its quality. The purity of drugs will determine their efficacy.

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. Reilly said: "Analytical chemistry is what analytical chemists do" (Ref. 2). The discipline has expanded beyond the bounds of just chemistry, but many have advocated using the name analytical science to describe the field. This term is used in a National Science Foundation

Chapter One

ANALYTICAL OBJECTIVES, OR: WHAT ANALYTICAL CHEMISTS DO

*“Unless our knowledge is measured and expressed in numbers,
it does not amount to much.”*

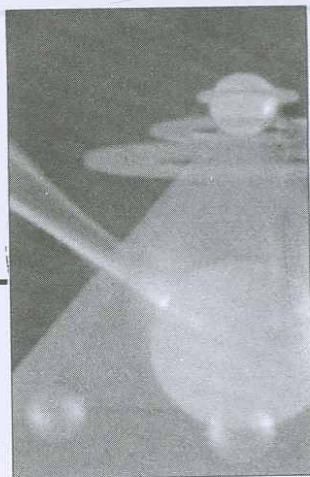
—Lord Kelvin

Analytical chemistry is concerned with the chemical characterization of matter and the answer to two important questions: what is it (qualitative) and how much is it (quantitative). 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 in cities must be analyzed for 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 murder defendant's hand will prove a gun was fired. The quality of manufactured products often depends on proper chemical proportions, and measurement of the constituents is a necessary part of **quality control**. The carbon content of steel will determine its quality. The purity of drugs will determine their efficacy.

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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* (Ref. 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?

The Division of Analytical Chemistry of the American Chemical Society provides a comprehensive definition of analytical chemistry, which may be found on their website (www.acs-analytical.duq.edu/whatisanalyticalchem.html). It is reproduced, in most 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 work to improve the reliability of existing techniques to meet the demands for better chemical measurements which arise constantly in our society. They adapt proven methodologies to new kinds of materials or to answer new questions about their composition and their reactivity mechanisms. They carry out research to discover completely new principles of measurement and are at the forefront of the utilization of major discoveries, such as lasers and microchip devices for practical purposes. Their efforts 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 a food are often calculated from its chemical analysis.

Analytical chemists also make important contributions to fields as diverse as forensics, archaeology, and space science.

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

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, the 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 Pharaoh 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. He placed lumps of gold and silver equal in weight to the wreath in 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.)

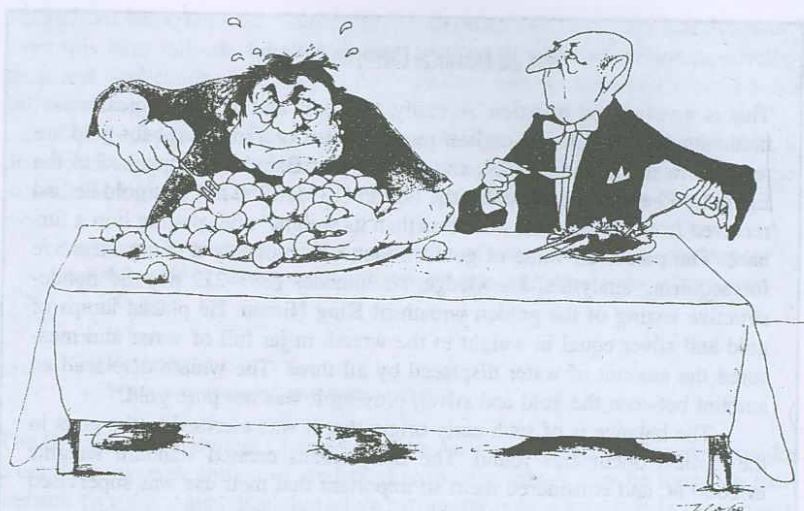
Gravimetry was developed in the seventeenth century, and titrimetry in the eighteenth and nineteenth centuries. Guy-Lussac, in 1829, assayed silver by titration with 0.05% relative accuracy and precision!

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 wissenschaftlichen Grundlagen 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 Ref. 7.

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 sulfur impurity present.



(Courtesy of Merck KGaA. Reproduced by permission.)

Quantitative analysis *Qualitative analysis*

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 to a dissolved sample indicates the presence of chloride. 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**:

- 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, few reactions are specific but many exhibit selectivity. Selectivity may be 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 with detecting reagents)
- Chromatography, which provides powerful separation

For quantitative analysis, a history of the sample composition will often be known (it is known that blood contains glucose), or else the analyst will have performed 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 than quantitative procedures. Qualitative analysis is 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.

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

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

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. Various techniques include immunoassays, gas chromatography, and liquid chromatography. 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 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.

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)

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 client, an engineer, or your grandmother—each of which will have different criteria or needs, and each having a different understanding of what a chemical analysis involves or means. It is

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

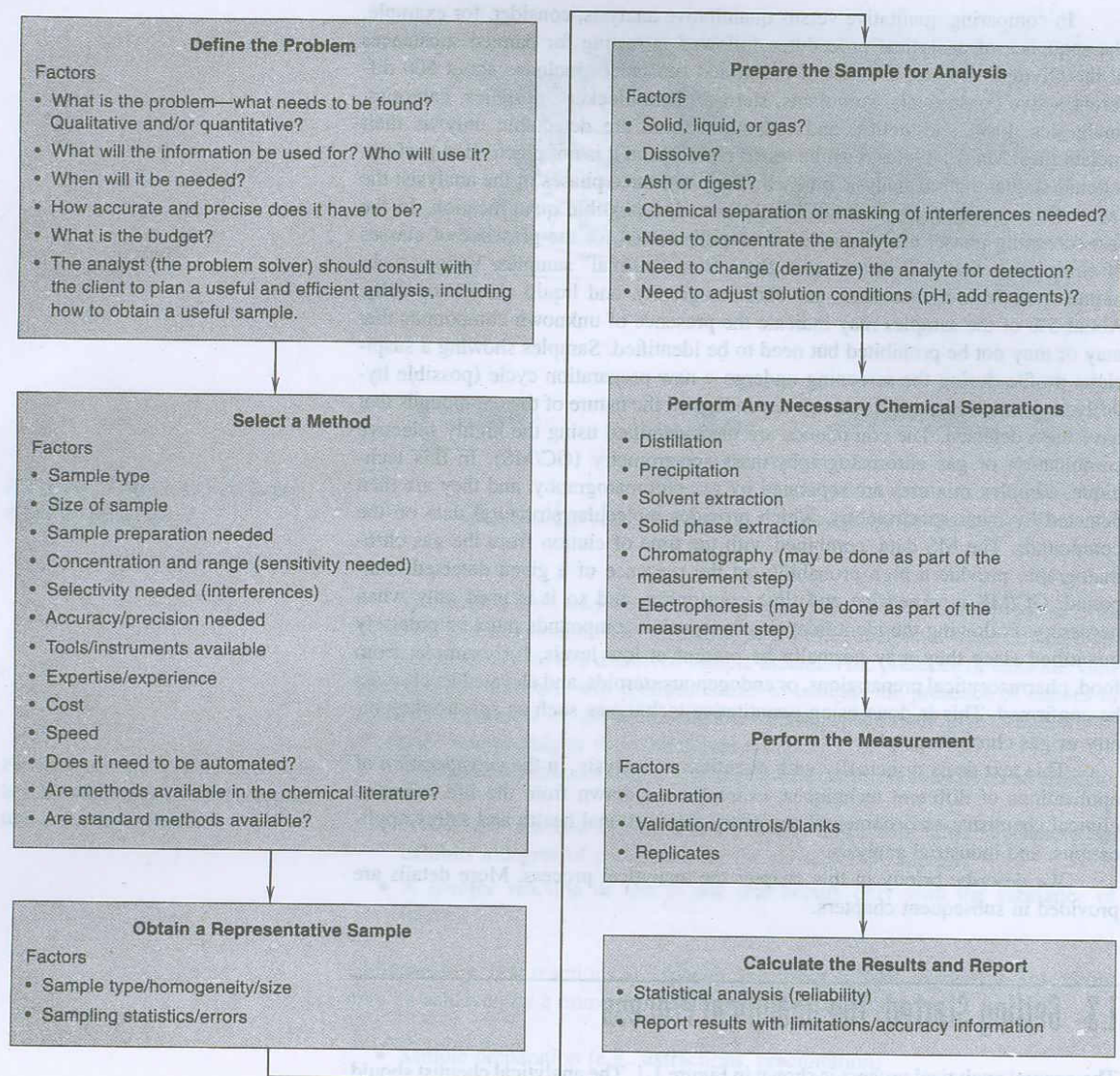


Fig. 1.1. Steps in an analysis.

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.

I have often had laypersons come to me 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.

The concept of “safe” or “zero/nothing” is one that is hard to define or understand by many. Telling someone their water is safe is not for the analyst to say. All you 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 ridiculously small amounts or concentrations, for example, parts per trillion. This presents a dilemma in making policy (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 precise¹ 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.

