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PROBLEMS AND SOLUTIONS IN CHEMISTRY EDUCATION

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Abstract: As an established research field, chemistry education is relatively a young one – its origins go back only to the 1970s. The present author has started his engagement with chemistry education since the late 1970s, and as a consequence he has followed the progress of the field over the years. This paper will focus on the challenges (the "problems") confronting a teacher of chemistry, and on suggestions for solutions as these follow from the findings of educational research, with an emphasis on the author's own research studies. These studies are informed by most of the theoretical and practical tools of chemistry education, such as Piagetian theory, the alternative conceptions or students' ideas or students' misconceptions, scientific literacy, context-based learning, cooperative learning, philosophy and history of chemistry, and the effect of the laboratory and new educational technologies. The following are the topics of the reviewed work: Teaching and learning science concepts in high school; instructional methodology; secondary chemistry curricula; structural concepts; higher-order cognitive skills (HOCS); problem solving in science, and chemistry in particular; and, last but not least, relevant chemistry education.

Keywords: Theories of science education, big ideas in chemistry education, instructional methodology; secondary chemistry curricula; structural concepts; higher-order cognitive skills (HOCS); problem solving; relevant chemistry education.

KİMYA EĞİTİMİNİN SORUNLARI VE ÇÖZÜMLERİ

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Öz: Kapsamlı bir araştırma alanı olarak kimya eğitimi, nispeten yenidir ve kökleri sadece 1970'li yıllara dayanmaktadır. Yazarın kimya eğitimi ile ilişkisi 1970'lerin sonlarında başlamış ve böylece yazar yıllar boyunca alandaki gelişmeleri takip etmiştir. Makalede bir kimya öğretmeninin karşılaştığı güçlükler ("sorunlar") ve yazarın kendi çalışmalarına vurgu yapılarak eğitim araştırmalarından ortaya çıkan çözümlere yönelik önerilere odaklanılacaktır. Bu çalışmalar, Piaget teorisi, alternatif kavramalar veya öğrenci fikirleri ya da öğrencilerin yanlış kavramaları, bilimsel okur-yazarlık, bağlam temelli öğrenme, işbirlikçi öğrenme, felsefe ve kimya tarihi gibi kimya

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eğitiminin teorik ve pratik araçlarının çoğu ile laboratuar ve yeni eğitimsel teknolojilerinin etkilerini içermektedir. Derlenen çalışmaların konuları; ortaöğretimde fen bilimleri kavramlarını öğretme ve öğrenme, öğretim yöntemleri, ortaöğretim kimya programları, yapısal kavramlar, üst düzey bilişsel beceriler (HOCS), fen bilimlerinde ve özellikle kimyada problem çözme ve son fakat aynı derecede önemli güncel konularla ilgili kimya eğitimidir.

Anahtar kelimeler: Fen bilimleri eğitimi teorileri; kimya eğitiminde büyük fikirler; öğretim yöntemleri; ortaöğretim kimya programları; yapısal kavramlar; üst düzey bilişsel beceriler (HOCS); problem çözme; güncel konularla ilgili kimya eğitimi.

INTRODUCTION

Chemistry Education as an activity has been existent "in one form or another as long as there has been chemistry" (Taber, 2015). As an established research field, however, it is relatively a young one – its origins go back only to the 1970s. As the originators of this research field we can consider the Americans J. Dudley Herron and Dorothy L. Gabel and the British Alex H. Johnstone.

J. Dudley Herron was a professor of chemical education in the Department of Chemistry of the University of Purdue. His most important contribution has been the introduction of the Piagetian ideas into the chemistry classroom (see below). In a book published in 1996, he has collected "formulas for successful teaching" (Herron, 1996) (see Figure 1a).

Dorothy L. Gabel was a professor of science education in the Department of Curriculum and Instruction of the Indiana University (Gabel, 1994) (see Figure 1b). She has made excellent work on chemistry problem solving (Gabel & Bunce, 1994).

Alex H. Johnstone was a professor of science education in the Department of Chemistry of the University of Glasgow. He has also made a great contribution to problem solving in science, but is most known for his famous "chemistry triangle" or the "chemistry triplet" (Johnstone & Wham, 1982) (see Figure 2).

Quite rightly, the above three persons were the recipients of the annual "ACS Award for Achievement in Research for the Teaching and Learning of Chemistry"[1] for the first three years 2007, 2008, and 2009 of this award, respectively.

[1] http://www.acs.org/content/acs/en/funding-and-awards/awards/national/bytopic/acs-award-for-achievement-in-research-for-the-teaching-and-learning-of-chemistry.html

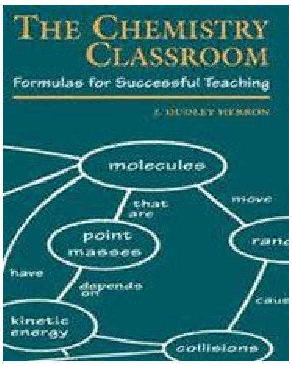

Figure 1a. The cover of the 1996 book by J. D. Herron "The Chemistry Classroom: Formulas for Successful Teaching".

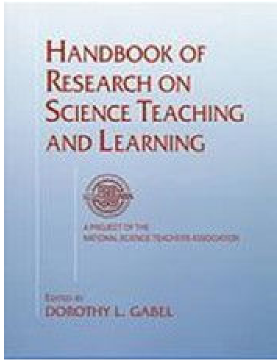

Figure 1b. The cover of "The Handbook of research on science teaching and learning" (1994), edited by D. L. Gabel.

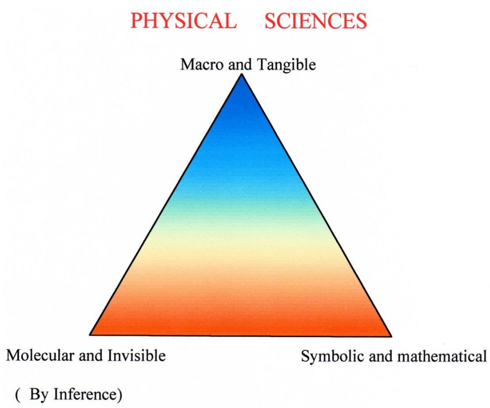

Figure 2. The Johnstone triangle for the three-level representation of chemistry and the physical sciences.

