QUALITY ASSURANCE IN THE ANALYTICAL CHEMISTRY LABORATORY

D. BRYNN HIBBERT

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This book is dedicated to my friends and colleagues on IUPAC project 2001-010-3-500, "Metrological Traceability of Chemical Measurement Results"

Paul De Bièvre, René Dybkaer, and Alěs Fajgelj

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Preface

Analytical chemistry impacts on every aspect of modern life. The food and drink we consume is tested for chemical residues and appropriate nutritional content by analytical chemists. Our health is monitored by chemical tests (e.g. cholesterol, glucose), and international trade is underpinned by measurements of what is being traded (e.g. minerals, petroleum). Courts rely more and more on forensic evidence provided by chemistry (e.g. DNA, gun-shot residues), and the war on terrorism has caused new research into detection of explosives and their components. Every chemical measurement must deliver a result that is sufficiently accurate to allow the user to make appropriate decisions; it must be fit for purpose.

The discipline of analytical chemistry is wide and catholic. It is often difficult for a food chemist to understand the purist concerns of a process control chemist in a pharmaceutical company. The former deals with a complex and variable matrix with many standard analytical methods prescribed by Codex Alimentarius, for which comparability is achieved by strict adherence to the method, and the concept of a "true" result is of passing interest. Pharmaceuticals, in contrast, have a well-defined matrix, the excipients, and a well-defined analyte (the active) at a concentration that is, in theory, already known. A 100-mg tablet of aspirin, for example, is likely to contain close to 100 mg aspirin, and the analytical methods can be set up on that premise. Some analytical methods are more stable than others, and thus the need to check calibrations is less pressing. Recovery is an issue for many analyses of environmental samples, as is speciation. Any analysis that must

be compared to a regulatory limit risks challenge if a proper measurement uncertainty has not been reported. When any measurement is scrutinized in a court of law, the analyst must be able to defend the result and show that it has been done properly.

Every chemical laboratory, working in whatever field of analysis, is aware of the need for quality assurance of its results. The impetus for this book is to bring together modern thinking on how this might be achieved. It is more than a text book that just offers recipes; in it I have tried to discuss how different actions impact on the analyst's ability to deliver a quality result. The quality manager always has a choice, and within a limited budget needs to make effective decisions. This book will help achieve that goal.

After a general introduction in which I discuss the heart of a chemical measurement and introduce commonly accepted views of quality, some basic statistical tools are briefly described in chapter 2. (My book on data analysis for analytical chemistry [Hibbert and Gooding 2005] will fill in some gaps and perhaps remind you of some of the statistics you were taught in your analytical courses.) Chapter 3 covers experimental design; this chapter is a must read if you ever have to optimize anything. In chapter 4, I present general QC tools, including control charts and other graphical help mates. Quality is often regulated by accreditation to international standards (chapter 9), which might involve participation in interlaboratory studies (chapter 5). Fundamental properties of any measurement result are measurement uncertainty (chapter 6) and metrological traceability (chapter 7). All methods must be validated, whether done in house or by a collaborative study (chapter 8). Each laboratory needs to be able to demonstrate that it can carry out a particular analysis to achieve targets for precision (i.e., it must verify the methods it uses).

There are some existing texts that cover the material in this book, but I have tried to take a holistic view of quality assurance at a level that interested and competent laboratory scientists might learn from. I am continually surprised that methods to achieve quality, whether they consist of calculating a measurement uncertainty, documenting metrological traceability, or the proper use of a certified reference material, are still the subject of intense academic debate. As such, this book runs the risk of being quickly out of date. To avoid this, I have flagged areas that are in a state of flux, and I believe the principles behind the material presented in this book will stand the test of time.

Many quality assurance managers, particularly for field laboratories, have learned their skills on the job. Very few tertiary courses exist to help quality assurance managers, but assiduous searching of the Internet, subscription to journals such as *Accreditation and Quality Assurance*, and participation in the activities of professional organizations allow analysts to build their expertise. I hope that this book will fill in some gaps for such quality assurance personnel and that it will give students and new professionals a head start.

Finally, I am not a guru. Please read this text with the same critical eye that you lend to all your professional work. I have tried to give practical advice and ways of achieving some of the more common goals of quality in analytical chemistry. I hope you will find useful recipes to follow. Have fun!

Reference

Hibbert, D B and Gooding, J J (2005), *Data Analysis for Chemistry: An Introductory Guide for Students and Laboratory Scientists* (New York: Oxford University Press).

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Acknowledgments

Some of the material for this book comes from a graduate course, "Quality assurance in chemical laboratories," that I have taught for a number of years at the University of New South Wales in Sydney. I am indebted to the many students who have given excellent feedback and hope I have distilled their communal wisdom with appropriate care. I also extend many thanks to my co-teachers, Tareq Saed Al-Deen, Jianfeng Li, and Diako Ebrahimi. Thanks also to my present PhD student Greg O'Donnell for his insights into the treatment of bias.

