THE FIRST YEAR GENERAL CHEMISTRY COURSE: GREAT CHALLENGES AND GREAT POTENTIALITIES

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Abstract–The first year general chemistry course is considered particularly challenging. It poses the challenges inherent to the secondary school – university transition and, simultaneously, the typical challenges of chemical education, largely related to the nature of chemistry and its interpretation models. The challenges are widely acknowledged and explorations of ways to address them constitute one of the most active areas within chemistry education research. The first year chemistry course is also a fertile source of potentialities, because it sets the foundations of the ways in which students will consider and approach chemistry afterwards.

The paper offers a broad overview of identified challenges, highlighting their main features and presenting some of the explored addressing options, with particular emphasis on approaches suitable for interactive teaching or aimed at stimulating students' active engagement. It also highlights the potentialities stemming from good levels of conceptual understanding attained in the first year.

Keywords: Epistemological access, language-related difficulties, language-visualization interplay, secondary school–university transition, visualization.

1.1. INTRODUCTION

The first year general chemistry course is considered particularly challenging. It has been so for many years and in many contexts. Students' pass-rate may be quite low. In periods and contexts with high selectivity, the pass-rate could be down to 25% or less (for instance, from the author's direct experience, 12 out of 49 chemistry students passed the course at the first attempt in the 1966-67 academic year, at the university of Pisa, Italy). Even in situations with less strict selectivity criteria (e.g., in contexts where the bare-pass mark is 50%, versus 60% in Italy), the pass-rate may be comparatively low. For instance, at the University of Venda (UNIVEN, South Africa), the pass-rate has remained unsatisfactory in recent years, despite several supporting measures, including numerous tutorial sessions.

The challenges of the course are widely acknowledged by educators. Explorations of ways to address them constitute one of the most active areas of chemistry education research, producing a wealth of information. Besides educational research in its more or less "traditional" forms, there have also been initiatives aimed at joining efforts across countries and cultures to promote improvements through collaborations. For instance, the *International Centre for First Year Undergraduate Chemistry Teaching (ICUC)* posed the teaching of first year chemistry courses at the centre of investigations and international collaborations. In the words of its founders (Castro-Acuña & Kelter, 2010), ICUC:

> is based on the fundamental construct that chemistry teachers from all countries and cultures have made important contributions to our global educational practice, and we must continue to encourage and honor this worldwide work.

The challenges of the first year general chemistry course can be considered from various different perspectives, among which:

- As a component of the overall transition from secondary school to university. Like the other first year courses, the first year chemistry course involves all the challenges inherent to this transition: major changes in the study approach (e.g., because of the greater independence expected from the learners) and in the epistemological ways through which the content needs to be approached.

- As a course posing the typical challenges of chemical education in a magnified way, because of often corresponding to the first students' encounter with "real chemistry". These challenges are largely related to the nature of chemistry as a science characterised by fundamental interplays: interplay between macroscopic and microscopic descriptions, interplay between *qualitative* and *quantitative*, and interplay between *general* and *particular*. The interplays – determined by the fact that chemistry is the science of substances and that the properties of substances depend on the properties of their molecules – pose substantial learning challenges because of their inherent complexities.
- As a course "looking" simultaneously in two directions: the past, i.e., the previous instruction, from which students have often inherited imprecise views and misconceptions, and also learning habits that are not adequate for the tertiary level; and the future, for which the first year course poses the foundations, particularly important for those students who will encounter other chemistry courses in their learning career.
- As a course often posing the "practical" challenges of large-enrolment groups, where the teacher has to try and actively engage a high number of students simultaneously, sometimes with the addition of the un-conduciveness stemming from inadequate physical spaces and overcrowded venues.

The next sections offer brief overviews for each of these aspects.

The first year chemistry course does not involve only challenges. It is also a fertile source of potentialities, because it sets the foundations of how students will consider and approach chemistry afterwards. This is important both for future chemistry professionals and for other scientists who will use chemistry information in their professional careers. For the foundations to be apt to foster interest in (or even passion for) chemistry, it is crucial to attract students' attention to primary issues: what is chemistry, what chemistry can do, why it is interesting to investigate certain themes, how we approach experiments and reflect on the observations, and other key aspects of chemistry as a science. For students to be able to approach future courses comfortably, it is necessary to ensure that all the basic concepts are clearly understood and their implications recognised and deeply internalised.