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 instruments 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. The major analytical chemistry journals may be consulted separately. Some of these are: *Analytica Chimica Acta*, *Analytical Chemistry*, *Analytical Letters*, *Analyst*, *Applied Spectroscopy*, *Clinica Chimica Acta*, *Clinical Chemistry*, *Journal of the Association of Official Analytical Chemists*, *Journal of Chromatography*, *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 analysis 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.

Examples of the manner in which the analysis of particular types of samples are made are given in Chapters 24 to 26. 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

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

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

Chemical Abstracts is a good source of literature.

¹Accuracy 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.

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.

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 sampling.

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.

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. Preservatives such as sodium fluoride for glucose preservation and anticoagulants may be added to blood samples when they 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 solidarity of 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). 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 **plasma** remaining can be analyzed. Plasma and serum are essentially identical in chemical composition, the chief difference being that fibrinogen has been removed from the latter.

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

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.

Details of sampling other materials are available in reference books on specific areas of analysis. See the references at the end of the chapter for some citations.

Certain precautions should be taken in **handling and storing samples** to prevent or minimize contamination, loss, decomposition, or matrix change. In general, one must prevent contamination or alteration of the sample by (1) the container, (2) the atmosphere, or (3) light. Also, a chain of custody should be established and will certainly be required for any analysis that may be involved in legal proceedings. In the O.J. Simpson case, there were television news clips of people handling samples, purportedly without proper custody, placing them in the hot trunk of a car, for example. While this may not have affected the actual analyses and correctness of samples analyzed, it provided fodder for the defense to discredit analyses.

The sample may have to be protected from the atmosphere or from light. It may be an alkaline substance, for example, which will react with carbon dioxide in the air. Blood samples to be analyzed for CO_2 should be protected from the atmosphere.

The stability of the sample must be considered. Glucose, for example, is unstable, and a preservative such as sodium fluoride is added to blood samples. The preservation must not, of course, interfere in the analysis. Proteins and enzymes tend to denature on standing and should be analyzed without delay. Trace constituents may be lost during storage by adsorption onto the container walls.

Urine samples are unstable, and calcium phosphate precipitates out, entrapping metal ions or other substances of interest. Precipitation can be prevented by keeping the urine acidic (pH 4.5), usually by adding 1 or 2 mL glacial acetic acid per 100-mL sample. Store under refrigeration. Urine, as well as whole blood, serum, plasma, and tissue samples, can also be frozen for prolonged storage. Deproteinized blood samples are more stable than untreated samples.

Corrosive gas samples will often react with the container. Sulfur dioxide, for example, is troublesome. In automobile exhaust, SO_2 is also lost by dissolving in condensed water vapor from the exhaust. In such cases, it is best to analyze the gas by a stream process.

PREPARING THE SAMPLE FOR ANALYSIS—IT PROBABLY NEEDS TO BE ALTERED

The first step in analyzing a sample is to measure the amount being analyzed (e.g., volume or weight of sample). This will be needed to calculate the percent composition from the amount of analyte found. The analytical sample size must be measured to the degree of precision and accuracy required for the analysis. An analytical balance sensitive to 0.1 mg is usually used for weight measurements. Solid samples are often analyzed on a dry basis and must be dried in an oven at 110 to 120°C for 1 to 2 h and cooled in a desiccator before weighing, if the sample is stable at the drying temperatures. Some samples may require higher temperatures and longer heating time (e.g., overnight) because of the great affinity of moisture for their sample surface. The amount of sample taken will depend on the concentration of the analyte and how much is needed for isolation and measurement. Determination of a major constituent may require only a couple hundred milligrams of sample, while a trace constituent may require several grams. Usually **replicate samples** are taken for analysis, in order to obtain statistical data on the precision of the analysis and provide more reliable results.

Analyses may be nondestructive in nature, for example, in the measurement of lead in paint by X-ray fluorescence in which the sample is bombarded with an X-ray beam and the characteristic reemitted X radiation is measured. More often, the sample must be in solution form for measurement, and solids must be dissolved. Inorganic materials may be dissolved in various acids, redox, or complexing

Care must be taken not to alter or contaminate the sample.

The first thing you must do is measure the size of sample to be analyzed.

Solid samples usually must be put into solution.

Ashing is the burning of organic matter. *Digestion* is the wet oxidation of organic matter.

The pH of the sample solution will usually have to be adjusted.

Always run a blank!

media. Acid-resistant material may require fusion with an acidic or basic flux in the molten state to render it soluble in dilute acid or water. Fusion with sodium carbonate, for example, forms acid-soluble carbonates.

Organic materials that are to be analyzed for inorganic constituents, for example, trace metals, may be destroyed by **dry ashing**. The sample is slowly combusted in a furnace at 400 to 700°C, leaving behind an inorganic residue that is soluble in dilute acid. Alternately, the organic matter may be destroyed by **wet digestion** by heating with oxidizing acids. A mixture of nitric and sulfuric acids is common. Biological fluids may sometimes be analyzed directly. Often, however, proteins interfere and must be removed. Dry ashing and wet digestion accomplish such removal. Or proteins may be precipitated with various reagents and filtered or centrifuged away, to give a **protein-free filtrate** (PFF).

If the analyte is organic in nature, these oxidizing methods cannot be used. Rather, the analyte may be extracted away from the sample or dialyzed, or the sample dissolved in an appropriate solvent. It may be possible to measure the analyte nondestructively. An example is the direct determination of protein in feeds by near-infrared spectrometry.

Once a sample is in solution, the solution conditions must be adjusted for the next stage of the analysis (separation or measurement step). For example, the pH may have to be adjusted, or a reagent added to react with and “mask” interference from other constituents. The analyte may have to be reacted with a reagent to convert it to a form suitable for measurement or separation. For example, a colored product may be formed that will be measured by spectrometry. Or the analyte will be converted to a form that can be volatilized for measurement by gas chromatography. The gravimetric analysis of iron as Fe_2O_3 requires that all the iron be present as iron(III), its usual form. A volumetric determination by reaction with dichromate ion, on the other hand, requires that all the iron be converted to iron(II) before reaction, and the reduction step will have to be included in the sample preparation.

The solvents and reagents used for dissolution and preparation of the solution should be of high purity (reagent grade). Even so, they may contain trace impurities of the analyte. Hence, it is important to prepare and analyze replicate **blanks**, particularly for trace analyses. A blank theoretically consists of all chemicals in the unknown and used in an analysis in the same amounts (including water), run through the entire analytical procedure. The blank result is subtracted from the analytical sample result to arrive at a net analyte concentration in the sample solution. If the blank is appreciable, it may invalidate the analysis. Oftentimes, it is impossible to make a perfect blank for an analysis.

PERFORMING NECESSARY CHEMICAL SEPARATIONS

In order to eliminate interferences, to provide suitable selectivity in the measurement, or to preconcentrate the analyte for more sensitive or accurate measurement, the analyst must often perform one or more separation steps. It is preferable to separate the analyte away from the sample matrix, in order to minimize losses of the analyte. Separation steps may include precipitation, extraction into an immiscible solvent, chromatography, dialysis, and distillation.

PERFORMING THE MEASUREMENT—YOU DECIDE THE METHOD

The method employed for the actual quantitative measurement of the analyte will depend on a number of factors, not the least important being the amount of analyte present and the accuracy and precision required. Many available techniques possess varying degrees of selectivity, sensitivity, accuracy and precision, cost, and

rapidity. **Gravimetric analysis** usually involves the selective separation of the analyte by precipitation, followed by the very nonselective measurement of mass (of the precipitate). In **volumetric**, or **titrimetric, analysis**, the analyte reacts with a measured volume of reagent of known concentration, in a process called **titration**. A change in some physical or chemical property signals the completion of the reaction. Gravimetric and volumetric analyses can provide results accurate and precise to a few parts per thousand (tenth of 1 percent) or better. But they require relatively large (millimole or milligram) quantities of analyte and are well suited for the measurement of major constituents. Volumetric analysis is more rapid than gravimetric analysis and so is preferred when applicable.

Instrumental techniques are used for many analyses and constitute the discipline of **instrumental analysis**. They are based on the measurement of a physical property of the sample, for example, an electrical property or the absorption of electromagnetic radiation. Examples are spectrophotometry (ultraviolet, visible, or infrared), fluorimetry, atomic spectroscopy (absorption, emission), mass spectrometry, nuclear magnetic resonance spectrometry (NMR), X-ray spectroscopy (absorption, fluorescence), electroanalytical chemistry (potentiometric, voltammetric, electrolytic), chromatography (gas, liquid), and radiochemistry. Instrumental techniques are generally more sensitive and selective than the classical techniques but are less precise, on the order of 1 to 5% or so. These techniques are usually much more expensive, capitalwise. But depending on the numbers of analyses, they may be less expensive when one factors in personnel costs. They are usually more rapid, may be automated, and may be capable of measuring more than one analyte at a time. Chromatography techniques are particularly powerful for analyzing complex mixtures. They perform the separation and measurement step simultaneously. Constituents are separated as they are washed down (eluted from) a column of appropriate material that interacts with the analytes to varying degrees, and the analytes are sensed with an appropriate detector as they emerge from the column, to give a transient peak signal, in proportion to the amount of analyte.

