Stoichiometry's PCK of University Chemistry Professors

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Abstract

The purpose of this paper is to document the Pedagogical Content Knowledge (PCK) for a set of four university chemistry professors teaching Stoichiometry; i.e. the study of the mass and amount of substance ratios between two or more substances undergoing a chemical change or, in brief, 'the science of chemical calculations'. This topic can be taught with a simple algorithmic purpose (going for immediate procedures without much understanding about what to do and/or why doing it) or it can be used to reinforce crucial concepts on the chemical reaction or even the particulate constitution of matter. A discussion is presented on the approach given by these four professors in their General Chemistry classes, which has been classified as Conceptual, Representational, Contextual and Procedural. Results are conclusive on the various pedagogical focuses on three of the approaches (Representational, Contextual and Procedural), and the equivalence of the four professors Conceptual approach. Results also reveal a link between Conceptual and Procedural knowledge.

Keywords

Pedagogical content knowledge, Content Representation, Conceptual profile zones, Stoichiometry, University level

Introduction

Shulman (1986, 1987) introduced the term pedagogical content knowledge (PCK) in order to draw attention to the value of the special amalgam of content and pedagogical knowledge that a teacher needs to be an outstanding one. Stoichiometry is a specific topic of the College General Chemistry course which PCK deserves to be documented and commented, as it has been pointed out by De Jong, Veal & Van Driel (2002). A survey on the literature on Stoichiometry is given and the contrast between algorithmic problem solving and conceptual understanding is included.

With the intention of documenting Stoichiometry's PCK, Loughran, Mulhall & Berry's (2004) proposal of Content Representation (CoRe) has been employed. The authors have used this methodology in previous researches and found it an interesting and appropriate method of documenting, portraying and analyzing PCK (Garritz, Porro, Rembado & Trinidad, 2007; Padilla, Ponce, Rembado & Garritz, 2008). Besides, we have chosen Magnusson's *et al.* proposal of five PCK elements, so the questions in the CoRe frame were adapted to this model.

Once the four General Chemistry teachers' CoRe was completed, in order to characterize them, the authors have used four categories of the sentences given therein: Conceptual (if understanding concepts is the central goal), Contextual (if he/she uses context as a motivational intention), Procedural (if he/she simply utilizes problem solving as an algorithmic objective) or Representational (if her/his aim is to make use of historical, analogical, metaphorical, demonstrational, experimental, digital, visual and other kinds of representations). In the next section this classification is explained in detail.

Stoichiometry teaching categories

Stoichiometry has played a key role in the evolution of chemistry as a science, marking the difference between qualitative and quantitative chemistry. As it was pointed out by Kolb (1978), the term ‘‘Stoichiometry’’ comes from the Greek *stoicheion* (element) and *metron* (measure). It was devised by German chemist Jeremias Benjamin Richter (1762–1807), as a concept designed to quantify the mass proportions of several combined substances. Richter found that the proportions of reagent masses were constant, e.g. the equivalent quantities of an acid and a base in a neutralization reaction were always constant. Richter was a mathematician interested in chemistry and he believed that chemistry should be considered a branch of mathematics; as Partington (1961) wrote: "he busied himself in finding regularities among the combining proportions". Richter was graduated as a Philosophiae Doctor in 1789, writing his thesis on the use of mathematics in chemistry. At that point in history, chemists were interested in making chemistry more mathematical, in the way that physicists had done subsequently starting with Galileo and Kepler.

As it was pointed out by Padilla & Furió (2008), Ernst Fischer (1754–1831) in 1802 called the attention to Richter's results saying that they could be presented in a table to show the equivalent weights of an acid and a base when they are compared with one thousand parts of sulphuric acid as the standard substance.

Just after the equivalentist paradigm was settled down, it came the atomic hypothesis by Dalton, who established an interpretation for the equivalent masses in terms of atoms and its amounts in compounds. The equivalentist paradigm belonged to a tradition of matter theory (continuity) that did not believe in the fundamental existence of the smallest particles (atoms). The atomistic paradigm belonged to a tradition of matter theory (discontinuity) that asserted the existence of discrete atoms and molecules.

The first special booklet, designed to specifically teach Stoichiometry to beginning students of chemistry, were written in 1865 by Frickhinger & Cooke (Jensen, 2003), which used the equivalent weights instead of the atomic weights, despite Cannizzaro's work presented in Karlsruhe in 1860.

Today, the literature related to Stoichiometry can be classified in two categories focusing:

- On problem solving, where we can find contextual problems (Pinto, 2005a, 2005b); analogies (Arce, 1993; Fortman, 1993; Merlo & Turner, 1993; Haim, *et al*., 2003); conceptual approaches (Krieger, 1997; Chandrasegaran, *et al*., 2009; Taasoobshirazi & Glynn, 2009); and visual representations (Ault, 2001; Arasasingham, *et al.*, 2004; 2005; Sanger, 2005; Evans, *et al.*, 2008);
- On students' conceptual understanding of fundamental ideas about the structure of matter before doing calculations (Nurrenbem & Pickering, 1987; Nakhleh, 1993; Lekhavat, & Jones, 2009).