The present author has started his engagement with chemistry and science education since the late 1970s, and as a consequence he has followed the progress of the field over the years. In this presentation, I will focus on some of the challenges (the "problems") confronting a teacher of chemistry, and on suggestions for solutions as these follow from the findings of educational research, with emphasis on my own research studies.[2] My own research interests and work have been on the following issues: teaching and learning science concepts in high school; instructional methodology; secondary chemistry curricula; structural concepts, with emphasis on quantum

[2] A part of the reviewed work has been published only in Greek. In this case, references to the original publications in Greek are provided. In case of work which has been published in English, only the references in English are supplied. Note that earlier versions of the latter work have also been published previously in Greek, but the relevant references are not quoted here.

chemical concepts; physical chemistry education; higher-order cognitive skills (HOCS); problem solving in science, and chemistry in particular, with emphasis on the study of the effects of cognitive factors on problem solving; application of nonlinear methodology to science education problem solving data; and, last but not least, relevant/context-based chemistry education**.** These studies are informed by many of theoretical and practical tools of science education, to which I will focus attention now.

Theories in science education

Piagetian theory was the first cognitive theory that became internal to science education in the late 1970s, in that not only were the students classified into developmental levels, but scientific concepts were also classified as requiring for their understanding either concrete or formal logic (Herron, 1978; Shayer & Adey, 1981). The impact of Piagetian theory on science education was confirmed by a special issue (Vol. 2, Issue 3, 1964) of the *Journal of Research in Science Teaching* that was dedicated to Piaget, which included a paper by Piaget himself. A central tenet of Piagetian theory, in addition to the developmental levels, was (personal) constructivism, which forwarded the notion that knowledge is constructed actively by the student through a process of *cognitive conflicts / disequilibria* and the subsequent *equilibration* / the *accommodation* of new concepts. This process is very relevant to what has become important to science educators in recent years, that is, to *conceptual change*.

Actually, the field of science education separated itself from Piagetian theory in the 1980s, and focused on the study of *alternative conceptions* or *students' ideas* or *students' misconceptions.* Conceptual change derives from the alternative conceptions movement that has dominated and continues to dominate the field of science education since the 1980s. The alternative conceptions movement is also supported by constructivism. In point of fact, constructivism acquired many forms, beyond Piagetian personal constructivism (Bodner, 2001).

It is noteworthy that both Piagetian theory and the alternative conceptions movement were associated with the epistemological theory of constructivism. Many other educational tools from the cognitive and the affective domain have also influenced chemistry education practices, including scientific literacy, context-based learning, cooperative learning, philosophy and history of chemistry, and the effect of the laboratory and new educational technologies.

PROBLEMS AND DIFFICULTIES OF CHEMISTRY IN LOWER CHEMISTRY SCHOOL

In most countries, including Greece, lower secondary education involves three grades (7th, 8th, and 9th) – ages 12-14. The way in which the various science subjects are treated at this level varies: in many countries (*e.g.* England, Scotland, Ireland, Israel, and some states of Germany) an integrated science course exists.[3] In some countries (*e.g.* Denmark), a grouping of physics with chemistry occurs or (*e.g.* France) of biology with geology. Finally, in many countries (*e.g.* Greece, and German states) the practice of separate subjects prevails.

As some of the work reviewed in this paper has been carried out in the Greek context, it is necessary to consider chemistry in the Greek secondary school (*gymnasion*), where chemistry is taught as a separate subject (and so are physics and biology), in the 8th and the 9th grades for one 45-minute period per week. A Greek peculiarity is that the time allocated to chemistry is only half of that made available for the teaching of physics, biology and geography.[4]

My first education research study (Tsaparlis, 1984a, in Greek) reported a survey of Greek teachers' perception of the difficulty of the various chemistry topics that were covered at the time of the study (the 1980s). The findings confirmed that the stoichiometry topics and concepts (RAM, RMM, mole, molar volume, balancing chemical equations, and analogical reasoning in stoichiometric calculations) were seen as the most difficult ones. Other difficult topics for the 8th grade were as follows: The periodic table; ionic and covalent bonds; structural and electronic formulas of covalent compounds; single-atom ions; multi-atom ions; ionic and molecular reactions; simple and double substitution reactions.

Piagetian theory was invoked for the explanation of the findings. Figure 3 shows the distribution of British students in Piagetian levels according to their age, as found in the 1975-1978 survey.

[3] In UK, secondary schools (age 12-16) can either teach biology, physics and chemistry as separate subjects or can teach integrated science. In general, the more academic schools continue to teach the subjects separately but more and more schools seem to have deserted to the integrated approach.
[4] Recently, an extra hour was given to physics, so the time of chemistry is now less than half of that of physics.

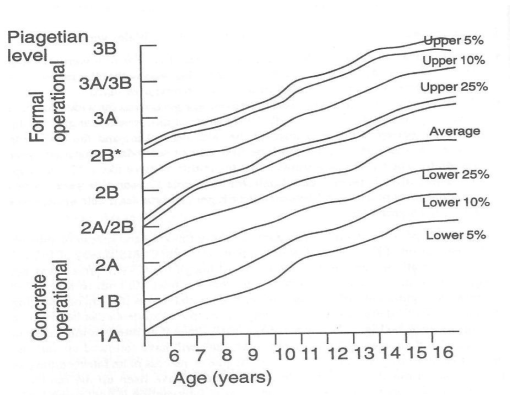

Figure 3. Concepts in Secondary Mathematics and Science (CMSS) Survey 1975-1978 (funded by the *British Social Science Research Council*).

Note that Piagetian theory was at the nucleus of a book of mine on teaching secondary physics and chemistry (Tsaparlis, 1989/1991, in Greek) (see Figure 4).

Figure 4. The cover of the book "Topics of teaching secondary physics and chemistry" (in Greek) by G. Tsaparlis (1989/1991)

Teaching and learning difficulties of fundamental chemistry concepts

In a subsequent study with beginning 10th grade students (Tsaparlis, 1991 and 1994, in Greek), the various topics tested showed the following percentages of correct responses:

- Symbols of elements (73.5%)
- Equation balancing (40.7%)
- Chemical formulas of binary compounds (11.2%)
- Placing of electrons in shells (10,5%)

- Number of electrons in ions (13.3%)
- Ionic and covalent compounds (14.0%)
- Prediction of reactions (11.0%).

With the exception of the symbols of the elements, and less so of equation balancing, the performance was very low, confirming the difficulty of the relevant concepts and topics.

Molecules, atoms, atomic and molecular structure

An important issue in science education has been the so-called big ideas in science (Harlen, 2010) (see Figure 5). The following is considered as the first big idea:

All material in the Universe is made of very small particles. … The behavior of the atoms explains the properties of various materials. … Chemical reactions involve the re-arrangement of atoms in substances, leading to the formation of new substances.

