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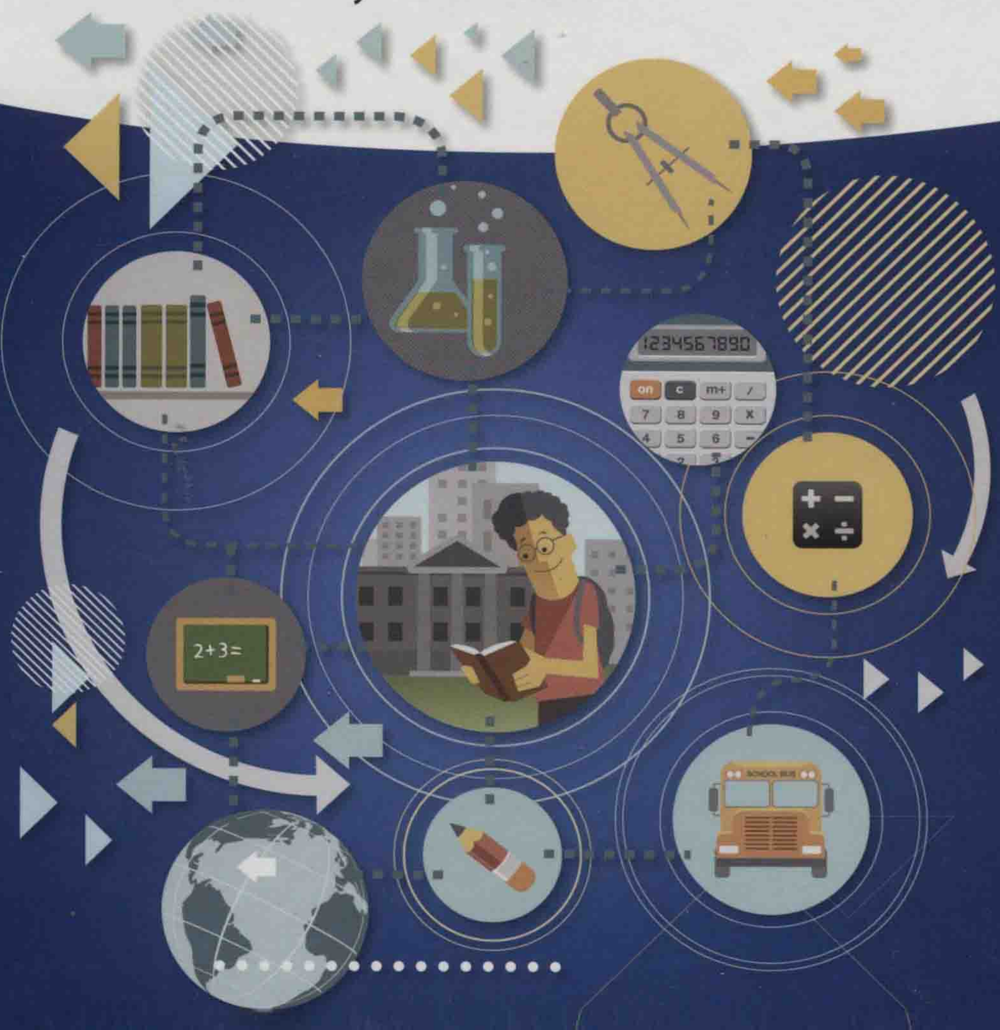
Chemistry Education

Best Practices, Opportunities and Trends

With a Foreword by Peter Atkins



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Foreword

What is it about chemistry? Why do so many students, having tasted it in high school, turn away from it with distaste and remember only the horror of their experience? Why, on the other hand, are other students immediately hooked on it and want it to lie at the core of their studies and subsequent careers? The issue is plainly important, for chemistry touches us all, like it or not, and everyone's role in and interaction with society depends on at least an appreciation of what chemists and the chemical industry achieve, especially in the light of dangers to the environment that it presents and the extraordinary positive contribution it makes to everyday and ever-longer life. Moreover, those who turn their back on chemistry are closing their minds to its cultural contribution to understanding the nature of the world around them. Motivation is plainly important, and there is plenty of it lying around, as the contributors emphasize: their message is that if you seek motivation, then look around, for chemistry deepens our understanding of the natural world, be it through our natural environment or the artifacts of the industry. Once motivated, there is an obligation, as the authors rightly argue, for that enthusiasm to be encouraged throughout life, not merely at the incubators of school and college.