This paper aims at providing an overview of the major challenges and potentialities of the first year general chemistry course. The previously-recalled perspectives are utilised as a convenient framework enabling a first-approximation grouping of observations, considerations and inferences. Both the cross-contexts character and significant contextual features are highlighted when relevant. The educational potentialities of the course are viewed as the "other side of the coin" with respect to the challenges and, therefore, are intrinsically embedded in the outlines of addressing options and their expected outcomes. A variety of explored addressing options are outlined and discussed, on the basis of more than twenty years direct experience with the first year general chemistry course. Particular emphasis is given to novel – or even unconventional – approaches suitable for interactive teaching, or aimed at stimulating students' active engagement both in the learning process and in the very addressing of the challenges they experience. Illustrative examples are provided to substantiate the discourse and make it concrete.

Following the active interest by researchers, the existing literature on the challenges posed by the first year chemistry course and its various aspects is very abundant. To be at least basically meaningful, a literature review for each of them would – alone – exceed the space suitable for an article. Therefore, only few examples are cited, to offer a hint of the attention that each issue has attracted.

1.2. THE TRANSITION FROM SECONDARY SCHOOL TO UNIVERSITY

The transition from secondary to tertiary education is a vast focus of educational research, in view of the difficulties frequently experienced by students entering universities. The transition implies major changes in study approaches and in the ways in which the content is approached. The "new" approaches require more attention to concepts, and the ability to relate concepts to each other, to the solution of problems and to experimental observations. They also require greater study independence. All this demands active mental engagement from the learner. When learners have acquired passive study-attitudes in previous instruction, the need for active engagement demands a huge paradigm shift in their habits.

Investigations of the difficulties of the transition have been carried out in many contexts (e.g., Chipere, 1993; Nyapfeme & Letseka, 1995; Mammino, Mathibeli & Mutambala, 2000; Markic & Eilks, 2008). Cherif & Wideen (1992) view it as a transition between two cultures and conclude that "It should come as no surprise that for many students a year is required to adjust to the new college/university setting". The different "cultures" are marked by changes both in some concepts' features and in the attitude toward science concepts: "In high school students were often taught that what was printed in the text was the truth, only to find it being challenged or changed by the time they reached university". The opinions of interviewed students offer interesting insights into the reasons for the gap in sciences courses: "High school science courses are centered around facts, while in university science courses are centered around theories and ideas as well as facts"; "While there is little challenge in high school science courses, there is a great deal of challenge in university science courses".

Students entering universities are increasingly underprepared for the requirements of university studies. Although most of the considerations and examples in this paper are based on direct experience in a disadvantaged context (UNIVEN), there is an increasing "globalisation" of factors for which students entering universities are often not ready for it. Many universities organise and advertise special programs to assist in the transition phase. Some educators propose approaches engaging both the secondary and the tertiary levels. For instance, Higgins, Mullamphy & Belward (2009), consider the problem of "the drop in standards of students entering first year university mathematics in Australia"; acknowledge that the common response "to reduce the difficulty level of the first year mathematics courses… has had limited success, with students passing first year mathematics but lacking preparation for the higher years". An analogous description could apply to first year chemistry courses in many contexts. Higgins, Mullamphy & Belward came to the conclusion that "If realistic change is to be made in bridging this gap, then the problem needs to be addressed at both the tertiary and secondary level" and designed a program to bring "mathematics into high schools" that proved "'to be a small but significant start in helping to bridge the secondary-tertiary gap". An analogous experiment (endorsed by OCED and OCCSE) had been carried out in the early Sixties in Italy, with "pilot" chemistry courses in selected secondary schools; students who took those courses went smoothly through first year chemistry courses; regrettably, the experiment did not have a continuation beyond the planned years of "pilot" testing.