This big idea is the basis of chemistry and this idea is called to serve the teaching of chemistry in secondary education. However (and as many research studies, including the ones of mine reviewed above, have demonstrated), the structural concepts prove hard for many students to learn. In addition, a critical analysis of the concepts of atomic and molecular structure (Tsaparlis, 1997) confirmed students' conceptual difficulties about the structural concepts by employing the following perspectives of science education (i) the Piagetian *developmental* perspective, (ii) the Ausubelian theory of *meaningful learning*, (iii) the *information - processing theory*, and (iv) the *alternative conceptions* movement, which all led to the same disappointing conclusion.

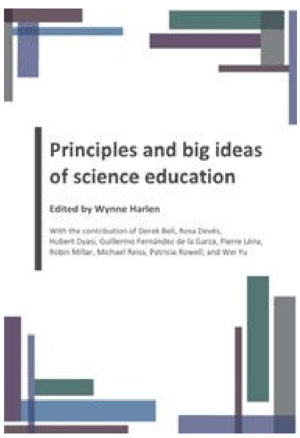

Figure 5. Cover of "Principles and big ideas of science education", edited by W. Harlen (2010).

Proposals for a revised curriculum

Based on the findings of the 1984a study, I made proposals for a revised Greek secondary chemistry curriculum (Tsaparlis, 1984b, 1989/1991, in Greek), which placed the emphasis on the macroscopic study of various topics, and maintained the concepts of molecule and atom, and of chemical notation but without atomic structure and bonding. In addition, I recommended avoiding complicated reactions without actual relevance to everyday life.

Instructional methodology: Two longitudinal research projects

The doctorate theses of two students of mine dealt with issues of chemistry teaching at the lower secondary level. Both studies were longitudinal (two-year long). In the first study (Zarotiadou & Tsaparlis, 2000), we compared two methods of teaching: A constructivist method (CM), based on Piaget's theory of cognitive development; and a meaningful-receptive method, based on Ausubel's theory of meaningful learning. It was found that the CM group scored statistically higher in theory in both the 8^{th} and the 9^{th} grades, while in stoichiometric calculations, the superiority of the CM group occurred only in the 9^{th} grade. The effect of developmental level, of gender and of motivational traits was also examined. Finally, the students generally expressed a preference for the CM.

In the second study (Georgiadou & Tsaparlis, 2000), we experimented with a three-cycle method, which went separately over the macro, the representational, and the submicro levels of chemistry, and concluded that it should be considered seriously as a good method for introductory chemistry. In the macro cycle, which occupied half of the teaching time, the students became familiar with chemical substances and their properties. Central here was the use of experiment, while chemical notation as well as atoms and molecules were not included. Applying the spiral curriculum, the representational cycle covered the same course material, but added chemical formulas and equations. Finally, the submicro cycle brought atoms and molecules into play. Evaluation of the method by end-of-school-year tests, as well as by beginning-of-next year repeating the same tests, showed that the three-cycle method made the largest single positive effect, compared with a traditional control class and a class in which teaching methods proposed by psychologist R. Case were applied.

A new program of studies and new textbook packages (1997-98)

In 1997-98, a new program of studies for Greek lower secondary chemistry was introduced and new textbook packages were written that adopted the proposals of educational research. The program retained atoms and molecules, but avoided the details of atomic and molecular structure. Also, stoichiometry was removed completely. An integral part of the new program was the execution of a number of experiments by the students; to this purpose, laboratory manuals were included in the book packages and the establishment and the fitting out of school labs was implemented. In 2001, I presented second thoughts of mine about lower secondary chemistry (Tsaparlis, 2001, in Greek). In these, I distinguished the aims of the course into three kinds: (1) aims of theoretical/formal chemistry; (2) aims of practical abilities; (3) aims of chemistry in context.

An integrated science program for the 7th grade

In Greece, while general science is taught in the 5th and the 6th grades, physics and chemistry were absent from the 7th grade (but a physics course was added recently). To overcome this deficiency, I proposed an integrated program of physics and chemistry for the 7th grade. A relevant book (in Greek), which includes experiments, theory, simple knowledge, and more demanding questions was written in collaboration with a colleague (Tsaparlis & Kampourakis, 2000). Basic features were the following: The spiral curriculum; qualitative treatment of concepts; taking account of student misconceptions; experimental-constructivist teaching and learning; simplicity of phenomena and principles; exclusion of atoms and molecules, of equations, and of graphs; and connection with everyday life. The program went on trial during 1998-99 and 1999-2000 in eleven schools, involving 24 teachers and about 1500 students. In subsequent work, biology lessons were incorporated into each of the ten units of the above book of integrated physics and chemistry (Tatsi and Tsaparlis, 2011, in Greek), and the output was subjected to a preliminary evaluation by experienced education and science experts (Tatsi & Tsaparlis, 2013, in Greek).

A chemistry course for the 8th Grade

A novel introductory lower-secondary chemistry course (for the 8th grade) that aims at the application of theories of science education, and in particular of conceptual/meaningful learning and of teaching methodology that encourages active and inquiry forms of learning was proposed (Tsaparlis, Kolioulis, & Pappa, 2010). The program is made of six units (matter and soil, water, chemical reactions, air, molecules, atoms) that contain twenty-four lessons. Special emphasis is paid to the meaningful introduction of the concepts of molecule and atom; this introduction is delayed until the last two units of the course (see the relevant lessons in Table 1). A textbook was written and subjected to a preliminary evaluation by four experienced Greek science teachers (Tsaparlis, Kolioulis, & Pappa, 2010).

Table 1 The contents (lessons) of units E and F of the book "Chemistry for the 8th Grade" by G. Tsaparlis & D. Kolioulis.

UNIT E. Molecules	*UNIT F. Atoms*
17. The concept of molecule in solids and liquids	20. The first two laws of chemistry
18. Ever-moving molecules	21. The concept of atom
19. The concept of molecule in gases	22. Chemical formulas and the mole concept
	23. The concept of chemical equation

Linking the macro and the micro worlds in the laboratory – Gases and the importance of the history of chemistry

Very important for the understanding of chemistry and the connection of the macroscopic level with the representational/symbolic and submicro levels are experiments with gases. Very relevant here is the history of chemistry. It took many years and the genius of various scientists for gases to take up their proper place in the study of chemistry (Levere, 2001). Joseph Priestley (1733-1804) discovered new kinds of air, including carbon dioxide (fixed air) and oxygen. Gases were central to Antoine-Laurent Lavoisier's (1743-1794) chemical revolution (see Figure 6). One of his key experiments was about the composition of water. In addition, he proposed the oxygen theory of combustion, overthrowing the phlogiston theory. The vast amount of data that was supplied by the experimental study of gases provided John Dalton the tools to develop the atomic theory, thus connecting the macro level of chemistry with the submicro one. The representational mode was also of great help, so it is not strange that Dalton had invented atomic symbols (Levere, 2001, p. 86).