The community of analytical chemists in Australia is a small one. I occupy the longest established (indeed perhaps the only) chair of analytical chemistry in the country and therefore have been fortunate to participate in many aspects of the nation's analytical and metrological infrastructure. I thank my colleagues at NATA (National Association of Testing Authorities, the world's first accreditation body), particularly Maree Stuart, Regina Robertson, Alan Squirrell, John Widdowson, and Graham Roberts. Alan, sometime chair of CITAC, and Regina were very free with their advice in the early days of the course. I also thank Glenn Barry, who was working on an Australian Standard for soil analysis, for making available the soil data used to illustrate homogeneity of variance in chapter 2. Until Australia's metrological infrastructure was brought under the aegis of the National Measurement Institute (NMI), I was involved with legal metrology through my appointment as a commissioner of the National Standards Commission (NSC). I thank the last chair, Doreen Clark, for her excellent work for the

NSC and analytical chemistry and education in general. I also acknowledge the skill and professionalism of Judith Bennett, Grahame Harvey, Marian Haire, and Yen Heng, and thank them for their help in explaining the field of legal metrology to a newcomer.

The National Analytical Reference Laboratory, now part of the NMI, was set up by Bernard King and then taken forward by Laurie Bezley. I am fortunate in chairing a committee that scrutinizes pure reference materials produced by the NMI and have worked fruitfully with organic chemists Steven Westwood and Stephen Davis. Thanks, too, to Lindsey MacKay, Adam Crawley, and many colleagues at NMI.

The Royal Australian Chemical Institute has supported metrology in chemistry through its "Hitchhiker's Guide to Quality Assurance" series of seminars and workshops. These have been excellently organized by Maree Stuart and John Eames and have been well attended by the analytical community. I particularly thank John Eames for allowing me to use his approach for quality control materials in chapter 4.

My greatest thanks go to my three colleagues from the IUPAC project "Metrological Traceability of Measurement Results in Chemistry," to whom this book is dedicated. If I have learned anything about metrology in chemistry, it is from Paul De Bièvre, René Dybkaer, and Alěs Fajgelj.

I thank the editors and production staff at Oxford University Press for efficiently turning my Australian prose into text that can be understood by a wider audience.

Finally, thanks and love to my family, Marian Kernahan, Hannah Hibbert, and Edward Hibbert, for continual support and encouragement. Was it worth it? I think so.

Contents

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1

Introduction to Quality in the Analytical Chemistry Laboratory

1.1 Measurement in Chemistry

1.1.1 Defining Measurement

To understand quality of chemical measurements, one needs to understand something about measurement itself. The present edition of the *International Vocabulary of Basic and General Terms in Metrology* (ISO 1993, term 2.1)[1] defines a measurement as a "set of operations having the object of determining a value of a quantity." Quantity is defined as an "attribute of a phenomenon, body or substance that may be distinguished qualitatively and determined quantitatively" (ISO 1993, term 1.1). Typical quantities that a chemist might be interested in are mass (not weight), length, volume, concentration, amount of substance (not number of moles), current, and voltage. A curse of chemistry is that there is only one unit for amount of substance, the mole, and perhaps because "amount of substance" is verbally unwieldy and its contraction "amount" is in common nonscientific usage, the solecism "number of moles" is ubiquitous and has led to general confusion between quantities and units.

The term "measurand," which might be new to some readers, is the quantity intended to be measured, so it is correct to say of a numerical result that it is the value of the measurand. Do not confuse measurand with analyte. A test material is composed of the analyte and the matrix, and so the measurand is physically embodied in the analyte. For example, if the measurand is the

mass fraction of dioxin in a sample of pig liver, the dioxin is the analyte and the liver is the matrix. A more rigorous approach of defining a quantity in terms of, System – Component; kind of quantity, has been under discussion in clinical medicine for some time. This concept of specifying a quantity has recently been put on a sound ontological footing by Dybkaer (2004).

A measurement result typically has three components: a number and an uncertainty with appropriate units (which may be 1 and therefore conventionally omitted). For example, an amount concentration of copper might be 3.2 ± 0.4 μmol L^{-1}. Chapter 6 explains the need to qualify an uncertainty statement to describe what is meant by plus or minus (e.g., a 95% confidence interval), and the measurand must also be clearly defined, including speciation, or isomeric form. Sometimes the measurement is defined by the procedure, such as "pH 8 extractable organics."

1.1.2 The Process of Analysis

Analytical chemistry is rarely a simple one-step process. A larger whole is often subsampled, and the portion brought to the laboratory may be further divided and processed as part of the analysis. The process of measurement often compares an unknown quantity with a known quantity. In chemistry the material embodying the known quantity is often presented to the measurement instrument first, in a step called calibration. Because of the complexity of matrices, an analyst is often uncertain whether all the analyte is presented for analysis or whether the instrument correctly responds to it. The measurement of a reference material can establish the recovery or bias of a method, and this can be used to correct initial observations. Figure 1.1 is a schematic of typical steps in an analysis. Additional steps and measurements that are part of the quality control activities are not shown in this figure.

1.2 Quality in Analytical Measurements

We live in the age of quality. Quality is measured, analyzed, and discussed. The simplest product and the most trivial service come from quality-assured organizations. Conspicuously embracing quality is the standard of the age. Even university faculty are now subject to "quality audits" of their teaching. Some of these new-found enthusiasms may be more appropriate than others, but I have no doubt that proper attention to quality is vital for analytical chemistry. Analytical measurements affect every facet of our modern, first-world lives. Health, food, forensics, and general trade require measurements that often involve chemical analysis, which must be accurately conducted for informed decisions to be made. A sign of improvement in developing countries is often a nation's ability to measure important aspects of the lives of its citizens, such as cleanliness of water and food.