Table 1.1 compares various analytical methods to be described in this text with respect to sensitivity, precision, selectivity, speed, and cost. The numbers given may be exceeded in specific applications, and the methods may be applied to other uses, but these are representative of typical applications. The lower concentrations determined by titrimetry require the use of an instrumental technique for measuring the completion of the titration. The selection of a technique, when more than one is applicable, will depend, of course, on the availability of equipment and personal experience and preference of the analyst. As examples, you might use spectrophotometry to determine the concentration of nitrate in river water at the 1 ppm ($1.6 \times 10^{-5} M$) level, using a diazotization reaction with nitrate to produce a color. Fluoride in toothpaste may be determined potentiometrically using a fluoride ion-selective electrode. A complex mixture of hydrocarbons in gasoline can be separated and determined using the technique of gas chromatography. Glucose in blood can be determined kinetically by the rate of the enzymatic reaction between glucose and oxygen, catalyzed by the enzyme glucose oxidase, with measurement of the rate of oxygen depletion or the rate of hydrogen peroxide production. The purity of a silver bar can be determined gravimetrically by dissolving a small sample in nitric acid and precipitating with chloride and weighing the purified precipitate.

The various methods of determining an analyte can be classified as either **absolute** or **relative**. Absolute methods rely upon accurately known fundamental constants for calculating the amount of analyte, for example, atomic weights. In gravimetric analysis, for example, an insoluble derivative of the analyte of known chemical composition is prepared and weighed, as in the formation of AgCl for

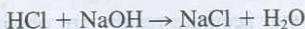
Instruments are more selective and sensitive than volumetric and gravimetric methods. But they may be less precise.

Most methods require calibration with a standard.

Table 1.1
Comparison of Different Analytical Methods

Method	Approx. Range (mol/L)	Approx. Precision (%)	Selectivity	Speed	Cost	Principal Uses
Gravimetry	10^{-1} – 10^{-2}	0.1	Poor-moderate	Slow	Low	Inorg.
Titrimetry	10^{-1} – 10^{-4}	0.1–1	Poor-moderate	Moderate	Low	Inorg., org.
Potentiometry	10^{-1} – 10^{-6}	2	Good	Fast	Low	Inorg.
Electrogravimetry, coulometry	10^{-1} – 10^{-4}	0.01–2	Moderate	Slow-moderate	Moderate	Inorg., org.
Voltammetry	10^{-3} – 10^{-10}	2–5	Good	Moderate	Moderate	Inorg., org.
Spectrophotometry	10^{-3} – 10^{-6}	2	Good-moderate	Fast-moderate	Low-moderate	Inorg., org.
Fluorimetry	10^{-6} – 10^{-9}	2–5	Moderate	Moderate	Moderate	Org.
Atomic spectroscopy	10^{-3} – 10^{-9}	2–10	Good	Fast	Moderate-high	Inorg., multielement
Chromatography	10^{-3} – 10^{-9}	2–5	Good	Fast-moderate	Moderate-high	Org., multielement
Kinetic methods	10^{-2} – 10^{-10}	2–10	Good-moderate	Fast-moderate	Moderate	Inorg., org., enzymes

chloride determination. The precipitate contains a known fraction of the analyte, in this case, fraction of Cl = at wt Cl/f wt AgCl = 35.453/143.32 = 0.24737.² Hence, it is a simple matter to obtain the amount of Cl contained in the weighed precipitate. Most methods, however, are relative in that they require comparison against some solution of known concentration. In titrimetric analysis, for example, the analyte is reacted with the solution of a reagent in a known stoichiometric ratio. Hydrochloric acid, for example, reacts with sodium hydroxide in a 1:1 ratio:



The volume of sodium hydroxide solution required to just completely react with the hydrochloric acid sample is measured. If we know the concentration of the sodium hydroxide solution in moles per liter, then the number of moles of NaOH added can be calculated (volume \times molarity), and so we know the number of moles of HCl in the sample. Therefore, in this relative method, it is necessary to prepare a reacting solution (sodium hydroxide) of accurately known concentration.

Most instrumental methods of analysis are relative. Instruments register a signal due to some physical property of the solution. Spectrophotometers, for example, measure the fraction of electromagnetic radiation from a light source that is absorbed by the sample. This fraction must be related to the analyte concentration by comparison against the fraction absorbed by a known concentration of the analyte. In other words, the instrumentation must be **calibrated**.

Instrument response may be linearly or nonlinearly related to the analyte concentration. Calibration is accomplished by preparing a series of standard solutions of the analyte at known concentrations and measuring the instrument response to each of these (usually after treating them in the same manner as the samples) to prepare an **analytical calibration curve** of response versus concentration. The concentration of an unknown is then determined from the response, using the calibration curve. With modern computer-controlled instruments, this is often done electronically or digitally, and direct readout of concentration is obtained.

The sample matrix may affect the instrument response to the analyte. In such cases, calibration may be accomplished by the **method of standard additions**. A portion of the sample is spiked with a known amount of standard, and the increase in signal is due to the standard. In this manner, the standard is subjected to the same environment as the analyte. These calibration techniques are discussed in more detail when describing the use of specific instruments.

A calibration curve is the instrument response as a function of concentration.

Standard additions calibration is used to overcome sample matrix effects.

CALCULATING THE RESULTS AND REPORTING THE DATA—THIS IS THE WHOLE OBJECT

Once the concentration of analyte in the prepared sample solution has been determined, the results are used to calculate the amount of analyte in the original sample. Either an *absolute* or a *relative* amount may be reported. Usually, a relative composition is given, for example, percent or parts per million, along with the mean value for expressing accuracy. Replicate analyses can be performed (three or more), and a precision of the analysis may be reported, for example, standard deviation. A knowledge of the precision is important because it gives the degree of uncertainty in the result (see Chapter 3). The analyst should critically evaluate whether the results are reasonable and relate to the analytical problem as originally stated. Remember that the customer often does not have a scientific background so will

The analyst must provide expert advice on the significance of a result.

²at wt = atomic weight; f wt = formula weight.

take a number as gospel. Only you, as analyst, can put that number in perspective, and it is important that you have good communication and interaction with the "customer" about what the analysis represents.

1.4 Validation of a Method—You Have to Prove It Works!

Great care must be taken that accurate results are obtained in an analysis. Two types of error may occur: *random* and *systematic*. Every measurement has some imprecision associated with it, which results in random distribution of results, for example, a Gaussian distribution. The experiment can be designed to narrow the range of this, but it cannot be eliminated. A systematic error is one that biases a result consistently in one direction. The sample matrix may suppress the instrument signal. A weight of an analytical balance may be in error, skewed either high or low. A sample may not be sufficiently dried.

Proper calibration of an instrument is only the first step in assuring accuracy. In developing a method, samples should be spiked with known amounts of the analyte (above and beyond what is already in the sample). The amounts determined (recovered) by the analysis procedure (after subtraction of the amount apparently present in the sample as determined by the same procedure) should be within the accuracy required in the analysis. A new method can be validated by comparison of sample results with those obtained with another accepted method. There are various sources of certified standards or reference materials that may be analyzed to assure accuracy by the method in use. For example, environmental quality control standards for pesticides in water or priority pollutants in soil are commercially available. The National Institute of Standards and Technology (NIST) prepares standard reference materials (SRMs) of different matrix compositions (e.g., steel, ground leaves) that have been certified for the content of specific analytes, by careful measurement by at least two independent techniques. Values are assigned with statistical ranges. Different agencies and commercial concerns can provide samples for round-robin or blind tests in which control samples are submitted to participating laboratories for analysis at random. The laboratory does not know the control value prior to analysis.

Standards should be run intermittently with samples. A *control sample* should also be run at least daily and the results plotted as a function of time to prepare a *quality control chart*, which is compared with the known standard deviation of the method. The measured quantity is assumed to be constant with time, with a Gaussian distribution, and there is a 1 in 20 chance that values will fall outside two standard deviations from the known value, and a 1 in 100 chance it will be 2.5 standard deviations away. Numbers exceeding these suggest uncompensated errors, such as instrument malfunction, reagent deterioration, or improper calibration.

Government regulations require careful established protocol and validation of methods and analyses when used for official or legal purposes. Guidelines of *good laboratory practice* (GLP) have been established to assure validation of analyses. They, of course, ideally apply to all analyses. These are discussed in detail in Chapter 4.

1.5 Range—What Size Sample?

Analytical methods are often classed according to size of sample. Such classification is arbitrary and there is no sharp dividing line. The analysis may be classed

The best way to validate a method is to analyze a standard reference material of known composition.

Good laboratory practice (validation) is required to assure accuracy of analyses.

Table 1.2
Classification of Analytical Methods According to Size of Sample

Method	Sample Weight (mg)	Sample Volume (μL) ^a
Meso	>100	>100
Semimicro	10–100	50–100
Micro	1–10	<50
Ultramicro	<1	

^a μL = Microliter. Sometimes the symbol λ (lambda) is used in place of μL .

as **meso**, **semimicro**, **micro**, or **ultramicro**; the last two categories are often classified as “trace analysis.” Table 1.2 gives approximate classifications according to sample weight or volume. The volume classifications are those employed in clinical laboratories. Special handling techniques and microbalances for weighing are required for micro and ultramicro operations.