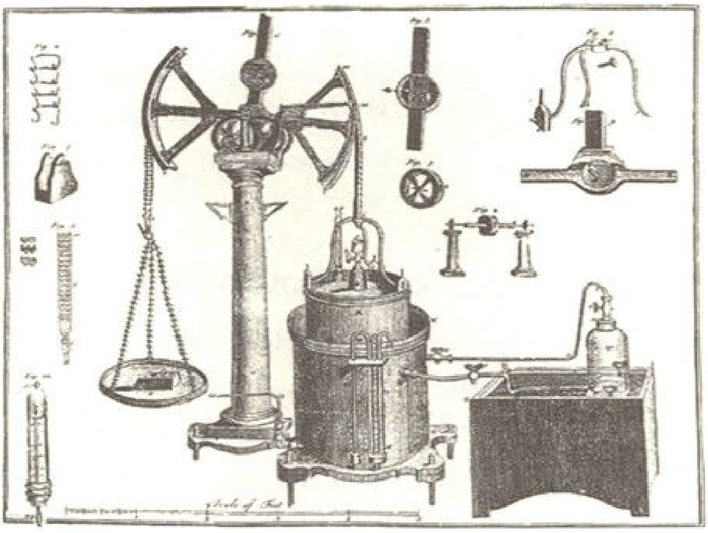

Figure 6. Lavoisier's gasometer (Levere, 2001).

The linking of the macro and the micro worlds of chemistry in the laboratory is treated in a chapter I have written (Tsaparlis, 2009) for an edited book entitled "*Multiple representations in chemical education* (Gilbert & D. Treagust, 2009) (see Figure 7a). In addition, in another chapter (Tsaparlis, 2014), in an edited book entitled "*Learning with understanding in the chemistry classroom*" (Devetak & Glažar, 2014) (see Figure 7b), I describe a large number of demonstrations and experiments that can contribute to the active/meaningful/conceptual learning about the linking of the macro with the submicro level of chemistry.

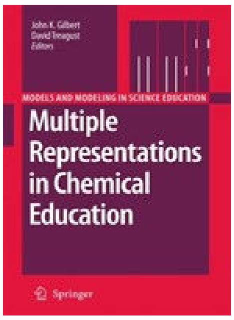

Figure 7a. The cover of the book on Multiple representations in chemical education, edited by J. Gilbert and D. Treagust (2009)

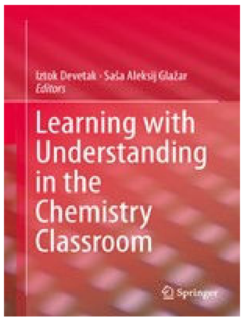

Figure 7b. The cover of the book on Learning with Understanding in the Chemistry Classroom, edited by I. Devetak & S. A. Glažar (2014)

Revision of formal curriculum in Greece (2014) – Chemistry for 7th and 8th grade

The present author was the coordinator of a committee that worked out a new program of studies for chemistry of the 7th and 8th grades in Greece, within the project "Education and Lifelong Education – New School (21st Century School)" (Tsaparlis *et al.*, 2014, 2016, in Greek). The main aims were as follows: (i) The re-arrangement of the topics and a rational organization of the material in the school books; (ii) the combination of the change of the program of studies with proper educational material (print and electronic). The methodology combines the macroscopic approach with the submicroscopic and the symbolic levels of chemistry, conceptual understanding, inquiry learning, laboratory teaching, and connection with everyday life. See Table 2 for the contents and the organization of this course.

Table 2. The contents and the organization of chemistry for the Greek 8th and 9th grades (2014).

Chemistry for the 8th grade (One period per week / 26 periods of 45 minutes each)
Introduction: Materials and their physical states (2 periods). 1) From soil and subsoil to chemical substances (5 periods). 2) From water to solutions (5 periods). 3) From water to atoms – From the macroworld to the microworld (7 periods). 4) From air to oxygen and to combustions (4 periods). 5) Pollution of the environment and how to deal with it (3 periods).
Chemistry for the 9th grade (One period per week / 26 periods of 45 minutes each)
Introduction: Classification of the elements – Periodic table (2 periods). 1) The chemistry of carbon and of life (9 periods). 2) Acids, bases and salts (10 periods). 3) (Chemical) elements with a special interest for chemistry and for everyday life (5 periods).

A delay of the introduction of structural and symbolic concepts (atoms and molecules) was attempted by placing these concepts in the third unit of the 8th grade, entitled "From water to atoms – From the macroworld to the microworld" (out of a total of five units). At the macroscopic level (before introducing atoms and molecules), emphasis is placed on distinguishing between substances and mixtures of substances, the separation of mixtures into their component substances, and the concept of substance (on the basis of fixed physical constants). Following these, we study chemical reactions, first between solid substances (lead nitrate plus potassium iodide) (de Vos & Verdonk, 1985), and then the thermal decomposition of solid substances (carbon carbonate, mercury (ii) oxide, sugar). At this point, we assumed that the use of the mass spectrometer ("the chemists's elemental analyzer") for the determination if a given substance is a chemical element or a chemical compound (Taber, 2012a) would be very useful (see Figure 8).[5] Chemical reactions in aqueous solutions [e.g. lead nitrate (aq) plus potassium iodide (aq)] are studied in the second unit entitled "From water to solutions". The classic experiment of the electrolysis of water is used for introducing the concept of atom (in addition, the thermal decomposition of water into its constituent elements is also considered). Chemical notation follows: formulas of compounds, submicro-representations / models of molecules, and chemical equations with models and symbols. The next unit deals with the study of gases, and the final one with the pollution of the environment (pollution of soil, of water, and of air).

Regarding the program for the 9th grade, a main feature is that, in accordance with Johnstone's practice and arguments[6] (Johnstone, Morrison, & Reid, 1981; Johnstone, 2000) of the teaching of organic chemistry before acid-base chemistry and the study of some chemical elements and their properties.