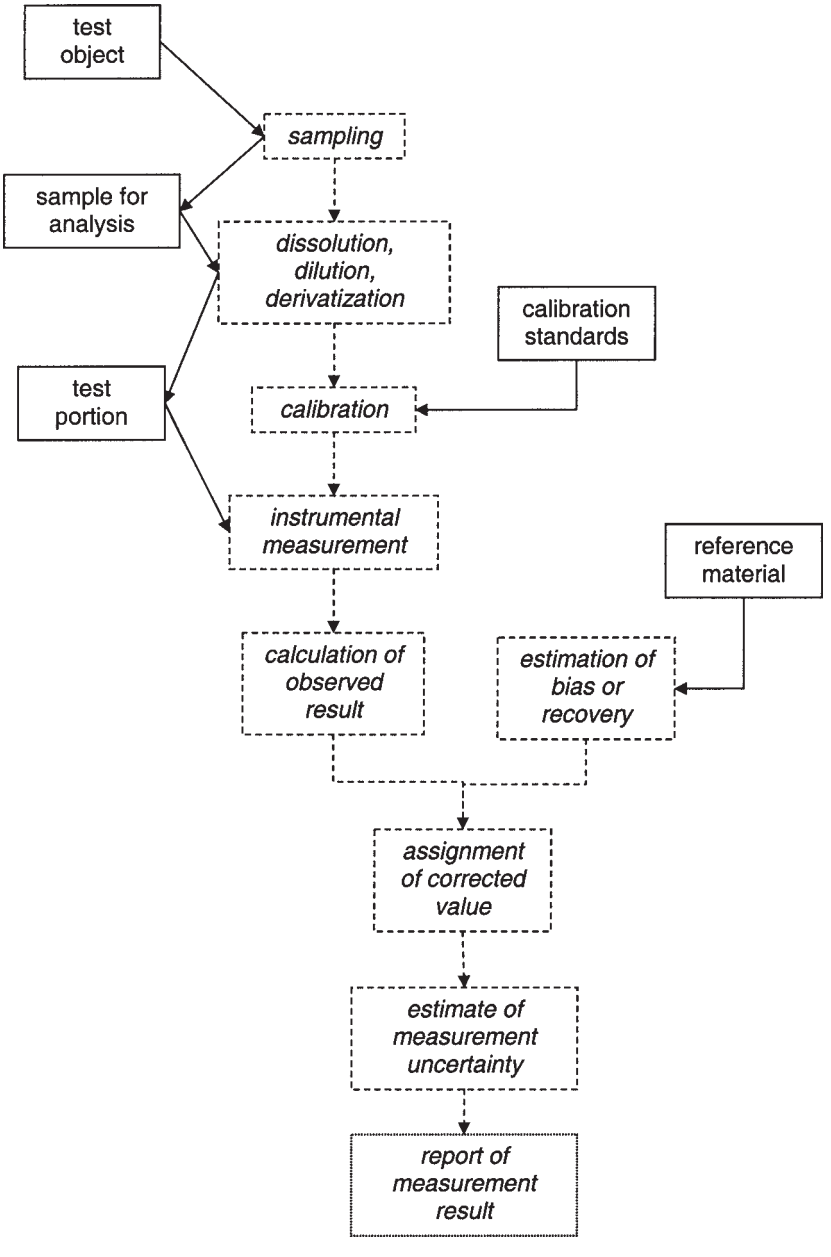

Figure 1.1. Steps and materials in an analysis. Procedures are shown in dashed boxes. Quality control materials that are presented to the analytical system are not shown.

1.2.1 The Cost of Quality

A well-known saying that can be applied to many areas of life is "if you think quality systems are expensive, look at the cost of not having them." The prevention of a single catastrophic failure in quality that might result in great loss (loss of life, loss of money through lawsuits, loss of business through loss of customer confidence) will pay for a quality system many times over. Of course, prevention of an outcome is more difficult to quantify than the outcome itself, but it can be done. Figure 1.2 is a conceptual graph that plots the cost of quality systems against the cost of failures. The cost of quality, after a setup cost, is a linear function of the activity. The more quality control (QC) samples analyzed, the more QA costs. Failures decrease dramatically with the most rudimentary quality system, and after a while the system is close to optimum performance. (This statement is made with due deference to the continuous-improvement school of total quality management.) The combination of the costs and savings gives a point at which an optimum amount of money is being spent. Remaining at the minimum failure point in the graph requires more work to reduce the point still further (and this is where total quality management [TQM] comes in). It is difficult to give an accurate graph for a real situation. The cost of the quality system can be determined, but the cost of failures is less well known. Most companies do not have the luxury of operating without a quality system simply to quantify the cost of failure.

I preface my lectures on quality assurance in the chemical laboratory by asking the rhetorical question, why bother with quality? The answer is "because it costs a lot to get it wrong." There are many examples of failures in chemical analysis that have led to great material loss, but as a first example here is a success story.