ANALYZE VERSUS DETERMINE—THEY ARE DIFFERENT

The terms *analyze* and *determine* have two different meanings. We say a sample is **analyzed** for part or all of its constituents. The substances measured are called the **analytes**. The process of measuring the analyte is called a **determination**. Hence, in analyzing blood for its chloride content, we determine the chloride concentration.

The constituents in the sample may be classified as **major** (>1%), **minor** (0.1 to 1%), or **trace** (<0.1%). A few parts per million or less of a constituent might be classed as **ultratrace**.

An analysis may be **complete** or **partial**; that is, either all constituents or only selected constituents may be determined. Most often, the analyst is requested to report on a specified chemical or perhaps a class of chemicals.

You *analyze* a sample to *determine* the amount of analyte.

1.6 Some Useful Websites

In addition to the various literature and book sources we have mentioned, and those listed in Appendix A (Literature of Analytical Chemistry), there are a number of websites that are useful for supplementary resources for analytical chemists. These, of course, often change and new ones become available. But the following are good starting points for obtaining much useful information.

Chemistry in General

1. www.acs.org: The American Chemical Society home page. Information on journals, meetings, chemistry in the news, search databases (including *Chemical Abstracts*), and much more.
2. www.chemweb.com: This is a virtual club for chemists. The site contains databases and lists relating to chemistry and incorporates discussion groups that focus on specific areas such as analytical chemistry. You must join, but it is free.
3. www.chemsoc.org: This is a chemistry societies network, maintained by the Royal Society of Chemistry in Britain, with information provided by about 30 national chemistry societies. It has a virtual periodic table, and you can download a periodic table screensaver.

4. <http://micro.magnet.fsu.edu/primer/java/scienceopticsu/powersof10/index.html>: Check out this Powers of Ten visual scene, from protons to viewing the Milky Way 10 million light years from Earth.

Analytical Chemistry

1. www.acs-analytical.duq.edu: This is the home page of the Division of Analytical Chemistry of the American Chemical Society. There are a number of links and resources throughout this site that will take you all over the Internet to sites involving analytical chemistry.
2. www.chem.uni-potsdam.de/linkcenter/analchem.html: This is an analytical chemistry link center that connects to university and other sites all over the world.
3. www.cstl.nist.gov/nist839/: The Analytical Division site of the National Institute of Standards and Technology (NIST). Provides information on each of its five divisions: Spectrochemical Methods, Organic Analytical Methods, Gas Metrology and Classical Methods, Molecular Spectrometry and Microfluidic Methods, and Nuclear Analytical Methods.
4. www.rsc.org/lap/rsccom/dab/analdiv.htm: The Analytical Division site of the Royal Society of Chemistry in Britain. The British equivalent of the ACS Division of Analytical Chemistry.
5. <http://chemweb.chem.uconn.edu/Microchem/Index.html>: American Microchemical Society site. Has links to analytical chemistry societies, conferences, and professors.
6. <http://analytical.chemweb.com/home>: The analytical chemistry forum of the Chemweb website above.
7. www.asdlib.org: Analytical Sciences Digital Library (ASDL). In its infancy, but will become the site of choice for listings of peer-reviewed websites dealing with pedagogy and techniques. See your text website for additional information about this site.

Learning Objectives

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

- Analytical science deals with the chemical characterization of matter—what, how much?, p. 1
- The analyst must know what information is really needed, and obtain a representative sample, pp. 5, 8
- Few measurements are specific, so operations are performed to achieve high selectivity, p. 9
- You must select the appropriate method for measurement, p. 10
- Validation is important, p. 14
- There are many useful websites dealing with analytical chemistry, p. 15

Questions

1. What is analytical chemistry?
2. Distinguish between qualitative analysis and quantitative analysis.
3. Outline the steps commonly employed in an analytical procedure. Briefly describe each step.
4. Distinguish between analyze, determine, sample, and analyte.
5. What is a blank?
6. List some of the common measuring techniques employed in analytical chemistry.
7. List some separation procedures employed in analytical chemistry.
8. Define instrumental analysis.
9. What is a calibration curve?
10. Distinguish between a specific reaction and a selective reaction.
11. Suggest a method from Table 1.1 to accomplish the following analyses: (a) the purity of NaCl in table salt, (b) the acetic acid content of vinegar, (c) the pH of swimming pool water.

Recommended References

GENERAL

1. J. Tyson, *Analysis. What Analytical Chemists Do*. London: Royal Society of Chemistry, 1988. A brief book that very succinctly discusses what analytical chemists do and how they do it.
2. R. W. Murray, "Analytical Chemistry Is What Analytical Chemists Do," Editorial, *Anal. Chem.*, **66** (1994) 682A.
3. G. M. Hieftje, "But Is It Analytical Chemistry?" *Am. Lab.*, October (1993) 53.
4. T. Kuwana, Chair, *Curricular Developments in the Analytical Sciences*, A Report from Workshops held in 1996 and 1997, Sponsored by the National Science Foundation. (kuwana@sunflower.com)
5. R. A. DePalma and A. H. Ullman, "Professional Analytical Chemistry in Industry. A Short Course to Encourage Students to Attend Graduate School," *J. Chem. Ed.*, **68** (1991) 383. This is a description of an industrial analytical chemistry short course for teachers and students that Proctor & Gamble Company scientists deliver at universities and colleges at invitation, to explain what analytical chemists do in industry. The emphasis is "The analytical chemist as a problem solver." (parry.d@pg.com)
6. C. A. Lucy, "How to Succeed in Analytical Chemistry: A Bibliography of Resources from the Literature," *Talanta*, **51** (2000) 1125. Surveys the literature for advice on how to purchase equipment, how to write a manuscript, and how to get a job in analytical chemistry.
7. G. D. Christian, "Evolution and Revolution in Quantitative Analysis," *Anal. Chem.*, **67** (1995) 532A. Traces the history of analytical chemistry from the beginning of humans.

ENCYCLOPEDIAS AND HANDBOOKS

8. R. A. Meyers, editor-in-chief, *Encyclopedia of Analytical Chemistry*. Chichester: Wiley, 2000. A 15-volume set, with 10 volumes on applications and 5 on theory and instrumentation.

9. A. Townsend, editor-in-chief, *Encyclopedia of Analytical Science*. London: Academic, 1995. A 10-volume set with comprehensive coverage of the practice of analytical science. Covers all techniques that determine specific elements, compounds, and groups of compounds in any physical or biological matrix.
10. J. A. Dean, *Analytical Chemistry Handbook*. New York: McGraw Hill, 1995. Detailed coverage of conventional wet and instrumental techniques, preliminary operations of analysis, preliminary separation methods, and statistics in chemical analysis.

SAMPLING

11. F. F. Pitard, *Pierre Gy's Sampling Theory and Sampling Practice*. Vol. 1: *Heterogeneity and Sampling*. Vol. II: *Sampling Correctness and Sampling Practice*. Boca Raton, FL: CRC Press, 1989.
12. P. M. Gy and A. G. Boyle, *Sampling for Analytical Purposes*. Chichester: Wiley, 1998. An abridged guide by Pierre Gy to his formula originally developed for the sampling of solid materials but equally valid for sampling liquids and multiphase media.
13. P. M. Gy, *Sampling of Heterogeneous and Dynamic Material Systems*. Amsterdam: Elsevier, 1992.
14. G. E. Baiulescu, P. Dumitrescu, and P. Gh. Zugravescu, *Sampling*. New York: Ellis Horwood, 1991.
15. N. T. Crosby, ed., *General Principles of Good Sampling Practice*. London: Royal Society of Chemistry, 1995.
16. P. M. Gy, "Introduction to Theory of Sampling I. Heterogeneity of a Population of Uncorrelated Units," *Trends Anal. Chem.*, **14**(2) (1995) 67.
17. P. M. Gy, "Tutorial: Sampling or Gambling?" *Process Control and Quality*, **6** (1994) 97.
18. B. Kratochvil and J. K. Taylor, "Sampling for Chemical Analysis," *Anal. Chem.*, **53** (1981) 924A.
19. B. Kratochvil, "Sampling for Microanalysis: Theory and Strategies," *Fresenius' J. Anal. Chem.*, **337** (1990) 808.
20. J. F. Vicard and D. Fraisse, "Sampling Issues," *Fresenius' J. Anal. Chem.*, **348** (1994) 101.
21. J. M. Hungerford and G. D. Christian, "Statistical Sampling Errors as Intrinsic Limits on Detection in Dilute Solutions," *Anal. Chem.*, **58** (1986) 2567.

INTERFERENCES

22. W. E. Van der Linden, "Definition and Classification of Interference in Analytical Procedures," *Pure & Appl. Chem.*, **61** (1989) 91.