In conclusion, the aim of the new program of study for the Greek 8th and 9th grades is to achieve that students develop a liking for the chemistry course through its many useful applications, but also that they are supplied with the necessary basic knowledge, which will help them move to the more advanced upper secondary chemistry course.

Pattern obtained for water

Pattern obtained for gas collected at cathode when water is electrolyzed

Pattern obtained for gas collected at anode when water is electrolyzed

Figure 8. The chemist's elemental analyzer: mass spectra of water, elemental hydrogen and elemental oxygen (Taber, 2012a)

[5] This material is from the book "Teaching Secondary Chemistry" (new 2nd edition), edited by Taber (2012b) (see figure 9).

[6] Organic chemistry involves only a few elements, while bonding in organic compounds is simple: a carbon atom makes four bonds; a hydrogen atom makes one bond; an oxygen atom makes two bonds; and a nitrogen atom makes three bonds.

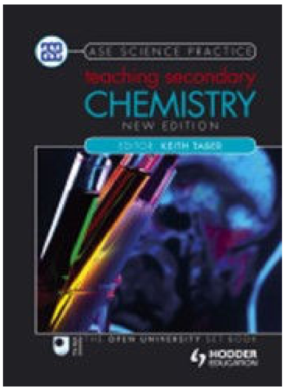

Figure 9. The cover of the book "Teaching Secondary Chemistry" (new 2nd edition), edited by K. S. Taber (2012).

CHEMISTRY IN UPPER SECONDARY EDUCATION

As in many countries, upper secondary education in Greece involves three grades (10th, 11th, and 12th) – ages 15-18. The 10th grade is an orientation year, with common curriculum for all students, while in the 11th and the 12th grades, in addition to general education subjects, students have to follow one out of three specialized streams.[7] All three science subjects (physics, chemistry, and biology) are treated as separate courses both as general education subjects, and in the specialized streams of study.

Three early studies identified Greek students' strengths and difficulties with chemistry, based on testing beginning first-year chemistry students (Tsaparlis, 1981, 1985a, 1985b, in Greek). The 1985b study used the findings of the 1981 and 1985a studies to identify some of the main difficulties of chemistry in upper secondary school (*lykeion*). Difficulties were detected about the following: The naming of compounds and the writing of chemical formulas; ionic and covalent compounds; polar and non-polar compounds; ionic and molecular reactions; oxidation numbers (n = 121).

Of special interest was the topic of chemical equilibrium (n = 85). In a question that asked for the expression of the chemical equilibrium constant K for the equilibrium reaction $N_2 + 3H_2 \rightleftharpoons 2NH_3$, 70.1% of the students gave the correct answer, while 5.7% wrote the reverse expression (1/K), and 4.6% each wrote $(2NH_3)^2/(N_2)(3H_2)^3$ and $(NH_3)^2/(N)(H)^3$. The application of the Le Châtelier

[7] A reform of the upper secondary program in Greece, which contains differences from the previous courses, has recently been introduced.

principle on the effect of increase of temperature on the yield of the same reaction (given the thermochemical equation $N_2 + 3H_2 \rightleftharpoons 2NH_3$ + 22 kcal) resulted in 82.4% correct answers, while 14.1% of the students predicted wrongly that the yield would increase. On the other hand, the correct answers dropped to 45.9% when the effect of an increase of temperature on the rate of the same reaction ($N_2 + 3H_2 \longrightarrow 2NH_3$) was investigated, with 48.2% of students providing wrong answers: no effect: 37.6%; decrease of rate: 10.6%. A misconception was seen to be at work here:

Le Châtelier's principle was being applied to reaction rate, when actually it could only be used to predict the direction of a reaction.

In the Anglophone literature, this misconception was reported in a study by Banerjee (1991), according to which students reasoned that when the temperature is increased in an exothermic reaction, the rate of the forward reaction decreases (see also Sözbilir, Pinarbasi, & Canpolat, 2010).

The topic of ionic equilibria is causing considerable difficulty to many students: Asked if HCO_3^- (aq) is an acid, a base, or an ampholyte, only 5.9% of students (n = 85) provided the correct answer (ampholyte), while 44.7% did not respond, and 49.4% gave wrong answers (29.4: acid; 18.8%: base). Asked about the acidity of an aqueous solution of NH_4Cl (acidic, basic or neutral solution), 31.8% of students gave the correct answer (acidic), while 11.8% did not respond, and 56.5% gave wrong answers (29.4%: basic; 27.1%: neutral)

Prediction of the products of inorganic reactions revealed erroneously thinking by a relatively small number of students, who assumed that as long as the products of a reaction are legitimate substances, then the resulting reaction is acceptable (it can actually occur), as the following results demonstrate (n = 127):

$2NaCl + H_2SO_4 \longrightarrow H_2 + Cl_2 + Na_2SO_4$ (5.9%)

$Cl_2 + SO_2 \longrightarrow SCl_2 + O_2$ (3.5%)

Note that the above equations are balanced correctly.

Problems were also detected with the writing of chemical formulas, *e.g.:* ZnCl (15.3%) MnCl (4.7%).

Conceptual understanding about the particulate and structural concepts of matter

The particulate nature of matter is very important to the disciplines of science as well as to school science curricula, having been identified as a *core idea* of the science content standards, with great emphasis placed in teaching certain of its aspects in Grades 8 through 12 (*National Science Education Standards* / National Research Council, 1996).

At this point let me distinguish between the terms *particulate* and *structural* concepts of matter. For various elaborate definitions[8] see Tsaparlis and Sevian (2013a). Most authors, however, maintain the term "particulate" to refer to particles such as atoms and molecules that are assumed "structureless". "*Structure*" can be defined as the distribution of the electrons in an atom (electron configuration) or the arrangement and bonding of the atoms in molecule. Therefore, the term "structural concepts" is used to describe "*atomic"* and "*molecular structure"* (Tsaparlis & Sevian, 2013a).

An edited volume by Tsaparlis & Sevian (2013b), entitled "Concepts of Matter in Science Education" (see Figure 10), deals in depth with the particulate and structural concepts of matter. The book is divided into six parts. Part I takes a learning progressions approach to studying how students develop understanding of the particulate nature of matter. Part II deals with the mental models held by preservice teachers, practicing teachers, and many educational levels of students, about various aspects related to the particulate nature of matter or phenomena requiring an understanding of matter's particulate nature. Part III focuses on the production and use of educational technology tools for aiding students in understanding the particulate nature of matter. Parts IV and V treat two fundamental ideas of chemistry that build on understanding of the PNM: chemical reactions and chemical phenomena and chemical structure and bonding. Finally, Part VI contains, on the one hand, an historical development of the concept of matter, and on the other hand, a synthesis of the ideas that have been presented in the book and the problems that have been raised, hoping to supply new knowledge that could result from realizing coherence and dissonance across a related set of research studies and reviews.