Why does chemical education play such a pivotal role? I think the essence of the difficulty of learning chemistry is the combination of the perceived abstraction of its concepts and the fact that (unlike so often in physics) there is such a tension between possible explanations that judgment is needed to arrive at the true explanation. The abstraction, of course, is perceived rather than real. We educated chemists *all* know that atoms and molecules are real, and we are confident about our reasoning about energy and entropy; however, the neophyte has no such confidence and needs to come to terms with the reality of the infrastructure of our explanations. A part of this volume is the exploration of how to convey our concepts in an accessible way, in part planting but also dispelling misconception, perhaps by using that powerful entry into the brain, visualization. Furthermore, there is the question of judgment: chemistry is, in fact, a multidimensional tug-of-war, with rival influences in perplexing competition. Is it ionization energy that should be dominant in an explanation or is it some other aspect of structure or bulk matter? How can the starting student learn to judge what is dominant and retain self-confidence?

Pervading these problems is the perennial problem of problem-solving. How can this most inductive of activities be ingrained into the thinking of our students? I frankly do not know; however, the authors struggle here with the challenge. It probably comes down to ceaseless demonstration of how we practitioners of chemistry practice our profession: a ceaseless Confucian exposure to the actions of masters in the hope that skill will emerge through observation and emulation. We see a little of what is involved in this text; however, it is central to education, and perhaps there should have been more of it. Volume 2, should it ever emerge, might take up that theme and explore another omission, the role of mathematics in science in a universe where confident deployment is in decline in many countries and is a source of worry to us all. Mathematics adds spine to otherwise jelly-like qualitative musings, enabling them to stand up to quantitative exploration and is absolutely central to the maintenance of chemistry as a part of the physical sciences. How can students be led from the qualitative into the quantitative, and how can they distil the meaning of, not merely derive, an equation? There is little of that here; however, it is crucial to the future of our subject and is related to the formulation of solutions to problems.

In short, the concepts of chemistry at first sight are abstract, its arguments intricate, its formulation sometimes mathematical, and its applications spanning widely between the horizons of physics and biology. This perfect storm of aspects can be overwhelming and, unless handled with the utmost care and professional judgment, results in confusion and disaffection. The responsibility of educators is to calm this storm.

The improvement of chemical education, to ensure not only a progression of specialists but also an appreciation of its content, role, and attitude among that most elusive but vital entity, the general public, is of paramount importance in the modern world. Collected in this volume are contributions from many notable thinkers and writers who have devoted their intellectual life to seeking ways to advance society by improving chemical education at all levels. Thus, they need to confront the identification of the central concepts of chemistry and how they can be rendered familiar and concrete. How do the ways that chemists think become deconstructed, then repackaged for transmission? How should the central importance of mathematics be illustrated, and how does quantitative reasoning get conveyed convincingly and attractively? How should the intricacies of applications be presented such that they do not overwhelm the simplicities of the underlying ideas? In all these considerations, where does the balance lie between the education of a specialist and the well-informed member of general society?

It is also not as though there is a shortage of ideas about how to proceed. This timely volume displays the current vigor of research into chemical education and the range of approaches being explored to carry out this most valuable and important of tasks. Should social conscience be deployed to motivate, as in concern for the environment, or should motivation be sought it an appreciation of the material fruits of chemistry? As an academic and probably out-of-touch purist, I wonder whether elaborately contrived motivation is helpful, believing that an emerging sunrise of intellectual love of understanding should be motivation enough. Should classrooms be inverted, as some authors argue, to generate more involvement in the process of learning, or should downward projection authority-to-student succeed more effectively in the transmission of learning? These matters are discussed here by those who have explored their efficacy in practice. I suppose the issue is whether learning can be democratized, with instructor and student as equal partners, or whether a touch of the whip of authority is advantageous.

The authors of this collection of essays are sensitive to the problems of introducing the young to the special language of chemistry. Common sense is all very well; however, a great deal of science is concerned with looking under everyday perceptions of the world and identifying their infrastructure, which at first sight sometimes seems to run against common sense and opens the door to misconception. Science, in fact, deepens common sense. The central point, apart from the precision that comes from careful definition, is to show how a new language is needed when entering any new country, in this case a country of the intellect.

With the language in place, or at least emerging, it is necessary to turn to a consideration of what is in effect its syntax: the stringing together of concepts and techniques to solve problems. Problem-solving is perhaps the most troublesome aspect of chemical education, being largely inductive, and a huge amount of attention is rightly directed at its techniques, including the roles of instructors and peers.