STANDARD SOLUTIONS

23. B. W. Smith and M. L. Parsons, "Preparation and Standard Solutions. Critically Selected Compounds," *J. Chem. Ed.*, **50** (1973) 679. Describes preparation of standard solutions of 72 inorganic metals and nonmetals.
24. M. H. Gabb and W. E. Latchem, *A Handbook of Laboratory Solutions*. New York: Chemical Publishing, 1968.
25. <http://pubs.acs.org/reagents/committee.html>, American Chemical Society Committee on Analytical Reagents.

CALIBRATION

26. H. Mark, *Principles and Practice of Spectroscopic Calibration*. New York: Wiley, 1991.

STANDARD REFERENCE MATERIALS

27. H. Klich and R. Walker, "COMAR—The International Database for Certified Reference Materials," *Fresenius' J. Anal. Chem.*, **345** (1993) 104.
28. Office of Standard Reference Materials, Room B311, Chemistry Building, National Institute of Standards and Technology, Gaithersburg, Maryland 20899.
29. National Research Council of Canada, Division of Chemistry, Ottawa K1A 0R6, Canada.
30. R. Alvarez, S. D. Rasberry, and G. A. Urriano, "NBS Standard Reference Materials: Update 1982," *Anal. Chem.*, **54** (1982) 1239A.
31. R. W. Seward and R. Mavrodineanu, "Standard Reference Materials: Summary of the Clinical Laboratory Standards Issued by the National Bureau of Standards," *NBS (NIST) Special Publications* 260–271, Washington, DC, 1981.
32. *Standard Coal Samples*. Available from U.S. Department of Energy, Pittsburgh Mining Technology Center, P.O. Box 10940, Pittsburgh, PA 15236. Samples have been characterized for 14 properties, including major and trace elements.



Chapter Two

BASIC TOOLS AND OPERATIONS OF ANALYTICAL CHEMISTRY

"Get your facts first, and then you can distort them as much as you please."

—Mark Twain

Read this chapter before performing experiments.

Analytical chemistry requires measurements in order to get the facts. Throughout the text, specific analytical equipment and instrumentation available to the analyst are discussed as they pertain to specific measuring techniques. Several standard items, however, are common to most analyses and will be required when performing the experiments. These are described in this chapter. They include the analytical balance and volumetric glassware and items such as drying ovens and filters. Detailed explanation of the physical manipulation and use of this equipment is best done by your laboratory instructor, when you can see and practice with the actual equipment, particularly since the type and operation of equipment will vary from one laboratory to another. Some of the general procedures of good laboratory technique will be mentioned as we go along.

See your CD for pictures of commonly used glassware and apparatus in the analytical laboratory.

2.1 The Laboratory Notebook—Your Critical Record

A well-kept laboratory record will help assure reliable analyses.

You should first realize that in the analytical laboratory, more than anywhere else, cleanliness and neatness are of the utmost importance. This also applies to the keeping of an orderly notebook. All data should be recorded permanently in ink *when they are collected*. When you go into the analytical laboratory, you will find that this orderliness is to your advantage. First of all, there is a saving of time in not having to reorganize and rewrite the data. There is probably an additional saving of time since you will be more organized in carrying out the operations of the analysis if you have trained yourself to put the data down in an orderly fashion. Chances for a mistake are reduced. Second, if you make an immediate record, you will be

able to detect possible errors in measurements or calculations. And data will not be lost or transferred incorrectly if they are recorded directly in a notebook instead of collected on scraps of paper.

For practicing analytical chemists and on-the-job applications, it is especially important to use the lab notebooks for entering observations and measurements directly. Complete documentation is essential for forensic or industrial laboratories for legal or patent considerations. In industrial research labs, the notebook must generally be signed (witnessed) and dated by another person familiar with the work to assure legal patent priority if applicable.

An example of a well-kept notebook with properly recorded data is illustrated below for the volumetric analysis of a soda ash unknown in your laboratory:

Date: 7 September, 2003

Analysis of soda ash unknown

Principle: The soda ash is dissolved in water and titrated to a bromocresol green end point with standard hydrochloric acid. The hydrochloric acid is standardized against primary standard sodium carbonate. Weigh sodium carbonate and soda ash unknown by difference.

Reference: Experiment 7

Titration Reaction $\text{CO}_3^{2-} + 2\text{H}^+ = \text{H}_2\text{CO}_3$

Standardization

$$M(\text{HCl}) = \frac{\text{mg Na}_2\text{CO}_3}{\text{f wt Na}_2\text{CO}_3 (\text{mg/mmol}) \times \frac{1}{2} (\text{mmol Na}_2\text{CO}_3/\text{mmol HCl}) \times \text{mL HCl}}$$

$$= \frac{\text{mg Na}_2\text{CO}_3}{105.99 (\text{mg/mmol}) \times \frac{1}{2} \times \text{mL HCl}}$$

	#1	#2	#3
Bottle + sample	24.2689 g	24.0522 g	23.8597 g
Less sample	24.0522 g	23.8597 g	23.6269 g
g Na ₂ CO ₃	0.2167 g	0.1925 g	0.2328 g
mg Na ₂ CO ₃	216.7 mg	192.5 mg	232.8 mg
Buret reading	40.26 mL	35.68 mL	43.29 mL
Initial reading	0.03 mL	0.00 mL	0.02 mL
Net volume	40.23 mL	35.68 mL	43.27 mL
Molarity:	0.1016 ₄ M	0.1018 ₀ M	0.1015 ₂ M
Mean: 0.1016 ₅			
Std. devn: 1.6 ppt			
Range: 2.8 ppt			

Soda Ash

$$\% \text{Na}_2\text{CO}_3 = \frac{M \times \text{mL} \times \text{f wt Na}_2\text{CO}_3 \times \frac{1}{2} (\text{mmol Na}_2\text{CO}_3/\text{mmol HCl})}{\text{mg sample}} \times 100$$

$$= \frac{0.1016_5 (\text{mmol/mL}) \times \text{mL} \times 105.99 (\text{mg/mmol}) \times \frac{1}{2}}{\text{mg sample}} \times 100$$

Bottle + sample	25.6728 g	25.4673 g	25.2371 g
Less sample	25.4673 g	25.2371 g	25.0027 g
g sample	0.2055 g	0.2302 g	0.2344 g
mg sample	205.5 mg	230.2 mg	234.4 mg
Buret reading	35.67 mL	40.00 mL	40.70 mL
Initial reading	0.00 mL	0.01 mL	0.05 mL
Net volume	35.67 mL	39.99 mL	40.65 mL
% Na ₂ CO ₃	93.50%	93.58%	93.42%
Mean: 93.50			
Std. devn: 0.9 ppt			
Range: 1.7 ppt			

The above example is an abbreviated version in which actual calculation or numerical setups are omitted. For complete record keeping, you should include the computational setups in your notebook so an error can be tracked down later, if necessary.

Rather than fill all the space in the laboratory notebook, it is recommended you leave alternate pages for scratch pages (e.g., the left page, leaving the right page for summarizing data). It is also important that you record your data to the proper number of significant figures. Significant figures are discussed in Chapter 3, and you should review this material before beginning in the laboratory.

The correct number of significant figures in measurements and calculations is critical in giving the proper significance to an analysis. See Chapter 3.

Read this chapter before performing experiments.

Laboratory Notebook Documentation

The laboratory notebook is a record of your job as an analytical chemist. It documents everything you do. It is the source for reports, publications, and regulatory submissions. The success or failure of a company's product or service may depend on how well you do that documentation. The notebook becomes a legal document for patent issues, government regulation issues (validation, inspections, legal actions), and the like. Remember, "if it isn't written down, it wasn't done." The notebook is where you record your original ideas that may form the basis of a patent, and so it is important to record what went into those ideas and when.

What are the features of a well-maintained notebook? They will vary with individual preferences, but here are some good rules:

- Use a hardcover notebook (no loose leafs).
- Number pages consecutively.
- Record only in ink.
- Never tear out pages. If not used, put a line through the page.
- Date each page, sign it, and have it signed and dated (maybe shortly later) by someone else, stating "Read and Understood by"
- Record the name of the project, why it is being done, and any literature references.
- Record all data on the day you obtain it.

A well-kept laboratory record will help you solve problems.

A word about *electronic notebooks*. Modern instrument software allows the analyst to collect, store, and process data directly from the instrument signal, based on appropriate calibration. It is important that the software and calibration be validated, as for the remainder of the analysis, as a part of good laboratory practice, discussed in Chapter 4.