[8] For instance: The particulate nature of matter is used to describe phenomena ranging in size from individual atoms up to the nanoscale, in other words, objects between about 0.1 and 100 nm. Atoms or molecules constitute the so-called submicro level, with a scale between 0.1 and 1 nm.

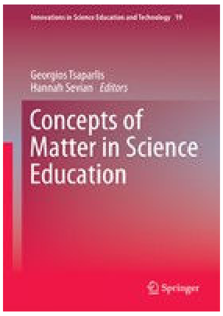

Figure 10. The cover of the book on "Concepts of Matter in Science Education", edited by G. Tsaparlis and H. Sevian (2013).

A main feature of the actual school chemistry of today, as it is taught and tested all over the world by many if not most teachers, is that it places the emphasis on learning rules and algorithms, which enable conscientious students to respond with success to examination questions, including relatively complicated computational questions. Examples of such 'dexterity' are the placing of electrons in electron shells and sub-shells or in atomic orbitals, the rote learning of oxidation numbers of the elements, the writing of chemical formulas, the balancing of chemical equations, the calculation of heats of reactions, *etc.* If we turn, however, to matters of conceptual understanding, we realize that our students are as a rule ignorant and cannot answer questions such as: why chlorine appears with so many oxidation numbers, why spontaneous endothermic reactions exist, and why reactions lead in general to equilibrium?

Concentrating on the structural concepts, we present to students as absolute truth the foundation of the whole edifice of chemistry. Students have to accept the teacher's word for questions such as:

- How do we know that molecules and atoms exist?
- What data forced us to accept that the molecules of several elements are diatomic?
- How the chemical formulae of compounds are determined?
- How did we discover the structure of the atom and nucleus?
- How electric charge and the mass of the electron were measured?
- How the atomic numbers of the elements were determined?
- On what experimental evidence the placing of electrons in shells and in orbitals was based?
- What is an atomic or a molecular orbital?
- How do we know that atoms in molecules vibrate, and that molecules in gases and in liquids rotate?

The states-of-matter approach (SOMA) and a context-based approach to upper secondary chemistry

Within a project for revising the upper secondary curricula in Greece, the present author as a member of a special committee contributed to the proposal of a chemistry program for all students in the 10th and 11th grades. For the 10th grade, chemistry was introduced through the separate study of the three states of matter [the states-of-matter approach (SOMA)] (Tsaparlis, 2000). There are three major units in the program, namely: Air, gases, and the gaseous state; Salt, salts, and the solid state; Water, liquids, and the liquid state. A relevant book was written (as part of a master's thesis) which was then submitted to a preliminary evaluation by teachers (Tsaparlis & Pyrgas, 2011).

The introduction in SOMA of the gaseous state first was based on the following facts: it is the simplest / the best understood by scientists; it is suitable for studying atoms and molecules; the elements and compounds which are, under normal conditions, in the gaseous state have small and simple molecules; we work with only few non-metals (H, O, N, halogens, and noble gases) and compounds (H_2O, O_3, NH_3, NO_x, CO, CO_2, H_2S, SO_2, HCl, and gaseous hydrocarbons); we start with the covalent bond (Johnstone, Morrison, & Reid, 1981; Johnstone, 2000); gas laws are included in the study; intermolecular forces are either absent or weak. By placing the solid state second we study the ionic bond, crystals, salts, metal oxides, metals and the metallic bond, the periodic table and oxidation numbers, but also covalent and amorphous solids. Finally, water, hydrogen and intermolecular bonding, liquid organic compounds, aqueous solutions, as well as acids and bases, and simple and double replacement reactions in aqueous solutions can be studied within the liquid state.

For the 11th grade, the program moved into the connection of chemistry with life and its applications. As part of another master's thesis, a book has recently been written which covers the 11th grade chemistry (Tsaparlis & Stergiou, 2014, 2016 in Greek). The material is based on the above program of studies, and specifically on the connection of chemistry with life and applications. It is divided into three major units: A: Organic chemistry (with four chapters: one on fossil fuels, two chapters on basic organic chemistry, and one chapter on polymers, plastics, and modern materials; b: Chemistry and our life (three chapters, one on drugs, one on foods and nutrition, and one on biomolecules); and c: Chemistry and energy (two chapters, one on electrochemical energy and one on nuclear energy and renewable forms of energy). The 11th grade course, was influenced greatly by one of the first books to adopt a contextual approach to chemistry (Sherman & Sherman, 1983).

Based on the available instructional time and on the evaluation of the book by experienced upper secondary chemistry students (Tsaparlis and Stergiou, 2016, in Greek), I suggest reducing and re-organizing the material as it is shown in Table 3 (note that nuclear energy and renewable forms of energy have been omitted).

Table 3. Modified material and its organization of chemistry for the 11th grade chemistry.

UNIT A CHEMISTRY AND ENERGY	UNIT B Organic chemistry	UNIT C Chemistry and life
A 1 Energy transfer in chemical reactions A 2 Fuels A 3 Electrochemical energy	B 1 Hydrocarbons B 2 Polymers, plastics, and new materials B 3 Alcohols– ethers – aldehydes and ketones– acids and esters	C 1 Drugs C 2 Foods and nutrition C3 Biomolecules

PROBLEM SOLVING

Problems vs. Exercises / HOCS vs. LOCS

At the outset, I must distinguish between what is known as *exercises* and what is known as ("*real*") *problems*. In the case of exercises, one applies a well-known procedure, which has usually been practiced (an *algorithm*). On the other hand, the 'real' problems or complex problems are not algorithmic, of which the solution requires the contribution of a number of mental resources. In a school context, a task can be an exercise or a real problem depending on the subject's expertise and on what had been taught. A task could be an exercise for a student, while the same task would be a problem for another student (Niaz, 1995).

Very relevant here is the distinction of cognitive skills into *Higher-Order Cognitive Skills* (HOCS) and *Lower-Order Cognitive Skills* (LOCS) (Zoller, 1993; Zoller & Tsaparlis, 1997). It has been demonstrated that students perform considerably lower on questions requiring HOCS than on those requiring LOCS. In addition, performance on questions requiring HOCS may not correlate with that on questions requiring LOCS (Zoller & Tsaparlis, 1997).