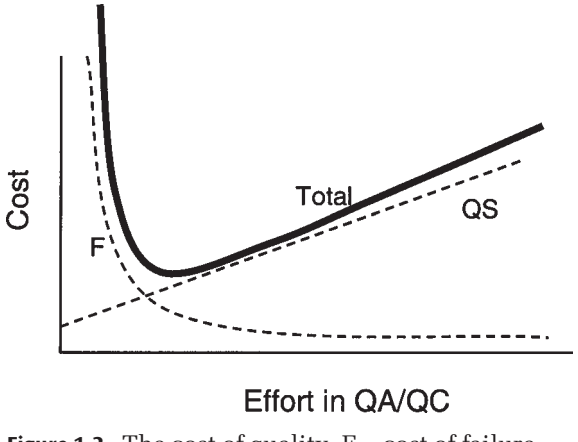

Figure 1.2. The cost of quality. F = cost of failure, QS = cost of the quality system. The minimum in the combined graph is the optimum overall cost.

The United States has been monitoring some of its common medical tests by reanalyzing samples using a more accurate method and determining levels of false positives and false negatives. In 1969 the false positive rate on cholesterol tests (concluding a patient has high cholesterol when he or she does not) was 18.5%. By 1994, when presumably modern enzyme methods were being used, the false positive rate was down to 5.5–7.2%, with concomitant savings of $100 million per year. The savings arise from not repeating doctor's visits, not prescribing unnecessary medication, and not adopting costly diets for people who, in fact, do not have a cholesterol problem.

During the same period, NIST (the National Institute of Standards and Technology, formerly the National Bureau of Standards) reported that the cost of nondiagnostic medical tests in the United States at the end of the 1990s was $36 billion, about one-third of the total cost of testing. Not all these tests are chemical, and so not all the retests would have been a result of poor quality in a laboratory, but the figure is very large (U.S. Senate 2001).

In recent years Chile has fallen foul of both the United States (because a grape crop allegedly contained cyanide; De Bievre 1993) and the European Union (because shrimp that contained cadmium below the limit of defensible detection was rejected), and each time Chile suffered losses in the millions of dollars. In a survey of users of analytical chemical results, the Laboratory of the Government Chemist (LGC) in the United Kingdom found that 29% of the respondents to a survey had suffered loss as a result of poor analytical chemistry, and 12% of these claimed "very serious" losses (King 1995).

It was stories such as these, circulating at the end of the twentieth century, that stirred the world of analytical chemistry and have caused analytical chemists to look at how a venerable profession is apparently in such strife.[2]

Even when the analysis is being performed splendidly, the limitation of any measurement due to measurement uncertainty always leads to some doubt about the result. See chapter 6 for an example of uncertainty concerning the amount of weapons-grade plutonium in the world.

1.2.2 Definitions of Quality

There is no lack of definitions of quality. Here are some general ones:

- Delivering to a customer a product or service that meets the specification agreed on with the customer, and delivering it on time
- Satisfying customer requirements
- Fitness for purpose
- Getting it right the first time.

The International Organization for Standardization (ISO) definitions of quality are:

- The totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs (ISO 1994)

- Degree to which a set of inherent characteristics fulfils requirements (ISO 2005), where "characteristics" are *distinguishing features*, and "requirements" are *need or expectation that is stated, generally implied, or obligatory*.

Clearly, quality is all about satisfying a customer. Herein lies the first problem of an analytical chemist. When a customer buys a toaster, his or her needs are satisfied if the appliance does indeed toast bread to a reasonable degree, in a reasonable time, and if the toaster does not cause a fire that burns down the kitchen. Many analytical measurements, whether they are made after a visit to the doctor or before a food product is sold, are done without the explicit knowledge or understanding of the consumer. Occasionally, perhaps after a misdiagnosis based on a laboratory analysis, a failure of quality might become apparent, but for the most part results are taken largely on trust. There is often a "middle man," a government department or medical personnel, who is better placed to assess the results, and this is how the public learns of the general concerns over quality. Knowing the requirements of the customer does allow some of the quality parameters to be set. The method must work within a certain concentration range and with a particular limit of detection; the measurement uncertainty must be appropriate to the end user's needs; and the cost and time of delivery of the results must be acceptable.

The assessment of the quality of a result must be drawn from a number of observations of the laboratory, the personnel, the methods used, the nature of the result, and so on. The great leap forward in understanding quality came in the twentieth century when people such as Deming, Shewhart, Ishikawa, and Taguchi formulated principles based on the premise that the quality of a product cannot be controlled until something is measured (Deming 1982; Ishikawa 1985; Roy 2001; Shewhart 1931). Once measurement data are available, statistics can be applied and decisions made concerning the future.

1.2.2.1 Quality Systems, Quality Control, and Quality Assurance

The Association of Official Analytical Chemists (AOAC, now AOAC International), uses the following definitions (AOAC International 2006):

Quality management system: Management system to direct and control an organization with regard to quality (AOAC International 2006, term 31)

Quality control: Part of quality management focused on fulfilling quality requirements (AOAC International 2006, term 29)

Quality assurance: Part of quality management focused on providing confidence that quality requirements will be fulfilled (AOAC International 2006, term 28).

A quality system is the overarching, enterprise-level operation concerned with quality. The day-to-day activities designed to monitor the process are the business of quality control (QC), while the oversight of the QC activities belongs to the quality assurance (QA) manager. Some definitions discuss quality in terms of planned activities. Noticing quality, or more likely the lack of it, is not a chance occurrence. Vigilant employees are to be treasured, but a proper quality system has been carefully thought out before a sample is analyzed and entails more than depending on conscientious employees. The way the activities of a quality system might be seen in terms of a measurement in an analytical chemistry laboratory is shown in figure 1.3.