2.2 Laboratory Materials and Reagents

Table 2.1 lists the properties of materials used in the manufacture of common laboratory apparatus. Borosilicate glass (brand names: Pyrex, Kimax) is the most commonly used material for laboratory apparatus such as beakers, flasks, pipets, and burets. It is stable to hot solutions and to rapid changes in temperature. For more

Table 2.1

Properties of Laboratory Materials

Material	Max. Working Temperature (°C)	Sensitivity to Thermal Shock	Chemical Inertness	Notes
Borosilicate glass	200	150°C change OK	Attacked somewhat by alkali solutions on heating	Trademarks: Pyrex (Corning Glass Works); Kimax (Owens-Illinois)
Soft glass		Poor	Attacked by alkali solutions	Boron-free. Trademark: Corning
Alkali-resistant glass		More sensitive than borosilicate		
Fused quartz	1050	Excellent	Resistant to most acids, halogens	Quartz crucibles used for fusions
High-silica glass	1000	Excellent	More resistant to alkalis than borosilicate	Similar to fused quartz Trademark: Vycor (Corning)
Porcelain	1100 (glazed) 1400 (unglazed)	Good	Excellent	
Platinum	ca. 1500		Resistant to most acids, molten salts. Attacks by aqua regia, fused nitrates, cyanides, chlorides at >1000°C. Alloys with gold, silver, and other metals	Usually alloyed with iridium or rhodium to increase hardness. Platinum crucibles for fusions and treatment with HF
Nickel and iron			Fused samples contaminated with the metal	Ni and Fe crucibles used for peroxide fusions
Stainless steel	400–500	Excellent	Not attacked by alkalis and acids except conc. HCl, dil. H ₂ SO ₄ , and boiling conc. HNO ₃	
Polyethylene	115		Not attacked by alkali solutions or HF. Attacked by many organic solvents (acetone, ethanol OK)	Flexible plastic
Polystyrene	70		Not attacked by HF. Attacked by many organic solvents	Somewhat brittle
Teflon	250		Inert to most chemicals	Useful for storage of solutions and reagents for trace metal analysis.

Reagent-grade chemicals are almost always used in analyses. Primary standards are used for preparing volumetric standard solutions.

specific applications, there are several other materials employed that may possess advantage with respect to chemical resistance, thermal stability, and so forth.

The different grades of chemicals are listed on the *back cover* of the text. In general, only *American Chemical Society (ACS) reagent-grade* or *primary standard* chemicals should be used in the analytical laboratory.

The American Chemical Society publishes a compendium of tests for evaluating the purity and quality of basic laboratory chemicals. Reagent chemicals that do not reference the ACS meet the manufacturer's own reagent specifications, which vary among suppliers.

The reagent-grade chemicals, besides meeting minimum requirements of purity, may be supplied with a report of analysis of the impurities (printed on the label). Primary standard chemicals are generally at least 99.95% pure. They are analyzed and the results are printed on the label. They are more expensive than reagent-grade chemicals and are used only for the preparation of standard solutions or for the standardization of a solution by reaction (titration) with it. Not all chemicals are available in primary standard grade. There are special grades of solvents for special purposes, for example, spectral grades or chromatographic grades. These are specifically purified to remove impurities that might interfere in the particular application. Likewise, there are trace metal analyzed acids that are specially refined and tested in greater detail for trace elemental impurities, typically in the parts per billion range.

In addition to commercial producers, the National Institute of Standards and Technology supplies primary standard chemicals. *NIST Special Publication 260* catalogs standard reference materials. (See <http://ts.nist.gov/ts/htdocs/230/232/232.htm> for information on the SRM program and lists of reference standards.) Reference standards are complex materials, such as alloys that have been carefully analyzed for the ingredients and are used to check or calibrate an analytical procedure.

The concentrations of commercially available acids and bases are listed on the inside of the *back cover*.

2.3 The Analytical Balance—The Indispensable Tool

Weighing is a required part of almost any analysis, both for measuring the sample and for preparing standard solutions. In analytical chemistry we deal with rather small weights, on the order of a few grams to a few milligrams or less. Standard laboratory weighings are typically made to three or four significant figures, and so the weighing device must be both accurate and sensitive. There are various sophisticated ways of achieving this, but the most useful and versatile device used is the **analytical balance**.

Most analytical balances used today are electronic balances. The mechanical single-pan balance is still used, though, and so we will describe its operation. Both types are based on comparison of one weight against another (the electronic one for calibration) and have in common factors such as zero-point drift and air buoyancy. We really deal with masses rather than weights. The **weight** of an object is the force exerted on it by the gravitational attraction. This force will differ at different locations on Earth. **Mass**, on the other hand, is the quantity of matter of which the object is composed and is invariant.

ELECTRONIC BALANCES—THE MOST CONVENIENT

Modern electronic balances offer convenience in weighing and are subject to fewer errors or mechanical failures than are mechanical balances. The operation of dialing

The balance measures mass.

Electronic balances are more convenient to use.



Fig. 2.1. Electronic analytical balance. (Courtesy of Denver Instrument Co. Denver Instrument Company owns all images.)

weights, turning and reading micrometers, and beam and pan arrest of mechanical balances are eliminated, greatly speeding the measurement. A digital-display electronic balance is shown in Figure 2.1, and the operating principle of an electronic balance is illustrated in Figure 2.2. There are no weights or knife edges as with mechanical balances. The pan sits on the arm of a movable hanger (2), and this movable system is compensated by a constant electromagnetic force. The position of the hanger is monitored by an electrical position scanner (1), which brings the weighing system back to the zero position. The compensation current is proportional to the weight placed on the pan. This is sent in digital form to a microprocessor that converts it into the corresponding weight value, which appears as a digital display. The weight of the container can be automatically subtracted.

These balances use the principle of electromagnetic force compensation first described by Angstrom in 1895. But they still use the principle of comparing one weight with another. The balance is "zeroed," or calibrated, with a known weight. When the sample is placed on the pan, its weight is electronically compared with the known. This is a form of self-calibration. Modern balances may have such features as compensating for wandering from true zero and averaging variations due to building vibrations.

A single control bar is used to switch the balance on and off, to set the display to zero, and to tare a container automatically on the pan. Since results are

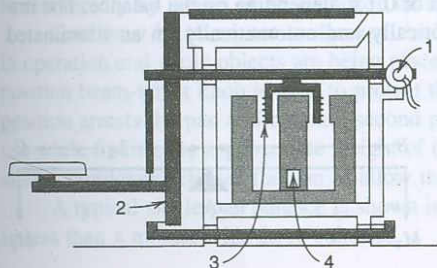


Fig. 2.2. Operating principle of electronic balance: 1, position scanner; 2, hanger; 3, coil; 4, temperature sensor. (From K. M. Lang, *American Laboratory*, March, 1983, p. 72. Reproduced by permission of American Laboratory, Inc.)

available as an electrical signal, they can be readily processed by a personal computer and stored. Weighing statistics can be automatically calculated.

Electronic analytical balances can be purchased with different weighing ranges and readabilities. A macrobalance will have a range on the order of 160 g, readable to 0.1 mg, and a semimicrobalance will have a range of about 30 g, readable to 0.01 mg. Microbalances weigh to 1 μg , and ultramicrobalances are available that are sensitive to 0.1 μg or less.

Electrochemical quartz balances are available with 100- μg range that can detect 1 ng (10^{-9} g) changes! The balance utilizes a thin quartz crystal disk oscillating at, for example, 10 MHz. The frequency of oscillation changes with any change in mass, and the frequency change measured by the instrument is converted to mass units. A film of gold is evaporated on the quartz, and the gold substrate can be coated with the material of interest. Mass changes as small as a few percent of a monolayer coverage of atoms or molecules on the gold surface can be measured. Mass changes with time can be recorded.

SINGLE-PAN MECHANICAL BALANCE

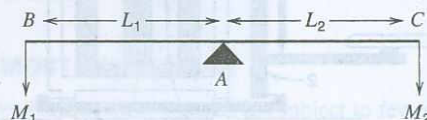
The mechanical analytical balance is a first-class lever that compares two masses. Figure 2.3 illustrates such a balance. The fulcrum A lies between the points of application of forces B and C . The term M_1 represents the unknown mass and M_2 represents a known mass. The principle of operation is based on the fact that at balance, $M_1L_1 = M_2L_2$. If L_1 and L_2 are constructed to be as nearly equal as possible, then, at balance, $M_1 = M_2$. A pointer is placed on the *beam* of the balance to indicate on a scale at the end of the pointer when a state of balance is achieved. The operator adjusts the value of M_2 until the pointer returns to its original position on the scale when the balance is unloaded. Although mass is determined, the ratio of masses is the same as the ratio of weights when an equal-arm balance is used. It is customary, then, to use the term *weight* instead of *mass* and to speak of the operator as *weighing*. The known masses are called **standard weights**.

Most analytical weighings using mechanical balances are made using a single-pan balance. A schematic diagram of a typical mechanical single-pan balance is shown in Figure 2.4 (see below for a description of modern electronic balances).

A first-class (unsymmetrical) lever is pivoted on a knife edge, and a pan is at one end in which the object is placed. However, there is no pan at the other end for placing weights. When the balance is not in use, a series of weights totaling 160 to 200 g are on the pan end of the beam. These are counterbalanced by a single weight on the other end of the beam, which also acts as part of a damping piston. When an object is placed on the pan, individual weights are *removed* from this end of the beam to restore it to equilibrium. This is accomplished by means of knobs on the front of the balance that lift weights or combinations of weights from the beam. Thus, the weights are never handled. These weights will be equal to the weight of the object on the pan.

Actually, the beam is not brought completely to balance, but weights are removed only to the nearest whole gram or 0.1 g, depending on the balance. The imbalance of the beam is registered optically and automatically on an illuminated

Fig. 2.3. Principle of analytical balance.