Complex tasks that require the use of HOCS are those which require both algorithmic ability and a deeper conceptual understanding. HOCS are hard to be taught and require special interventions (Zoller & Tsaparlis, 1997).

Problem solving: Effect of selective cognitive factors

Various researchers have examined the effect of a number of cognitive factors (variables) in the solution of problems in chemistry and more generally in science. In this review, I will focus on the following cognitive variables: Scientific reasoning (developmental level in the Piagetian sense), working memory capacity; functional mental capacity (*M*-capacity); and disembedding ability (*i.e.*, the degree of perceptual field dependence–independence).

Scientific reasoning is a measure of a student's level of intellectual development. In the past, the term 'developmental level' has been used instead. Working-memory capacity and functional *M*-capacity refer to the information-holding and information-processing capacity, but there are different underlying models and tasks for measuring them.

A predictive model in problem solving refers to the *working memory overload hypothesis,* and states that a subject is likely to be successful in solving a problem if it has a mental demand (*M*-demand) which is less than or equal to the subject's WM capacity (W) ($M \leq W$) (Johnstone, 1984; Johnstone & El-Banna, 1986). The model provided a reasonable explanation of students' failure, but it was not applicable to all kinds of empirical data.

Tsaparlis (1998) examined the limitations of the model and stated the necessary conditions that must be fulfilled in order for it to be valid. These are: (1) the partial steps must be *available* in long-term memory, and (easily) *accessible* from it; (2) the model must be valid for actual problems, and not only for familiar 'problems' (exercises). [Familiarity with a problem, and/or 'chunking' of a problem into familiar chunks reduces the *M*-demand and thus improves student performance.] In a follow-up study, simple organic chemical synthesis problems, with a simple logical structure and varying *M*-demand were studied (Tsaparlis & Angelopoulos, 2000), *e.g.* suggest a synthesis of *formaldehyd*e, HCHO, from *sodium acetate*, CH_3COONa. The data showed the pattern of the expected drop in performance, and this was more striking in the case of the students without previous training in this kind of problems (see Figure 11).

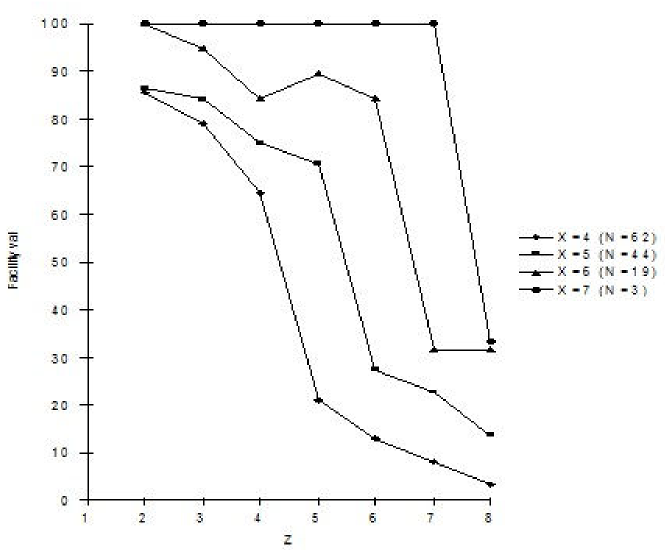

Figure 11. Twelfth-grade student performance (facility values) in organic-synthesis problems of varying mental demand (*Z*-demand), according to the measured working-memory capacity *X* of the students. The data is for students without previous training in this kind of problems.

A decline in student performance might occur not only because of the limitation of their working memory capacity but also because of the interference of variables, such as *disembedding ability* (degree of field dependence/independence), which play an essential role in science problem solving.

The degree of field dependence/independence, which is actually the ability to separate *signal* from *noise*, acts as a moderator variable to information processing. Field dependent students appear to possess lower WM capacity and/or *M*-capacity because they process simultaneously irrelevant information. It has been found that disembedding ability is involved in situations that require conceptual understanding alone (especially in demanding cases), and in combination with chemical calculations (Demerouti, Kousathana, & Tsaparlis, 2004).

Tsaparlis (2005) carried out a correlation study of the effect of selective cognitive factors on non-algorithmic quantitative problem solving in university physical chemistry. An example of the problems used is provided below:

The equilibrium pressure of gaseous hydrogen (H_2) over a mixture of solid uranium (U) and solid uranium hydride (UH_3) at 500°C is 1.04 mm Hg. Calculate the standard free energy of formation of UH_3(s) at 500°C (Ritchie, Thistlethwaite, & Craig, 1975).

Table 4 shows the results of a quasi meta-analysis in terms of values of various estimators of common correlation for the four cognitive factors employed.

Table 4. Estimators of common correlation for various cognitive factors in the case of non-algorithmic quantitative problem solving in university physical chemistry (Tsaparlis, 2005).

Estimator of common correlation (n = 250)	Scientific reasoning	Working memory capacity	Functional M-capacity	Field dependence/ independence
ρ_1	0.043	0.177*	0.348***	0.326***
ρ_2	0.068	0.165*	0.307***	0.318***
ρ_3	0.074	0.176*	0.306***	0.322***
ρ_4	0.099	0.203**	0.291***	0.320***

*Statistically significant correlations ($p < 0.05$). **Statistically significant correlations ($p < 0.01$). ***Statistically significant correlations ($p < 0.002$).

The effects of the cognitive factors under examination vary with the nature and complexity of the problem and under different assessment formats as well. Tsaparlis, Kousathana, and Niaz (1998) examined the effect on student performance of the manipulation of the logical structure (specified by the number of *operative/logical schemata* entering the problems) (see Table 5), as well as of the *M*-demand of chemical equilibrium problems. Simple regression analyses showed that developmental level was the main predictor variable in most cases.

For instance, for problem (4,6) (four logical schemata and an *M*-demand of 6), developmental level alone can explain 38.0% of the variance, working memory 23.3% functional *M*-capacity 14.0%, field dependence/independence 8%. All cognitive variables were correlated with achievement only when the logical structure was fairly complex and even when the *M*-demand was relatively low. Working memory maintained some importance, while the developmental level played the dominant part. Note that the students had an extended practice with them (the ‘training effect’), so the problems were of the algorithmic type for the students.

The effect of developmental level on conceptual understanding and problem-solving ability has also been examined in the area of acid-base equilibria (Demerouti Kousathana and Tsaparlis, 2004) and it was found to be connected with most cases of concept understanding and applications, but less so with situations involving complex conceptual situations and/or chemical calculations.

Table 5. Logical schemata and *M*-demand in molecular-equilibrium problems.