1.2.2.2 Qualimetrics

In recent years the term "qualimetrics" has been coined to refer to the use of chemometrics for the purposes of quality control (Massart et al. 1997). It relates particularly to the use of multivariate analysis of process control measurements. Other texts on quality assurance in chemical laboratories include the latest edition of Garfield's book published by AOAC International (Garfield et al. 2000), material published through the Valid Analytical Measurement program by the LGC (Prichard 1995), and books from the Royal Society of Chemistry (Parkany 1993, 1995; Sargent and MacKay 1995). Wenclawiak et al. (2004) have edited a series of Microsoft PowerPoint presentations on aspects of quality assurance.

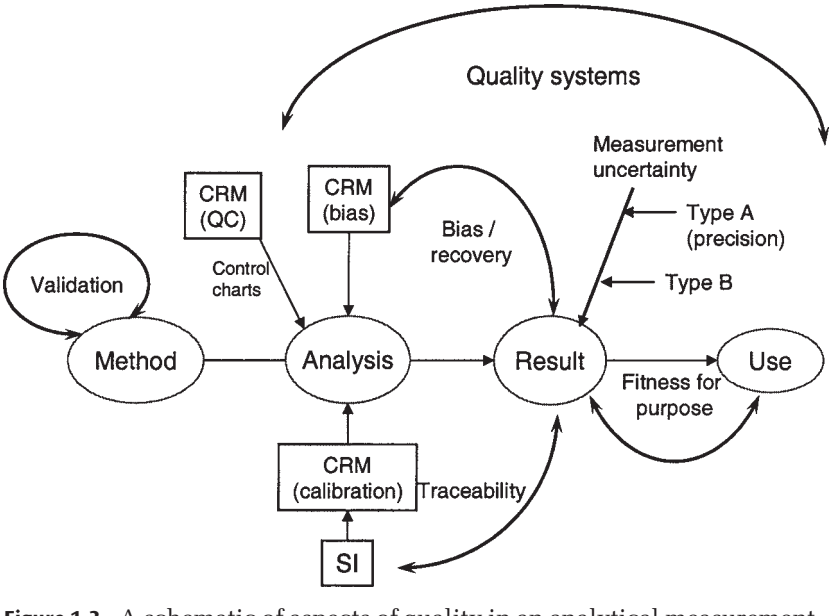

Figure 1.3. A schematic of aspects of quality in an analytical measurement.

1.2.2.3 Valid Analytical Measurement

The Valid Analytical Measurement (VAM; LGC 2005) program of the LGC (the U.K. National Measurement Institute for chemical measurements) typifies a modern approach to quality in chemical measurements. The program's six principles are a clear exposition of the important aspects of making reliable analytical measurements:

1. Analytical measurements should be made to satisfy an agreed requirement.
2. Analytical measurements should be made using methods and equipment that have been tested to ensure they are fit for purpose.
3. Staff making analytical measurements should be both qualified and competent to undertake the task.
4. There should be a regular independent assessment of the technical performance of a laboratory.
5. Analytical measurements made in one location should be consistent with those elsewhere.
6. Organizations making analytical measurements should have well-defined quality control and quality assurance procedures.

Each of these principles will arise in some guise or other in this book. For example, principle 5 relates to metrological traceability (chapter 7) and measurement uncertainty (chapter 6). These principles will be revisited in the final chapter.

1.3 The International System of Measurement

1.3.1 The Treaty of the Metre

The French revolution of 1789 gave an opportunity for the new regime under Talleyrand to lay down the basic principles of a universal measurement system. By 1799 the Metre and Kilogram of the Archives, embodiments in platinum of base units from which other units were derived, became legal standards for all measurements in France. The motto of the new metric system, as it was called, was "for all people, for all time." Unfortunately, despite initial support from England and the United States, the new system was confined to France for three quarters of a century. The Treaty of the Metre was not signed until 1875, following an international conference that established the International Bureau of Weights and Measures. Having universally agreed-upon units that would replace the plethora of medieval measures existing in Europe opened possibilities of trade that, for the first time, would allow exchange of goods (and taxes to be levied) on a standardized basis. The original 18 countries that signed the Treaty of the Metre have now become 51, including all the major trading nations, and the ISQ (international system of quantities) of which the SI is the system of units, is the only sys-

tem that can claim to be worldwide. Table 1.1 lists the base quantities and base units in the SI system, and table 1.2 lists the derived quantities and units.

1.3.2 International Metrology

The General Conference on Weights and Measures (CGPM) meets every 4 years and makes additions to, and changes in, the international system of units (SI).[3] A select group of 18 internationally recognized scientists from the treaty nations is the International Committee of Weights and Measures

Table 1.1. Base quantities and their base units in SI, as determined by the General Conference of Weights and Measures (BIPM 2005)

Quantity	Unit (symbol)	Definition of unit
mass	kilogram (kg)	The mass of the international prototype of the kilogram
length	meter (m)	The length of the path traveled by light in a vacuum in 1/299,792,458 second
time	second (s)	9,192,631,770 cycles of radiation associated with the transition between the two hyperfine levels of the ground state of the cesium-133 atom
thermodynamic temperature	kelvin (K)	1/273.16 of the thermodynamic temperature of the triple point of water
electric current	ampere (A)	The magnitude of the current that, when flowing through each of two long parallel wires of negligible cross-section and separated by 1 m in a vacuum, results in a force between the two wires of 2×10^{-7} newton per meter of length
luminous intensity	candela (cd)	The luminous intensity in a given direction of a source that emits monochromatic radiation at a frequency of 540×10^{12} hertz and that has a radiant intensity in the same direction of 1/683 watt per steradian
amount of substance	mole (mol)	The amount of substance that contains as many elementary entities as there are atoms in 0.012 kilogram of carbon-12