Mechanical balances are being replaced by electronic balances, but many are still in use (and are excellent balances), so they are described here.

Burns' Hog Weighing Method:

- 1) Get a perfectly straight plank and balance it across a sawhorse.
 - 2) Put the hog on one end of the plank.
 - 3) Pile rocks on the other end until the plank is again perfectly balanced.
 - 4) Carefully guess the weight of the rocks.
- Robert Burns

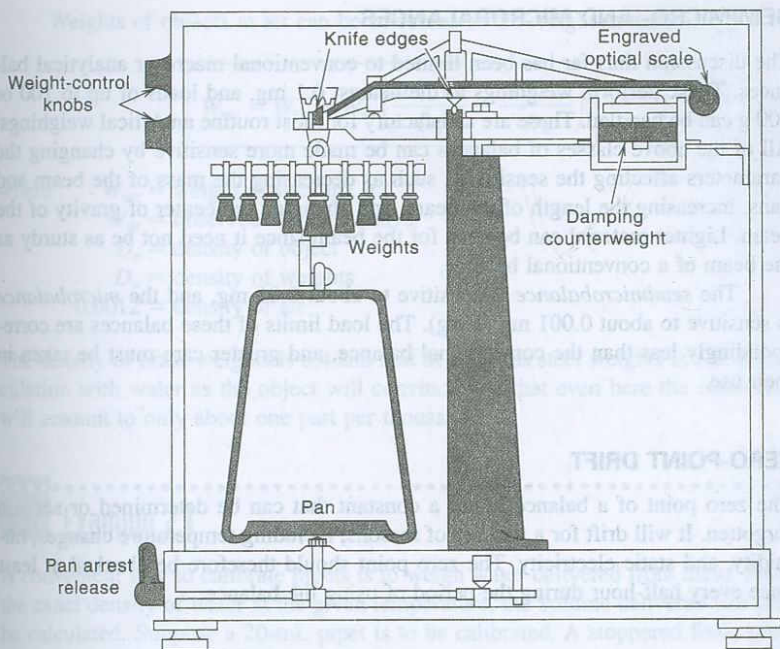


Fig. 2.4. Schematic diagram of a typical single-pan balance.

vernier scale by a light ray reflected from an engraved optical scale on the beam. The last digits (nearest 0.1 mg) are read from this scale. Alternatively, the imbalance may be read on a digital counter.

The original no-load reading or position is called the **zero point**, and the position under load is called the **rest point**. In operation, the rest point is made to coincide with the zero point. The zero point is generally adjusted to read zero by adjusting the vernier by means of a knob.

Single-pan balances are under constant load of 160 or 200 g, a required feature since they are not brought back to a state of balance. The sensitivity of a balance varies with the load because it is governed by the center of gravity of the beam; the beam bends slightly under load, causing a change in the center of gravity and the sensitivity. Calibration of the vernier or digital readout of a single-pan balance to read the amount of imbalance is done at a given sensitivity, that is, at a given load. Therefore, the load must remain constant.

All weights of a single-pan balance are concealed and are removed by means of control knobs on the front of the balance: one for tens (e.g., 10 to 90 g), one for units (1 to 9 g), and, if applicable, one for 0.1 units (0.1 to 0.9 g). The weights removed are registered on a counter on the front of the balance. The beam is brought to rest rapidly by means of an air piston damper.

Care must be taken not to damage the knife edges while the balance is not in operation and while objects are being placed or removed from the pan. A three-position beam-arrest knob is used to protect the knife edges and beam. The center position arrests the pan and beam; a second position partially releases the pan for use while finding the approximate weight of the object on the pan; and a third position completely releases the pan to allow the balance to come to rest.

A typical single-pan balance is shown in Figure 2.5. Weighings can be made in less than a minute with these balances.

Always check the zero point before making weighings.

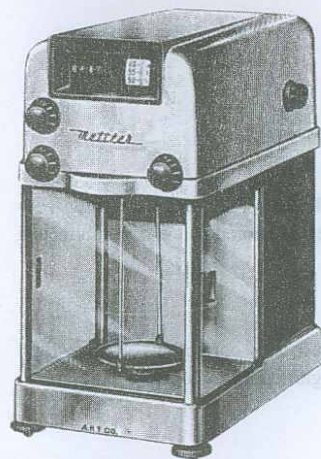


Fig. 2.5. Typical single-pan balance. (Courtesy of Arthur H. Thomas Company.)

We make most quantitative weighings to 0.1 mg.

SEMIMICRO- AND MICROBALANCES

The discussion thus far has been limited to conventional macro or analytical balances. These perform weighings to the nearest 0.1 mg, and loads of up to 100 or 200 g can be handled. These are satisfactory for most routine analytical weighings. All of the above classes of balances can be made more sensitive by changing the parameters affecting the sensitivity, such as decreasing the mass of the beam and pans, increasing the length of the beam, and changing the center of gravity of the beam. Lighter material can be used for the beam since it need not be as sturdy as the beam of a conventional balance.

The *semimicrobalance* is sensitive to about 0.01 mg, and the *microbalance* is sensitive to about 0.001 mg (1 μg). The load limits of these balances are correspondingly less than the conventional balance, and greater care must be taken in their use.

ZERO-POINT DRIFT

The zero point of a balance is not a constant that can be determined or set and forgotten. It will drift for a number of reasons, including temperature changes, humidity, and static electricity. The zero point should therefore be checked at least once every half-hour during the period of using the balance.

WEIGHT IN A VACUUM—THIS IS THE MOST ACCURATE

The weighings that are made on a balance will, of course, give the weight in air. When an object displaces its volume in air, it will be buoyed up by the weight of air displaced (**Archimedes' principle**—see the box in Chapter 1 on how analytical chemistry originated). The density of air is 0.0012 g (1.2 mg) per milliliter. If the density of the weights and the density of the object being weighed are the same, then they will be buoyed up by the same amount, and the recorded weight will be equal to the weight in a vacuum, where there is no buoyancy. If the densities are markedly different, the differences in the buoyancies will lead to a small error in the weighing: One will be buoyed up more than the other, and an unbalance will result. Such a situation arises in the weighing of very dense objects [e.g., platinum vessels (density = 21.4) or mercury (density = 13.6)] or light, bulky objects [e.g., water (density \approx 1); and in very careful work, a correction should be made for this error. For comparison, the density of weights used in balances is about 8. See Ref. 14 for air buoyancy corrections with a single-pan balance. (Reference 10 describes the calibration of the weights in a single-pan balance.)

Actually, in most cases, a correction is not necessary because the error resulting from the buoyancy will cancel out in percent composition calculations. The same error will occur in the numerator (as the concentration of a standard solution or weight of a gravimetric precipitate) and in the denominator (as the weight of the sample). Of course, all weighings must be made with the materials in the same type of container (same density) to keep the error constant.

An example where correction in vacuum is used is in the calibration of glassware. The mass of water or mercury delivered or contained by the glassware is measured. From a knowledge of the density of the liquid at the specified temperature, its volume can be calculated from the mass. Even in these cases, the buoyancy correction is only about one part per thousand. For most objects weighed, buoyancy errors can be neglected. Handbooks contain tables for converting weight of water or mercury in air to volume at different temperatures, using brass weights.

An object of 1-mL volume will be buoyed up by 1.2 mg!

The buoyancy of the weighing vessel is ignored, since it is subtracted.

Buoyancy corrections are usually significant in glassware calibration.

Weights of objects in air can be corrected to the weight in vacuum by

$$W_{\text{vac}} = W_{\text{air}} + W_{\text{air}} \left(\frac{0.0012}{D_o} - \frac{0.0012}{D_w} \right) \quad (2.1)$$

where W_{vac} = weight in vacuum, g
 W_{air} = observed weight in air, g
 D_o = density of object
 D_w = density of weights
 0.0012 = density of air

The density of brass weights is 8.4 and that of stainless steel weights is 7.8. A calculation with water as the object will convince you that even here the correction will amount to only about one part per thousand.

Example 2.1

A convenient way to calibrate pipets is to weigh water delivered from them. From the exact density of water at the given temperature, the volume delivered can then be calculated. Suppose a 20-mL pipet is to be calibrated. A stoppered flask when empty weighs 29.278 g. Water is delivered into it from the pipet, and it now weighs 49.272 g. If brass weights are used, what is the weight of water delivered, corrected to weight in vacuum?

Solution

The increase in weight is the weight of water in air:

$$49.272 - 29.278 = 19.994 \text{ g}$$

The density of water is 1.0 g/mL (to 2 significant figures from 10 to 30°C—see Table 2.4). Therefore,

$$W_{\text{vac}} = 19.994 + 19.994 \left(\frac{0.0012}{1.0} - \frac{0.0012}{8.4} \right) = 20.015 \text{ g}$$

Example 2.2

Recalculate the weight of the water delivered by the pipet in Example 2.1, using stainless steel weights at density 7.8 g/cm³.

Solution

Do not round off until the end of the calculation. Then the same value results:

$$W_{\text{vac}} = 19.994 + 19.994 \left(\frac{0.0012}{1.0} - \frac{0.0012}{7.8} \right) = 20.015 \text{ g}$$

This illustrates that the buoyancy corrections in Table 2.4 are valid for either type of weight.