Crucial to this endeavor is the demonstration that the concepts and calculations of chemistry relate to actual physical phenomena (or should) and that experiment and observation, not ungrounded algebra, lie at the heart of science. The contributions acknowledge this core feature of science, and although microscale experiments, which are discussed here, are not to everyone's taste, they are far better than unsupported printed assertion and unadorned abstraction.

Many of the problems of chemical education have been around for decades, perhaps a century or more, ever since chemistry became a rational subject and numbers were attached to matter. New problems and concomitantly extraordinary opportunities are now emerging as new technologies move to an educator's reach. The later sections of this book are like the emergence of mammals in the world of dinosaurs (I do not intend to be in the least disrespectful to my wonderful colleagues, but merely to draw an analogy!): new technologies are the future, possible savior, and, undoubtedly, enhancer of chemical education. They do not simply enhance our present procedures; they have the potential to be transformative in the same way that plastics have replaced wood.

Almost by definition, "new technologies" are in their infancy, with even the far-sighted seeing only dimly the extraordinary opportunities that they will bring to chemical education. However, the crucial point is that those opportunities must not run wild: they must build on the extraordinary insights and expertise of the extant practitioners of chemical education, developing securely on a strong foundation. This collection of chapters contributes substantially to that strong foundation and will provide inspiration and insight for old-timers and newcomers alike.

For me, the most exciting chapter of this collection is the one that peers into the future to explore the consequences of the ubiquity of devices that tap into that store of universal knowledge we know as the Internet. We are all currently groping to find ways to employ this extraordinary resource, currently standing on the shore of the ocean of opportunity that it represents, still unaware of what lies over the horizon. It is already influencing publishing and the dissemination of knowledge, and it is facilitating the involvement of the entire academic community in corporate activity, transforming the attitude to personally stored information as distinct from publicly available data, affecting the deployment of information, and encouraging interpersonal accessibility and cooperation. The future of chemical education lies here, and this volume provides a glimpse of what it might bring.

I am not a chemical educator in the professional sense of the term; however, I am deeply involved in the deployment of its activities. As such, I welcome a volume that brings together in a single source so many different, multiple facets of this intricate and rewarding exercise. The authors and their editors should be congratulated on the timeliness of this publication, acting as a pivot between good practice in the present and opportunity in the future.

Peter Atkins
University of Oxford

Preface

The Science of Teaching and Learning Chemistry

The world we live is increasingly complex and interconnected; a world where an event in a corner of a remote country can rapidly grow and affect millions of people in places thousands of kilometers away. Both globalization and technology provide us with great opportunities and also with enormous challenges. Our planet is becoming increasingly crowded and interdependent. From climate change to access to water and from food security to new pandemics, the number of global challenges and their implications on our future is truly daunting.

But as US President John F. Kennedy said in 1963: "Our problems are man-made; therefore they may be solved by man." Many solutions, from new vaccines to cleaner ways to produce energy, will only be made possible by the right science and technology. As in the past, mankind has overcome its problems through science: terrible illnesses and poor living conditions have been overcome through the ingenuity and hard work of great men and women. From the artificial synthesis of ammonia, which allowed the green revolution, to the discovery of antibiotics, the breakthroughs of a few have improved the lives of many.

But with all that science has achieved to date, technological advances alone are insufficient to continue to address mankind's challenges. The *human* drive for improvement, the attitude, the willingness to contribute, and the desire to help solve problems is at least as important as having the right tools. Therefore, investment in education is also an essential component of any attempt to build a better and more sustainable future, as education interconnects the human desire to help with the science that creates solutions. Science and education are two of the most common elements discussed when talking about how to build a better future. Part of this "investment" is exactly allocating enough resources to make sure that long-term objectives are possible. Financial investment is not enough; we need to be able to teach science in the most effective way to create a new generation of scientists who are able to find the solutions to our global challenges and then take those solutions from the laboratory to the market place.

Both the teaching and learning of science in general – and chemistry in particular – are not easy tasks. Each requires hard work, dedication, and practice. There is definitely a component of "art" (one could even say craftsmanship) in effectively communicating complex chemistry concepts, many related to the molecular world. But there is much more science in chemistry education than many teachers and students appreciate. Years of research in chemistry education have provided clear and well-established results in terms of best practices, common mistakes, and which tools are most effective.