Schema 1: The process of establishment of the chemical equilibrium.
Schema 2: The condition of chemical equilibrium.
Schema 3: The case of gaseous systems, with use of partial and total pressures as well as of K_p
Schema 4: The disturbance of the equilibrium and the establishment of a new equilibrium.

RELEVANT CHEMISTRY EDUCATION

Relevance in science education has a number of connotations, with most notable being (i) the embedding of science into contexts connected to students lives, (ii) the meeting of student needs, and (iii) the inclusion of real-life applications for individuals and society. In general, relevant chemistry education is more general than, although closely related to, the so-called "context-based chemistry education"[9]. The importance of relevance and context-based approaches to science education is made evident by the existence of three international educational projects that aim at enhancing students' interest in science and technology: *Relevance of Science Education* (ROSE); *Popularity and Relevance of Science Education for scientific Literacy* (PARSEL); and *Professional Reflection Oriented Focus on Inquiry-based Learning and Education through Science* (PROFILES).[10]

A recent edited volume by Eilks and Hofstein (2015) is dedicated to the theme of relevant chemistry education (see Figure 12). In this book, relevance is manifested in three dimensions: individual, societal, and vocational relevance. Furthermore, each of the three dimensions covers both intrinsic and extrinsic components, as well as present and future aspects. According to the editors of the book, the three dimensions are not independent of each other, but are interrelated and partially overlap. A review of this book is available (Tsaparlis, 2015).

[9] Issue no, 9 of volume 28 (2006) of the *International Journal of Science Education* was a special issue on the theme of "Context-based chemistry education". It had a theoretical article on the nature of 'context' in chemistry education (Gilbert, 2006), which was followed by specific context-based approaches in the USA, England, Israel, Germany, and the Netherlands.

[10] PARSEL and PROFILES share a three-step teaching model as follows: (1) *contextualization* (a scenario that deals with an everyday issue or concern); (2) *de-contextualization* (the scientific ideas and problems to be solved); (3) *re-contextualization* (consolidation of science learning by bringing the science gained into the everyday issue being discussed).

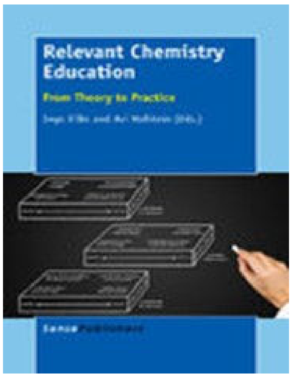

Figure 12. The cover of the book "Relevant Chemistry Education – From Theory to Practice", edited by Eilks and Hofstein (2015).

Connection of the taught chemistry with students' everyday life

Two studies on the connection of the taught chemistry with students' everyday life - one on lower-secondary education (Tsaparlis & Vlachou, 1987, in Greek) the other on upper-secondary education (Tsaparlis & Vlachou, 1991, in Greek) revealed very poor knowledge; for instance, 97% of lower-secondary students ignored the content of a liquefied-gas bottle, 96% ignored the content of a fire extinguisher, 89% could not explain what a bleaching liquid was, and 81% were unsure of what petrol is. In the case of upper-secondary students, 77% ignored the gas or gases contained in a liquefied gas, 64% the content of a fire extinguisher, 60% failed to appreciate that sulfuric acid is the electrolyte in lead batteries, and 57% that benzoic acid is a common food preservative.

Coupling of secondary chemistry to the PARSEL modules

Chemistry, as a secondary school subject for all, should aim to provide students with chemical literacy and chemical culture, to develop higher-order cognitive skills, and to be a useful, interesting, and enjoyable subject (Tsaparlis, 2000). As such it should target at both the cognitive and the affective domains. Within the affective domain, the current trend is towards a contextual approach to teaching and learning. PARSEL[11] is a project which has produced educational materials that are available free of charge on the Internet, at: http://icaseonline.net/parsel/www.parsel.uni-kiel.de/cms/indexe435.html?id=home.

The modules aim to promote scientific literacy and to enhance popularity and relevance of science teaching and learning. The materials in the form of modules (*e.g. Growing plants: does the soil*

[11] *Popularity And Relevance of Science Education for scientific Literacy*.

matter?; Milk: keep refrigerated; Should vegetable oil be used as fuel?) cover a range of student levels (Grade 7 upwards) and science subjects. The materials have been developed by a consortium involving eight European Universities (from Estonia, Denmark, Germany (2), Greece, Israel, Portugal and Sweden) and the International Council of Associations for Science Education (UK).

A personal retrospective comment on relevant chemistry education

In the year 1988, during a Greek conference, influenced greatly by the Sherman and Sherman (1983) contextual approach to chemistry, I made a presentation about "*chemistry and tomorrow's citizens*", about "*chemistry as a general education subject at the threshold of the 21th century*" (Tsaparlis, 1988, in Greek). The following were the concluding comments of my presentation:

"*We live in a chemical world, … (where) a general public, … adopts an attitude hostile to chemistry, (where) people are scared by the word 'chemistry'… It is a necessity that this public … considers critically the chemical view of life, (and) the capabilities and the problems of chemistry. (In this way), chemistry will become an interesting, practical, useful subject, in one word, a most urgent subject*".

POSTSCRIPT: Return to the big ideas in chemistry education

De Jong and Talanquer (2015) categorize big ideas into contextual and conceptual ones. Contextual big ideas can be general (*e.g.* chemistry for sustainability) or specific (*e.g.* ozone layer chemistry), while conceptual big ideas belong to chemistry (*e.g.* bonding, chemical equilibrium) or are about chemistry (nature and methods of chemistry). The authors discuss various sets of early and recent big ideas, with latest being the ones proposed by Talanquer & Pollard (2010): Chemical identity - Structure-property relationship - Chemical causality - Chemical mechanism - Chemical control - Benefits-costs-risks. Big ideas in the chemistry classroom are guided and constrained by a set of curricular perspectives, with each perspective characterized by a dominant conception about chemistry as follows: Fundamental Chemistry (FC) perspective; Knowledge Development in Chemistry (KDC) perspective; Chemistry, Technology, and Society (CTS) perspective. In addition, De Jong and Talanquer (2015) focus on educators' and students' views of big ideas in chemistry. Their findings indicated the dominant influence on teachers' beliefs of current chemistry curricula, which strongly focus on teaching and learning conceptual big ideas *of* chemistry. Nevertheless, the teachers considered important to also pay attention, although to a lesser extent, to contextual big ideas and to conceptual big ideas *about* chemistry.

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