The same buoyancy corrections apply for mechanical or electronic balances (which are calibrated with weights of known density).



SOURCES OF ERROR IN WEIGHING

Several possible sources of error have been mentioned, including zero-point drift, the weights, and buoyancy. Change in ambient temperature or temperature of the object being weighed is probably the biggest source of error, causing a drift in the zero or rest point due to air current convections. Hot or cold objects must be brought to ambient temperature before being weighed. Hygroscopic samples may pick up moisture, particularly high-humidity atmosphere and exposure to air prior to and during weighing must be minimized.

GENERAL RULES FOR WEIGHING

We have seen that there are several types of balances, and the operation of these will differ according to the manufacturer. The specific operation of your particular balance will be explained by your instructor. The main objectives are to (1) protect the knife edges, (2) protect all parts from dust and corrosion, (3) avoid contamination or change in load (of sample or container), and (4) avoid draft (air convection) errors. Some general rules you should familiarize yourself with before weighing with any type of analytical balance are:

1. Never handle objects to be weighed with the fingers. A piece of clean paper or tongs should be used.
2. Weigh at room temperature, and thereby avoid air convection currents.
3. Never place chemicals directly on the pan, but weigh them in a vessel (weighing bottle, weighing dish) or on powder paper. Always brush spilled chemicals off immediately with a soft brush.
4. Always close the balance case door before making the weighing. Air currents will cause the balance to be unsteady.
5. When using a mechanical balance, never place objects or weights on the pans or remove them without securing the beam arrest and the pan arrest.

WEIGHING OF SOLIDS

Solid chemical (nonmetal) materials are usually weighed and dried in a **weighing bottle**. Some of these are shown in Figure 2.6. They have standard tapered ground-glass joints, and hygroscopic samples (which take on water from the air) can be weighed with the bottle kept tightly capped. Replicate weighings are most conveniently carried out by **difference**, at least with slower mechanical balances. With electronic balances, not much time is saved. The sample in the weighing bottle is weighed, and then a portion is removed (e.g., by tapping) and quantitatively transferred to a vessel appropriate for dissolving of the sample. The weighing bottle and sample are reweighed, and from the difference in weight, the weight of sample is calculated. The next sample is removed and the weight is repeated to get its weight by difference, and so on. This is illustrated under The Laboratory Notebook for the soda ash experiment.

It is apparent that by this technique an average of only one weighing for each sample, plus one additional weighing for the first sample, is required. However, each weight represents the difference between two weighings, so that the total

Learn these rules!

Weighing by difference is required for hygroscopic samples.

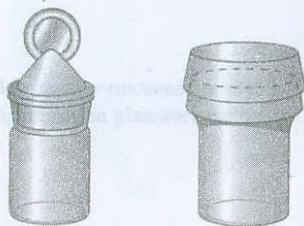


Fig. 2.6. Weighing bottles.

experimental error is given by the combined error of both weighings. Weighing by difference *with the bottle capped* must be employed if the sample is hygroscopic or cannot otherwise be exposed to the atmosphere before weighing. If there is no danger from atmospheric exposure, the bottles need not be capped.

For **direct weighing**, a **weighing dish** is used (Figure 2.7). Or, weighing paper or a plastic weighing boat is used. The dish, paper, or boat is weighed empty and then with the added sample. This requires two weighings for each sample. The weighed sample is transferred with the aid of a camel-hair brush after tapping. Direct weighing is satisfactory only if the sample is nonhygroscopic.

When making very careful weighings (e.g., to a few tenths of a milligram), you must take care not to contaminate the weighing vessel with extraneous material that may affect its weight. Special care should be taken not to get perspiration from the hands on the vessel because this can be quite significant. It is best to handle the vessel with a piece of paper. Solid samples must frequently be dried to a constant weight. Samples must always be allowed to attain the temperature of the balance room before weighing.

WEIGHING OF LIQUIDS

Weighing of liquids is usually done by direct weighing. The liquid is transferred to a weighed vessel (e.g., a weighing bottle), which is capped to prevent evaporation during weighing, and is then weighed. If a liquid sample is weighed by difference by pipetting out an aliquot from the weighing bottle, the inside of the pipet must be rinsed several times after transferring. Care should be taken not to lose any sample from the tip of the pipet during transfer.

TYPES OF WEIGHING—WHAT ACCURACY DO YOU NEED?

There are two types of weighing done in analytical chemistry, **rough** and **accurate**. Rough weighings to two or three significant figures are normally used when the amount of substance to be weighed need only be known to within a few percent. Examples are reagents to be dissolved and standardized later against a known standard, or the apportioning of reagents that are to be dried and then later weighed accurately, or simply added as is, as for adjusting solution conditions. That is, only rough weighings are needed when the weight is not involved in the computation of the analytical result. Rough weighings need not be done on analytical balances but may be completed on triple-beam, top-loading, or torsion balances.

Accurate weighings are reserved for obtaining the weight of a sample to be analyzed, the weight of the dried product in gravimetric procedures, or the weight of a dried reagent being used as a standard in a determination, all of which must generally be known to four significant figures to be used in calculating the analytical result. **These are performed only on an analytical balance, usually to the nearest 0.1 mg.** An exact predetermined amount of reagent is rarely weighed (e.g., 0.5000 g), but rather an approximate amount (about 0.5 g) is weighed accurately (e.g., to give 0.5129 g). Some chemicals are never weighed on an analytical balance. Sodium hydroxide pellets, for example, are so hygroscopic that they continually absorb moisture. The weight of a given amount of sodium hydroxide is not reproducible (and its purity is not known). To obtain a solution of known sodium hydroxide concentration, the sodium hydroxide is weighed on a rough balance and dissolved, and the solution is standardized against a standard acid solution.

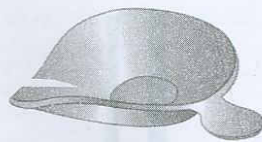


Fig. 2.7. Weighing dish.

Only some weighings have to be done on an analytical balance, those involved in the quantitative calculations.

2.4 Volumetric Glassware—Also Indispensible

Although accurate volume measurements of solutions can be avoided in gravimetric methods of analysis, they are required for almost any other type of analysis involving solutions.

VOLUMETRIC FLASKS

Volumetric flasks are used in the diluting of a sample or solution to a certain volume. They come in a variety of sizes, from 2 L or more to 1 mL. A typical flask is shown in Figure 2.8. These flasks are designed to **contain** an accurate volume at the specified temperature (20 or 25°C) when the bottom of the meniscus (the concave curvature of the upper surface of water in a column caused by capillary action—see Figure 2.14) just touches the etched “fill” line across the neck of the glass. The coefficient of expansion of glass is small, and for ambient temperature fluctuations the volume can be considered constant. These flasks are marked with “TC” to indicate “to contain.” Other, less accurate containers, such as graduated cylinders, are also marked “TC.” Many of these are directly marked on the face by the manufacturer as to the uncertainty of the container measurement; for example, a 250-mL volumetric flask is “ ± 0.24 mL,” or roughly a 0.1% error.

Initially, a small amount of diluent (usually distilled water) is added to the empty flask. Reagent chemicals should never be added directly to a dry glass surface, as glass is highly absorbent. When using a volumetric flask, a solution should be prepared stepwise. The desired reagent chemical (either solid or liquid) to be diluted is added to the flask, and then diluent is added to fill the flask about two-thirds (taking care to rinse down any reagent on the ground glass lip). It helps to swirl the solution before diluent is added to the neck of the flask to obtain most of the mixing (or dissolving in the case of a solid). Finally, diluent is added so that the bottom of the meniscus is even with the middle of the calibration mark (at eye level). If there are any droplets of water on the neck of the flask above the meniscus, take a piece of tissue and blot these out. Also, dry the ground-glass stopper joint.

The solution is finally thoroughly mixed as follows. Keeping the stopper on securely by using the thumb or palm of the hand, invert the flask and swirl or shake it *vigorously* for 5 to 10 s. Turn right side up and allow the solution to drain from the neck of the flask. Repeat at least 10 times.

Note. Should the volume of liquid go over the calibration mark, it is still possible to save the solution as follows. Paste against the neck of the flask a thin strip of paper and mark on it with a sharp pencil the position of the meniscus, avoiding parallax error. After removing the thoroughly mixed solution from the flask, fill the flask with water to the calibration mark. Then by means of a buret or small volume graduated pipet, add water to the flask until the meniscus is raised to the mark on the strip of paper. Note and record the volume so added and use it to mathematically correct the concentration calculation.

PIPETTS

The pipet is used to transfer a particular volume of solution. As such, it is often used to deliver a certain fraction (**aliquot**) of a solution. To ascertain the fraction, the original volume of solution from which the aliquot is taken must be known, but it need not all be present, so long as it has not evaporated or been diluted. There are two common types of pipets, the **volumetric**, or **transfer**, pipet and the

Volumetric flasks contain an accurate volume.



Fig. 2.8. Volumetric flask.

Volumetric pipets deliver an accurate volume.