Table 1.2. Derived quantities and their units in the SI system

Derived quantity	Name (symbol)	Expression in terms of other SI units	Expression in terms of SI base units
plane angle	radian (rad)	1	$m\ m^{-1}$
solid angle	steradian (sr)	1	$m^2\ m^{-2}$
frequency	hertz (Hz)		s^{-1}
force	newton (N)		$m\ kg\ s^{-2}$
pressure, stress	pascal (Pa)	N/m^2	$m^{-1}\ kg\ s^{-2}$
energy, work, quantity of heat	joule (J)	N m	$m^2\ kg\ s^{-2}$
power, radiant flux	watt (W)	J/s	$m^2\ kg\ s^{-3}$
electric charge, quantity of electricity	coulomb (C)		s A
electric potential difference, electromotive force	volt (V)	W/A	$m^2\ kg\ s^{-3}\ A^{-1}$
capacitance	farad (F)	C/V	$m^{-2}\ kg^{-1}\ s^4\ A^2$
electric resistance	ohm (Ω)	V/A	$m^2\ kg\ s^{-3}\ A^{-2}$
electric conductance	siemens (S)	A/V	$m^{-2}\ kg^{-1}\ s^3\ A^2$
magnetic flux	weber (Wb)	V s	$m^2\ kg\ s^{-2}\ A^{-1}$
magnetic flux density	tesla (T)	Wb/m^2	$kg\ s^{-2}\ A^{-1}$
inductance	henry (H)	Wb/A	$m^2\ kg\ s^{-2}\ A^{-2}$
Celsius temperature	degree Celsius (°C)		K
luminous flux	lumen (lm)	cd sr	$m^2\ m^{-2}\ cd = cd$
illuminance	lux (lx)	lm/m^2	$m^2\ m^{-4}\ cd = m^{-2}\ cd$
activity (of a radionuclide)	becquerel (Bq)		s^{-1}
absorbed dose specific energy (imparted)	gray (Gy)	J/kg	$m^2\ s^{-2}$
dose equivalent	sievert (Sv)	J/kg	$m^2\ s^{-2}$
catalytic activity	katal (kat)		s^{-1} mol

(CIPM), which meets annually and oversees the work of the International Bureau of Weights and Measures (BIPM). The BIPM, based at Sevres just outside Paris, has the responsibility for international standards and is a center for international research and cooperation in metrology.[4] The CIPM has created a number of advisory specialist committees (consultative committees) that are each chaired by a member of CIPM. The committee of interest to chemists is the Consultative Committee on the Amount of Substance (CCQM). It oversees the Avogadro project and coordinates a series of international interlaboratory trials called Key Comparisons (BIPM 2003), which

are detailed in chapter 5. The hierarchy of organizations responsible for the Treaty of the Metre is shown in figure 1.4.

1.3.3 National Measurement Institutes

Many countries have established national measurement institutes to oversee their metrology systems and obligations to the Treaty of the Metre. Sometimes chemistry and other sciences are separated (as in the National Physical Laboratory and the LGC in the United Kingdom), but increasingly chemical mea-