The difficulties regarding learning and communication skills are often comprehended under the concept of inadequate *epistemological access*. The major factor is inadequate language mastery, which is now-a-days reaching worrying levels not only in second-language-instruction contexts (Mammino, 2005, 2006, 2007 & 2009; Mtshali & Smillie, 2011), but also in mother-tongue-instruction contexts in which the extent of the theoretical study of the mother tongue at pre-university level has decreased sharply in the last decades (Mastrocola, 2010). The problem mostly concerns the ability to read complex sentences, to understand complex discourses, and to write about something in a logically organised way, using grammatically correct sentences and selecting a wording consistent with the nature of the scientific information involved (Mammino, 1995). This has huge hampering effects on science learning, because understanding concepts depends on understanding the language through which they are expressed and because of the general fundamental importance of language in the science discourse (Bruner, 1975; Munby, 1976; Carré, 1981; Davies & Green, 1984; Muralidhar, 1991; Sutton, 1992; Wellington & Osborne, 2001; Norris & Phyllis, 2003; Fang 2006; Brooks, 2006; Mammino, 2014a). Remedial measures have already been introduced in some contexts; for instance, in Italy, several universities have introduced Italian language courses for incoming students, to upgrade the mastery of the mother tongue to the complexity levels that are required for university studies (Mastrocola, 2010). The integration of science learning and language learning, combining English and mother tongue, can be a viable option to upgrade the epistemological access in contexts like UNIVEN, or other institutions in South Africa (Mammino, 2012). It is practically impossible to compensate, within the general chemistry course (or other first year courses), all what a student has not learnt previously, but should be part of the acquired knowledge and skills necessary to approach university contents. A period when the student learns how to approach chemistry at a basic literacy level (how to understand a chemistry text instead of memorising it, how to write about chemistry concepts, how to understand the logic of a problem-solving procedure – all of this utilising a limited number of fundamental themes) can be the most effective remedy to bridge the gap (Mammino, 2012).

Other components of the epistemological-access inadequacies of students entering the first year are often determined by language-mastery inadequacies, as these hamper the development of other skills (Mammino, 2010a). The outcome may comprise inadequate of poor visual literacy, inadequate familiarity with essential features of the scientific approach, and inadequate familiarity with mathematics and its roles in the other sciences. Again, approaches integrating language and chemistry (or science) learning can be viewed as potentially effective (Mammino, 2012).

Inadequate language-mastery is often a major cause of the frequent all-pervasive passive attitude equating learning to passive memorization, divorced from understanding. Secondary instruction rarely opposes the development of passive attitudes, and in some contexts fosters it. The shift from passive attitudes to active engagement is not easy for the learner. Interactive teaching options since the first year courses constitute the best choice, by implicitly presenting the shift as a component of the overall secondary-tertiary transition. Furthermore, the advantages of interactive teaching (enabling early identification of existing problems – from misconceptions to inadequacies in specific skills – and real-time responses) have paramount importance. Stimulating students' participation and active engagement may require the design of unconventional approaches, tuned to the attitudes and responses in a specific group and in a specific time; some examples are given in Mammino (2011).

1.3. THE CHALLENGES OF CHEMISTRY LEARNING

The first year chemistry course poses the typical challenges of chemical education in a magnified way, because students often encounter "real chemistry" for the first time. The challenges are largely related to the nature of chemistry as a science characterised by fundamental interplays: interplay between macroscopic and microscopic descriptions, interplay between *qualitative* and *quantitative*, and interplay between *general* and *particular*. The interplays – largely determined by the individuality of substances and by the fact that the properties of substances depend on the properties of their molecules – pose substantial learning challenges because of their inherent complexity and their inherent relationships with crucial aspects of the scientific method.