Despite the decades of research on chemistry education, the authors of this book were moved by how little the broad chemistry community knows about the results of this work. We felt it was about time to invite some of the world's leading experts to contribute an original piece to a compendium of the most effective ways to teach and learn chemistry. Obviously, no single person could write such a book. This book is therefore a diverse, sometimes controversial, but always interesting collection of chapters written by leading experts in chemistry education.

Learning and teaching chemistry is far from an exact science, but there are plenty of lessons to take from the research done so far. In fact, it is quite surprising how little has changed the way chemistry is taught in the last century despite all the recent advances in chemistry and the numerous possibilities that information technologies offer. A typical vision of a general chemistry course will still be an image of a large classroom packed with students who passively listen to a single person.

Some of the most interesting research in chemistry education deals with the way we learn: how we grasp new concepts and connect the macro with the micro world. The three traditional thinking levels of chemistry: macroscopic, molecular, and symbolic, all require a different way to communicate, visualize, and comprehend new concepts. Another critically important topic in chemistry education is the role of misconceptions. Every student enters the classroom with his or her own bag of ideas about "how the world works." Many of these come from the way previous teachers have taught them key concepts. Other preconceptions come from students' personal interpretations of their experience. Identifying these misconceptions and knowing how to challenge them is critically important, but rarely done in a chemistry course.

In addition to all the opportunities that the years of research conducted on how to efficiently teach and learn chemistry offer to the those interested in chemistry education, technology itself is also bringing a whole set of opportunities (and of course challenges) to both educators and learners. The easy and immediate access to chemistry courses through different Internet-based platforms is radically changing the way our students study, expand their own interests, and interact with their teachers and peers.

And of course, in addition to all of this, the more fundamental fact remains that every single student is a different person. Although there are many things we can do to improve the way chemistry is taught, there are no silver bullets. Our students are evolving individuals, with their own personalities, interests, and challenges.

This book consists of 28 chapters grouped into three parts: *Chemistry Education: A Global Endeavor*, *Best Practices and Innovative Strategies,* and *The Role of the New Technologies.*

The first part, covering Chapters 1 – 6, provides a broad introduction to the book and touches on critically important aspects of chemistry education. The opening chapter introduces the reader to the scope and the context of the book. In this chapter, Prof. Peter Mahaffy of the King's University College provides an excellent analysis of the connection between human activity and education in general, and then in chemistry in particular. Prof. Mahaffy asserts that the difference between "Chemical Education" and "Chemistry Education" is human activity. The tetrahedral chemistry education metaphor, an extension of the triangle of thinking levels that includes the focus on human activity in their three dimensions in learning and teaching chemistry, is nicely reviewed to give some keys to overcome the barriers to change from "Chemical" to "Chemistry" education.

Chapter 2, by Prof. Cathy Middlecamp of the University of Wisconsin-Madison, is focused on the connection between chemistry education and "the real world" as a high-level thinking skill. As pointed out by the author, "if we can better see the connections, we have set the stage for transforming the way we think. In turn, we can better recognize and meet our responsibilities." Further on, the connection between chemistry curriculum and the content of chemistry news is addressed by Prof. Mei-Hung Chiu and Prof. Chin-Cheng Chou in Chapter 3, where a deep analysis of the need to bridge formal school chemistry with chemistry in everyday life is carried out.

In Chapter 4, Prof. Goedhart of the University of Groningen sketches how curricula in universities transformed as a result of a changing environment and the effectiveness of the new pedagogical approaches, based on the combination of pedagogical ideas and the use of authentic learning environments on the teaching and learning of chemistry. Finally, a new division of chemistry from a competency-based perspective, which can be used as the basis for the structure of a new curriculum, is proposed.

Chapters 5 and 6 are written based on the idea that chemistry teachers need to develop their professional knowledge and practice throughout their entire career, a field closely related to the main focus of this book. Chapter 5, by Prof. Jan H. van Driel of the University of Leiden and Prof. Onno de Jong of Utrecht University, focuses on empowering chemistry teachers' professional learning, identifying successful approaches to promote chemistry teacher learning and the specific areas that present challenges to chemistry teachers. In particular, the authors address context-based teaching, teaching about models and modeling, and the use of computer-based technologies. Chapter 6, by Prof. John K. Gilbert of King's College London and Dr. Ana Sofia Afonso of the University of Minho, discusses the need for increased efforts to both revise the school chemistry curriculum, so that more students are encouraged to persist in the study of the subject, and make the ideas of chemistry more readily available and appealing to adults.