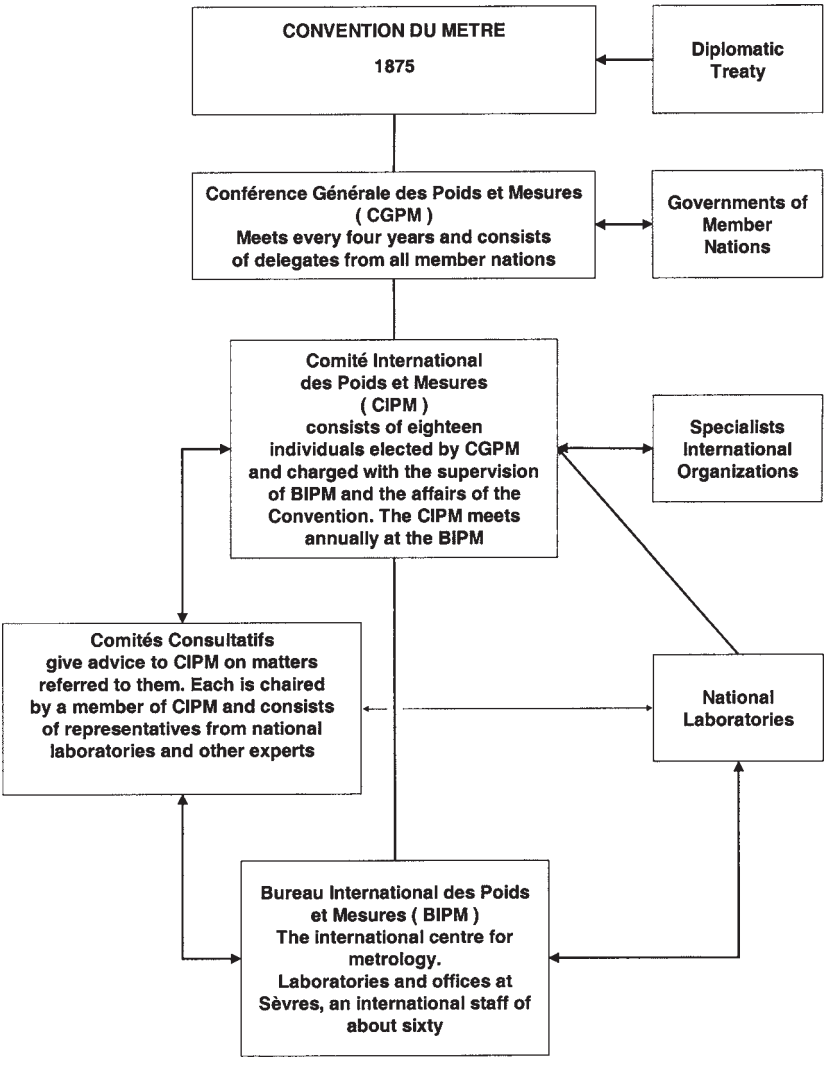

Figure 1.4. The Treaty of the Metre and its associated organizations.

surements are seen as an integral part of national metrology. Many of these national measurement institutes take part in the Key Comparisons program of the CCQM (BIPM 2003). An important role of the chemical laboratories in national measurement institutes is to demonstrate a primary measurement capability (i.e. measurements made without reference to other standards) in fields that are deemed important to the country. For example, in sports-mad Australia, the National Analytical Reference Laboratory (NARL) has become a world leader in making reference materials for sports-drugs testing. By demonstrating that these laboratories can make traceable (and therefore comparable) measurements in a wide range of important fields (e.g., trade, health, forensics), a platform for international metrology in chemistry has been set. International cooperation has been enhanced by the formation of regional groupings of national measurement institutes. A list of some national measurement institutes are given in table 1.3, and regional organizations are listed in table 1.4.

1.3.4 The SI and Metrological Traceability

Chapter 7 is devoted to metrological traceability, but for now it is important to stress the crucial role that the SI plays in traceability of measurement results. By using the unit mole, kilogram, or meter, there is an implication that the result is indeed traceable to the SI base unit. Although sometimes this might be no more than a forlorn hope, the system of calibrations using certified reference materials is designed to establish the traceability chain and its associated measurement uncertainty. Without an internationally agreed-upon anchor (the SI), measurements made around the world in local systems of units would not be comparable, even if they happened to have the same name or symbol. It is the existence of the SI and its attendant organizational structure that means that 1 kg of rice in China is equivalent to 1 kg of rice in Germany.

1.4 Quality Systems

There are many approaches to ensuring quality in an organization. The approach used will depend on the size and nature of the business, the cost of the product, the cost of failure, and the current fashion. It is not my intent to advocate one or another approach. The work of a laboratory is often dictated by accreditation requirements or the law and I offer here what a laboratory can do, not a philosophical framework for quality assurance. Nonetheless, it may be useful to know some of the acronyms and popular trends, so a discerning manager can make a decision about what is best for her or his organization. The following headings do not imply that the methods are mutually exclusive. For example, accreditation might be sought in the context of a TQM approach to quality.

Table 1.3. Some National Metrology Institutes

Country	Name of the NMI	URL
Argentina	Instituto Nacional de Tecnología Industrial	http://www.inti.gov.ar/
Australia	National Measurement Institute (NMI)	http://measurement.gov.au/
Austria	Bundesamt für Eich- und Vermessungswesen (BEV)	http://www.bev.gv.at/
Belgium	Service de la Métrologie (SMD)	http://mineco.fgov.be/metrology.en
Brazil	The National Institute of Metrology, Standardization and Industrial Quality (InMetro)	http://www.inmetro.gov.br/
Canada	Institute for National Measurement Standards (INMS)	http://inms-ienm.nrc-cnrc.gc.ca
Chile	Instituto Nacional de Normalización	http://www.inn.cl/
China	National Institute of Metrology (NIM)	http://en.nim.ac.cn/
Denmark	Danish Safety Technology Authority (SIK)	http://www.danak.dk/
European Commission	Joint Research Centre (JRC)	http://ies.jrc.cec.eu.int/ http://www.irmm.jrc.be/
France	Laboratoire national de métrologie et dessais (LNE)	http://www.lne.fr/
Germany	Federal Institute for Materials Research and Testing (BAM)	http://www.bam.de/ or http://www.ptb.de/
India	National Physical Laboratory	http://www.nplindia.org/
Italy	Consiglio Nazionale delle Ricerche (CNR)	http://www.enea.it/; http://www.ien.it/; or http://www.imgc.cnr.it/
Japan	National Metrology Institute of Japan (NMIJ/AIST)	http://www.aist.go.jp/
Korea	Korea Research Institute of Standards and Science (KRISS)	http://www.kriss.re.kr/
Mexico	Centro Nacional de Metrologia	http://www.cenam.mx/
Netherlands	Netherlands Metrology Service	http://www.nmi.nl/

(*continued*)

Table 1.3. (*continued*)