The interplay between the macroscopic and microscopic descriptions is the most amply investigated (e.g., Gabel, Samuel, & Hunn, 1987; Gabel, 1993; Smith, 1996; De Posada, 1997), because of its fundamental role in chemistry, where observed properties and behaviours are interpreted in terms of what atoms and molecules do. Visualization plays important roles in the familiarisation with the microscopic level of atoms and molecules (Tasker & Dalton, 2006 & 2008; Gilbert, 2005 & 2008; Mammino, 2008), and the interplay between language and visualization can largely enhance the benefits of visualization, above all in situations in which students' visual literacy is not fully adequate and they need guidance to read images (Mammino, 2010b & in press). Visualisation and its interplay with language are also effective interaction tools, e.g., for the introduction of molecular formulas and the 3-dimensional structure of molecules through collaborative drawing of representations on the basis of essential geometry information (Mammino, 1999). Fig. 1 (Mammino, 1994 & 2003) shows an example concerning the nature of chemical reactions. The teacher draws the first image on the board, with only reactants present; then starts drawing the second image, showing two water molecules formed, and asks the students to complete it, individually, on their notebooks. Most students copy the two water molecules on the products side, but do not delete the corresponding oxygen and hydrogen molecules from the reactants side. This prompts a discussion, until students identify which molecules, and how many for each element, should be deleted from the left hand side. The exercise proceeds with the subsequent formation of more water molecules and corresponding deletion of reactants molecules. In the first exercise of this type, reactants are proposed in stoichiometric proportions. When the main concepts (formation of products and parallel disappearance of the reactants in certain proportions) are acquired, a new exercise considers a situation with one of the reactants in excess; the way it illustrates that part of the reactant in excess remains unreacted, because the other reactant is exhausted, is quite effective, as the students reach this conclusion "manually", through their drawing.

The interplay between *quantitative* and *qualitative* aspects is extensive in chemistry, where the qualitative component (the nature of individual substances) is all-permeating. It can be highlighted on many occasions. For instance, the qualitative features of chemical reactions (which types of atoms, which types of molecules) and the quantitative ones (how many of each type) both play essential roles for conceptual understanding and for applications in stoichiometric calculations. Systematically reading chemical equations in these terms ("x moles of X react with y moles of Y to give p moles of P and q moles of Q") facilitates the internalisation of the association of qualitative and quantitative aspects.

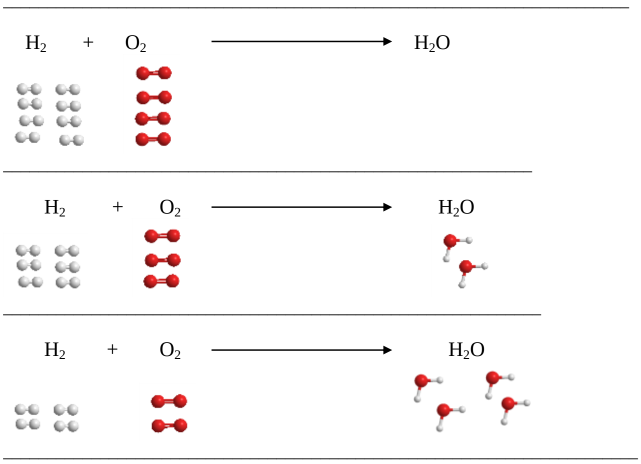

Figure 1. Stepwise illustration of what happens during a chemical reaction, utilising visualizations suitable for in-class interactions (collaborative building of the representations.

The distinction and interplay between *general* and *particular* are fundamental method-related aspects. They require the ability to distinguish between what is valid in general (for all the cases of a given type) and what is valid for particular cases (where often the *particular* refers to something that is different for different substances). Students often experience difficulties with the distinction, likely because their attention has never been explicitly attracted to it, and because of the impact of inadequate language mastery (Mammino, 2001). Typical examples are statements such as "a solid melts at 273 K" or "a liquid boils at 100°C", frequently encountered at first year level. The impact is not limited to the expression level, but has also implications for problem solving, even in further courses. In the second year physical chemistry (chemical thermodynamics) course, a non-negligible number of students assume that any solid melts at 0^oC and any liquid boils at 100^oC on solving problems on the enthalpy or entropy changes accompanying multi-step processes (e.g., by treating nitrogen as if its melting point were 0^oC). When difficulties with the distinction are diagnosed, it becomes necessary to stress the difference frequently, in different contexts. For instance, it can be part of the short in-class questions utilised to check students' existing conceptions (Mammino, 2013a), by asking questions like "at what temperature does a solid melt?". The nearly unanimous answer "0^oC" provides the opportunity to stress that different substances have different melting points, and also the importance of checking whether we are talking of something that is true for all the cases, or something that is true only for a specific substance or a specific case. Examples from the surroundings (all the things that are solid in one's environment) are particularly effective because of their concreteness. They also contribute to counteract the dichotomy between students' awareness of everyday experience (they obviously know that lots of things are solid around us and that the room temperature is above 0^oC) and their perceptions of what they expect to be correct in the chemistry classroom (0^oC as melting point for any solid).