The second part of the book (Chapters 7–22) deals with the most innovative practices and strategies derived from years of research in chemistry education for efficacious learning and teaching of chemistry at different levels. Chapter 7, by Prof. Renée Cole of the University of Iowa, gives an excellent survey of the general field and a comprehensive introduction of teaching strategies and the design of instructional materials (research-based materials) developed so far to improve chemistry education. In Chapter 8, Prof. George M. Bodner of Purdue University focuses on problem solving in chemistry, describing the model developed by the author's research group and their more than 30 years of research in this content domain. Chapter 9, by Prof. Brian P. Coppola of the University of Michigan, deals with the design of real work for a successful learning of chemistry based on a six-part framework of tenets: (i) use of authentic texts; (ii) a balance of team and individual work; (iii) peer presentation, review, and critique; (iv) student-generated instructional material; (v) a balance of convergent and divergent tasks against the traditional homework; and (vi) as important to the class as the teacher's work.

Active learning pedagogies such as the so-called context-based learning (CBL), problem-based learning (PBL), and inquiry-based student-centered instruction are carefully reviewed in Chapters 10–12, respectively. Chapter 10, by Prof. Ilka Parchman of the University of Kiel *et al.*, focuses on CBL pedagogy. As pointed out by the authors, chemistry seems to be an interesting and encouraging area for some students, while others do not see relevance for it to their own life and interests. The CBL pedagogy aims to overcome this challenge by not only linking chemistry to applications that often refer to daily life or societal issues but also linking chemistry to modern research and development. In a similar way, in Chapter 11 Prof. Judith C. Pöe of the University of Toronto Mississauga carefully reviews the use of PBL, a process by which the content and methods of a discipline are learned in an environment in which they are to be used to address a real-world problem, on the learning and teaching of chemistry. In Chapter 12, Prof. Ram S. Lamba of Carlos Albizu University describes the most recent advances in student-centered inquiry-based instruction, giving guidance to instructors on how to interact with students during instruction, how to design activities for classroom use and what to emphasize, as the goal of instruction is to enable students to think like scientists do. These active learning pedagogies, all of them recommended to reach beyond the front rows of our classes, allow the students to develop an enhanced sense of responsibility for their learning and for the applications of their learning, a key point in global learning communities. The implementation of an efficacious flipped classroom as a model based on a student-centered learning environment, and the use of those and the related active learning pedagogies as a part of the flipped-class process, is then discussed in Chapter 13 by Dr. Julie Shell and Prof. Eric Mazur of Harvard University.

A critical review of developments in community-based learning and community-based research in chemistry education at second and third levels is provided in Chapter 14 by Prof. Claire McDonnell of Dublin Institute of Technology.

Chapter 15, by Prof. Keith S. Taber of the University of Cambridge, is aimed to highlight the importance of the notion of conceptual integration in teaching and learning chemistry from two perspectives: (i) the theory of learning (the linking of concepts within current understanding is considered to facilitate further learning and later accessing of that learning); (ii) the nature of science (NOS) – increasingly considered a central curricular aim – for helping students to relate ideas about the submicroscopic realm of molecules, ions, and electrons to the macroscopic description of the subject. Related to conceptual integration, Chapter 16, by Prof.

Hans-Dieter Barke of the University of Münster, is centered on the most representative student's preconcepts and student's misconceptions related to chemistry, giving some instructions on how to prevent it and to overcome them during the teaching of chemistry at different levels. In a broader way, Chapter 17, by Prof. Peter E. Childs *et al.* of the University of Limerick, looks at the role of language in the teaching and learning of chemistry, focusing not only on the typical problems related to terminology and symbols but also on other language-related problems such as the use of nontechnical terms in chemistry which have a different meaning to their use in everyday discourse, for example, to students that are non-native speakers, suggesting some teaching strategies to reduce the barrier and facilitate a novice's mastery of chemical language.

Chapter 18, by Prof. Robert Bucat of the University of Western Australia, deals with the use of the cognitive conflict strategy in classroom chemistry demonstrations. This chapter, oriented to secondary school teachers and university lecturers, concerns the use of discrepant events to induce cognitive conflict in students' understanding of chemistry, with references to particular experiences and some theoretical references, and consideration of the conditions under which they may (or may not) be effective.