Country	Name of the NMI	URL
New Zealand	Measurement Standards Laboratory, Industrial Research	http://www.irl.cri.nz/msl/
Pakistan	National Physical & Standards Laboratory	http://www.pakistan.gov.pk/divisions
Russia	Federal Agency on Technical Regulation and Metrology of Russian Federation (Rostechregulirovanie)	http://www.gost.ru
Singapore	Standards, Productivity and Innovation Board (SPRING Singapore)	http://www.psb.gov.sg/
South Africa	CSIR–National Metrology Laboratory	http://www.nml.csir.co.za/
Spain	Spanish Centre of Metrology (CEM)	http://www.cem.es/
Sweden	Swedish National Testing and Research Institute (SP)	http://www.sp.se/ http://www.ssi.se/
Switzerland	Swiss Federal Office of Metrology and Accreditation (METAS)	http://www.metas.ch/
United Kingdom	Laboratory of the Government Chemist (LGC)	http://www.lgc.co.uk/
United States	National Institute for Standards and Technology	http://www.nist.gov/
Venezuela	Servicio Autónomo de Normalización, Calidad y Metrología (SENCAMER)	http://www.sencamer.gov.ve/

A current comprehensive list of metrology laboratories is given on the NIST web site at http://www.nist.gov/oiaa/national.htm

Table 1.4. Regional groupings of metrology institutes

Organization	URL
The Asia Pacific Metrology Programme (APMP)	http://www.apmpweb.org/
Euro-Asian Cooperation of National Metrological Institutions (COOMET)	http://www.coomet.org/
European Collaboration in Measurement Standards (EUROMET)	http://www.euromet.org/
The Inter-American Metrology System (SIM)	http://www.sim-metrologia.org.br/
South African Development Community Cooperation in Measurement Traceability (SADCMET)	http://www.sadcmet.org/

1.4.1 Accreditation

Chapter 9 is about accreditation to Good Laboratory Practice (GLP; OECD 1998) and ISO/IEC17025 (ISO/IEC 2005), but I discuss here what accreditation actually accredits and its place in the wider scheme of quality systems. There has been much debate, particularly in the pages of the journal *Accreditation and Quality Assurance*, about whether accreditation implies accuracy of measurement results or whether this is an accidental consequence. Certainly the laws of some countries are now specifying that laboratories making particular legal measurements must be accredited to ISO/IEC17025, and accreditation to GLP is a requirement for laboratories around the world that want their results on the stability and toxicity of new drugs to be considered by the U.S. National Institutes of Health. To be accredited to ISO/IEC17025 means that the laboratory's procedures and personnel have been critically reviewed, and that as well as meeting the management quality requirements of the ISO 9000 series, the laboratory methods and practices also meet an ISO standard. Maintenance of accreditation might also require participation in interlaboratory trials (proficiency testing, see chapter 5), which can be a direct demonstration of competence. However, because an inspection that focuses on standard operating procedures and "paper" qualifications of staff can always be open to a certain amount of exaggeration and manipulation, coupled with the accreditation body's desire to give accreditation rather than deny it, accreditation should be seen as a necessary but not sufficient condition for quality. At least in recent years accreditation organizations have an ISO standard (ISO/IEC 2004) to which they, too, must be accredited—"Sed quis custodiet ipsos Custodes," indeed.[5]

1.4.2 Peer Review and Visitors

Peer review, initiated by the accreditation body, is the most common method of determining suitability for accreditation. "Peer review" in this case re-

fers to an organization using outsiders as part of its quality system. Popular in academia and government circles, the invitation of selected professionals to investigate an organization has become one means of reviewing overall quality. A review committee is set up with outside participation, and members are asked to address certain issues and questions concerning the organization. Peer review of laboratories is less an ongoing process as it is a one-time procedure directed to a specific issue (accreditation) or problem. If initiated by senior management, peer review is often seen as a prelude to some kind of shake-up in the organization, personnel are typically nervous about the outcome. A properly independent panel can, with a little intelligent probing, can uncover some of the most seemingly intractable problems of a laboratory, and with sensitivity recommend changes that are in the best interests of the institution. The usefulness of peer review rests on the people chosen to make the visit and the willingness and ability of the organization to implement their suggestions. Questions must be addressed such as, do they have the right mix of expertise? Have they been given enough time to complete their tasks? Do they have the authority to see everything they deem relevant? Will the management take any notice of their report?

1.4.3 Benchmarking

Benchmarking is like peer review from the inside. In benchmarking an organization goes outside to other organizations that are recognized as leaders in the sector and compares what is being done in the best-practice laboratory with their own efforts. First, the field must have developed enough to have agreed-upon best practices. At universities, for example, the sheer number of chemistry departments means that an institution can readily be found that can act as an exemplar for the procedures. The exemplar may not necessarily be the department that is academically the best. Having many Nobel Laureates that are funded by generous alumni donations may be the dream of every university, but it may be better to benchmark against a midstream university that is of about the same size and funding base. Another consideration is whether the targeted institution will agree to share the secrets of its success, especially if it is seen as a rival for clients, funds, or students. Finally, benchmarking can be very selective. No organizations are the same, and what works well for one might not be the best for another. Management needs to be realistic in the choice of what facets of a benchmarking exercise can be usefully applied in their own business.

1.4.4 Total Quality Management

Total quality management became popular in the 1990s, after decades of a move toward taking quality control from the factory floor operator to a management-centered operation (total quality control of Ishikawa in 1950–1960 [Ishikawa 1985, page 215]) to the holistic approach enshrined in stan-