1.4. A COURSE BETWEEN PAST AND FUTURE

The first year chemistry course is a course "looking" simultaneously in two directions: the past, i.e., the previous instruction, from which students have often inherited imprecise views and misconceptions; and the future, for which the first year course poses the foundations, important above all for those students who will encounter other chemistry courses in their learning career. Experience in a given context makes a teacher aware of the possible inherited misconceptions, thus enabling timely suitable interventions at early stages in the course. Direct experience with the teaching of more advanced courses also highlights aspects that are often not completely understood at first year level. Combining the two perspectives (awareness of the past and of the future) enables higher systematicity in the interventions within the first year course. A high number of examples could be considered; some are briefly recalled in the next paragraphs. The general underpinning (or methodological and philosophical perspective) is that of using rigour as a pedagogical tool (Mammino, 2000a) and simultaneously training students to rigour in chemistry (Bradley, Brand & Gerrans, 1987) to ensure clearer understanding.

Misconceptions may concern mathematical tools that are important in chemistry, such as the direct and inverse proportionality concepts. Experience at UNIVEN has shown nearly generalised misconceptions based on previously provided definitions for which two quantities, x and y, are directly proportional if y increases as x increases and inversely proportional if y decreases as x increases. Consistently with these definitions, many students identify dependences such as quadratic, logarithmic or exponential as direct proportionality, because for all of them "y increases as x increases", and identify a straight line with negative slope as inverse proportionality because "y decreases as x increases". The importance of correcting these misconceptions in a convincing way since the first year level is stressed by the frequent permanence of these errors in second and third year courses. The combination of language and visualization offers the best tool to clarify these concepts (Mammino, 2014b).

Definitions play fundamental roles in the sciences. An important aspect, requiring adequate stressing, is their operational role: a definition must provide all the information that is necessary for the identification of the object or situation that is being defined (Mammino, 2000b). The awareness of this is rarely acquired in pre-university instruction. The previously mentioned definitions of direct and inverse proportionality constitute a clear example, as they do not provide criteria to distinguish between direct or inverse proportionality and other types of relationships also corresponding to "y increases as x increases" or "y decreases as x increases". Several other definitions inherited from the past require deep analysis, whose most apt place is the first year course. For instance, the definition of molecule as "the smallest part of a compound that maintains the properties of that compound" requires critical analysis, because it would exclude the molecules of elements (H_2, O_2, etc.), thus not providing criteria for one to be able to recognise all molecules. The more rigorous definition of molecule as a “stable grouping of atoms bonded to each other” (or simply “a stable grouping of atoms”) provides a sound criterion, which can be stressed through visualization of molecular structures, becoming integral part of the familiarization with the world of molecules.

The definition of catalyst as “a substance that speeds up a chemical reaction without taking part in the reaction” requires critical analysis, because the catalyst does take part in some steps of the reaction (intermediate steps).

The definition of oxidation number as “a number that indicates the number of electrons lost, gained or shared as a result of chemical bonding” requires critical analysis, because the concept of “electrons lost” or “electrons gained” applies only to ionic compounds, and the oxidation number surely does not indicate the number of shared electrons. The last aspect is clearly highlighted by drawing the Lewis structure of any molecule of elements (H_2, F_2, etc.) and recalling that the oxidation number of each of the two atoms is zero, but the number of shared electrons is two. The use of visualization to explain a rigorous definition of oxidation number and its operational character is outlined in Mammino (2014b).

If the operational character of definitions is not adequately established in the first year course, definitions without operational character may surface in subsequent courses. For instance, second or third year students may provide the definition of chemical equilibrium as “a chemical reaction is at equilibrium if the chemical potentials are equal at both sides”; however, this is not operational, because chemical potentials of individual species are not measured directly in the laboratory (while concentrations are). Altogether, familiarising students with the meaning and roles of definitions contributes to a better understanding of the first year material, to the correction of misconceptions, and to set sound bases for future chemistry courses.