Chapter 19, by Prof. Manabu Sumida and Dr. Atsushi Ohashi of Ehime University, outlines the characteristics of gifted learners in science, focusing on identification, curriculum development, and the implementation of gifted education in chemistry from diverse contexts. In this chapter, Prof. Manabu Sumida also illustrates how giftedness in chemistry is required in the new century by analyzing the world trends of Nobel Laureates in chemistry from 1901 to 2012. According to *The New York Times* (December 15, 2013), "even gifted students can't keep up, in math and science, the best fend for themselves. The nation (US) has to enlarge its pool of the best and brightest science and math students and encourage them to pursue careers that will keep the country competitive."

Chapter 20, by Prof. Jens Josephsen and Prof. Søren Hvidt of Roskilde University, discusses the outcomes of the use of different types and aims of experimental work in chemistry education, including the project-based learning pedagogy as an effective tool for students' experience with scientific inquiry processes and obtains practical laboratory skills, experimental experience, and other skills needed by an experimental chemist. In the same vein, research-based evidence showing that high-order learning skills can be developed by involving the students in inquiry-oriented high school laboratories in chemistry is discussed by Prof. Avi Hofstein of Weizmann Institute of Science in Chapter 21.

The second part of the book concludes with a chapter on microscale experiments, by Prof. John D. Bradley *et al.* of the University of Witwatersrand (Chapter 22), where different case studies are analyzed. This chapter is dedicated to Prof. Erica Steenberg (1953–2013), whose valuable contributions to chemistry education were many, especially through microscale experimentation.

In the third part of this book (Chapters 23–28), the central question is focused on the role of new technologies on learning and teaching of chemistry. This part begins with an introductory chapter by Prof. Jan Apotheker and Ingeborg Veenstra of the University of Groningen on several resources on the Internet that can be used in education, introducing the concept of technological pedagogical content knowledge as a condition for the design of instructional materials, and giving some recommendations derived from a particular case study on augmented reality developed at this university (Chapter 23). Chapter 24, by Prof. Jerry P. Suits of the University of Northern Colorado, is more focused on the design of dynamic visualizations to enhance conceptual understanding in chemistry courses. Recent advances in visualization technologies (good multimedia software) and research studies in this field applied to chemistry education are carefully reviewed to analyze how students use dynamic visualizations to internalize concepts and imagery and to explore chemical phenomena.

From students in universities, high school, college, and graduate school, to chemical professionals, and teachers, everyone has a mobile computing device such as smartphone or/and a tablet. So, many chemistry-related apps are seeing dramatic growth with increasing adoption rates to enhance the chemistry teaching and learning experience in the classrooms and laboratories. Chapter 25, by Prof. Ling Huang of Hofstra University, covers the use of these chemistry apps in different teaching contexts, analyzing the pros and cons of using them in chemistry education and extracting conclusions about future trends.

The shift from the picture of a general chemistry course composed by a large classroom packed with students, who passively listen to a single person, to learner-centered collaborative based on active learning environments has provoked a parallel increase in the use of Web 2.0/3.0 technologies in active learning pedagogies. Two closely related approaches on this topic are included in this book, Chapter 26, by Dr. Michael K. Seery and Dr. Christine O'Connor of Dublin Institute of Technology, and Chapter 27, by Prof. Gwendolyn Lawrie and Prof. Lisbeth Grøndahl of the University of Queensland. Chapter 26 is more focused on e-learning and blended learning in chemistry education, while Wiki technologies and communities as a part of e-learning and blended learning approaches are covered by Chapter 27.

Finally, this book is concluded with Chapter 28 by Prof. Robert E. Belford *et al.* by the University of Arkansas, which attempts to contextualize contemporary Information and Communication Technologies (ICT) challenges to education and the practice of science in a perspective of relevance to the twenty-first-century chemical educators.

This book was inspired by many interactions with members of the IUPAC Committee on Chemistry Education, a truly dedicated group of educators, and it is the result of several years of work conducted by a large number of experts in the field, many chemistry professors with decades of experience. The final product is a fascinating read, covering a wide range of topics. But let us be clear, there are no magic solutions. However, if you are interested in knowing what years of research on how to best teach and best learn chemistry has produced, and how to take these lessons into your own classroom, this book is a great source of information and, we hope, of inspiration too. All of the contributing authors have put a significant amount of time aside from their daily work to produce this collective work, in order to help others to teach and learn chemistry more effectively. We want to thank all and each of them for their work and invaluable contributions. Hopefully, this book will help you learn about the best practices, opportunities, and trends that years of research in chemistry education has to offer to anyone involved in the teaching or learning of chemistry.

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