The statements of laws may also require critical analysis. For instance, the memorised statement of the Hess law that most students have inherited from previous instruction states that ‘the heat accompanying a chemical reaction is the same whether the reaction occurs in one step or in many steps”. Although this is literally true, it does not respond to reality for most of the cases in which we apply the Hess law. We apply it as a “formal” tool, i.e., the set of chemical reactions that we utilise to obtain the reaction whose enthalpy change we want to calculate is a “formal” set, and has nothing to do with the steps through which the reaction actually occurs; it is an algebraic exercise, not the chemical reality (Mammino, 2013b). The inherited previous statement leads students to believe that those steps are real. For instance, after an exercise in which the enthalpy of combustion of propene was calculated utilising the known enthalpies of the following reactions.

a) $C_3H_{6\,(g)} + H_{2\,(g)} \longrightarrow C_3H_{8\,(g)}$

b) $C_3H_{8\,(g)} + 5\,O_{2\,(g)} \longrightarrow 3\,CO_{2\,(g)} + 4\,H_2O_{(l)}$

c) $H_{2\,(g)} + \frac{1}{2}\,O_{2\,(g)} \longrightarrow H_2O_{(l)}$

A quick survey showed that students believed these to be the actual steps through which the combustion of propene occurs.

Many other themes and concepts of the first year chemistry course could be analysed in similar ways. A number of them have been objects of individual studies. For instance, the inherited perceptions of atomic orbitals as something like “houses” or “rooms” for electrons, and the misconception considering the spin as related to a rotation of the electron around its axis, have been analysed in Mammino (2013c).

Some interventions to better elucidate first year concepts may be prompted not by diagnosed misconceptions, but by the requirements of more advanced courses (a sort of “feedback” from the future). For instance, teaching the process technology course (introduction to chemical engineering, a third year course at UNIVEN) has highlighted the importance of stressing conservation and non-conservation aspects in chemical reactions since the first introduction of the reaction concept.

Analysing what is conserved (the total mass, the mass of each element, the moles of each element) and what is not conserved (the mass of individual substances, the moles of individual substances) favours a better understanding of what happens in a chemical reaction even in the first year, and provides bases for future courses (Mammino, 2005b).

1.5. EDUCATIONAL IMPLICATIONS OF LOGISTIC CHALLENGES

The first year chemistry course is often a large-enrolment course, above all when the course is not individualised in view of different degree options, but is comprehensively offered to all students registered for science-related degrees (as is the situation at UNIVEN). Educational research has investigated the challenges of large-enrolment classes and the possible adaptations of educational options to meet the needs of these classes without renouncing important benefits, including the benefits of in-class interactions. Writing may become a teacher-student interaction tool simultaneously available to many students and enabling follow-ups that benefit all students (Cooper, 1993; Mammino, 2013a). Experience within a specific context enables a teacher to "invent" approaches that can be suitable to attract students' attention and stimulate participation even in large-enrolment classes in disadvantaged contexts, by responding to the specific features of each specific group (although somewhat changing with the changing students' population from year to year) (Mammino, 2011).

1.6. DISCUSSION AND CONCLUSIONS

The main objectives of the first year general chemistry course comprise students' familiarization with chemistry and its interpretation models (including the microscopic world of atoms and molecules), and the acquisition and possibly deep internalization of fundamental concepts, to build a sound foundation for further chemistry courses, or for the use of basic chemistry information in other professional activities.

The challenges and potentialities of the first year chemistry course are common to all contexts, although concrete features may differ – even widely – from one context to another. They relate mostly to the transition from secondary to tertiary instruction. In recent years, the difficulties are enhanced by inadequate acquisition of basic concepts in previous instruction, and inadequate development of fundamental learning tools, first of all language-mastery.

The ways of approaching the challenges may be different in different contexts. However, the analogies between several diagnosed problems and between observed trends (including the lowering of secondary instruction levels, or the fast deterioration of language-mastery levels, affecting many contexts) point to a phenomenon that, although possibly not yet world-wide generalised, concerns a large portion of the world educational contexts. Thus, the search for effective addressing approaches, and for their continuous optimisation, can be viewed as a common effort, which is continuously enriched by interchanges of experiences.

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