Nevertheless, the research related to teachers' conceptions about Stoichiometry is usually referred to pre-service or secondary school teachers and there is almost nothing related to university professors. That is why our main subject is college chemistry professors' Stoichiometry PCK.

Based on the literature, we have chosen four different ways to classify Stoichiometry teaching as conceptual, contextual, procedural, and representational.

Conceptual

We will refer in this way to the construction of a holistic view of the content by inductive and deductive critical thinking (Arons, 1997). Conceptual knowledge is assembled by using different kinds of representation forms of the concept (especially verbal, graphic and symbolic), while procedural knowledge has rather a mathematical expression and meaning in applied actions. The aim is to get a full authentic comprehension of the underlying concepts and theories; to reorganize that knowledge using evidence; and to maintain a critical and more objective view of the subject.

Nowadays there are two main complementary trends that guide the purpose of teaching in this new century: one is the critical thinking ability to reason, which involves the dominion of specific contents, conceptual understanding of frameworks and processes of science; the other is the problem-solving/decision-making capacity to become an effective citizen.

We want to point out that our definition of conceptual understanding emphasizes breadth and depth of knowledge (Alao & Guthrie; 1999). Breadth is related to ‘‘the extent of knowledge that is distributed and represents the major sectors of a specific domain’’ and depth to ‘‘the knowledge of scientific principles that describes the relationship among concepts’’ (p. 244).

There are different authors who have pointed out the importance of helping students to get a better comprehension of what Stoichiometry means, further than just memorizing the steps required to make a calculation (Niaz & Lawson, 1985; Yarroch, 1985; BouJaoude & Barakat; 2003; Agung & Schwartz, 2007; Hand *et al.*, 2007; Taasoobshirazi & Glynn, 2009; Chandrasegaran *et al.*, 2009;). However, this conceptual process is not far away from problem solving; the point is what kind of problems should be proposed to students to let them have a better comprehension of Stoichiometry, like chemical equations, balancing, limiting reagent, chemical formulas, and so on. In this sense, BouJaoude & Barakat (2003, p. 2) mention that the solving problem process goes from “algorithmic, when conceptual knowledge is missing, to conceptual, when conceptual knowledge is available and when algorithms are stored meaningfully in memory". Yarroch (1985) did a research to identify how students understand chemical equation balancing and he reported that many students could balance an equation but when they are asked to represent it in molecular terms, many of them cannot do it. In this sense Yarroch says that students could make chemical equations balancing just in an algorithmic way without showing any evidence of understanding. Niaz & Lawson (1985) did a similar research and they say that "it is not recommended that students be given algorithmic solution strategies because this would allow them to correctly balance equations without the need for formal reasoning, thus depriving them of an opportunity for its development".

Acording to Ramsdem (1983) and Woods *et al.* (2001), (cited by BouJaoude & Barakat, 2003) meaningful learners have a deep approach to learning when they "build a holistic description of content, reorganize new content by relating it to prior knowledge and/or to personal experiences, are inclined to use evidence, and maintain a critical and a more objective view". In the same way, Hand *et al.* (2007) say that "conceptual scientific knowledge is an understanding of the ideas and theories that form the backbone of the scientific community's knowledge and includes the application of knowledge in novel problem-situations"

Contextual

Many other proposals to teach Stoichiometry suggest the importance of contextualizing exercises and lab work to make it interesting and motivational to students.

It may include several strategies (Crawford, 2001), such as learning:

1) In the context of one's life experiences or preexisting knowledge (relating);

2) By doing —through exploration, discovery, and invention (experiencing);

3) By putting the concepts to use (applying);

4) In the context of sharing, responding, and communicating with other learners (cooperating);

5) By using knowledge in a new context or novel situation —one that has not been covered in class (transferring).

We go beyond Alao & Guthrie's, as mastery of concepts in a specific area of science is not of main importance, but include their relationships and interactions discussed within everyday life phenomena (e.g., burning of a candle, tarnish of silver cutlery) and topics in the area of Science, Technology, Society and Environment (e.g., greenhouse effect, waste management and recycling).

In the context of this study, contextual learning is thus interpreted as students' ability to apply the learned scientific concepts to scientific phenomena in everyday life situations. This includes, for example, the ability to recognize new information as something different from one's current understanding and beliefs, to identify inconsistencies, and to construct explanations to reconcile knowledge conflicts, or to seek connections among diverse pieces of information.

Pinto (2005) says that contextualization can help students not just with Stoichiometry problems but, besides, to think critically and to realize the relevance of chemistry in their daily lives. In this sense some topics are: boron in fertilizers, mineral waters, calcium and physiology (Pinto, 2005a, b), gas chamber as the production of HCN from polyacrylonitrile (Hunter *et al.*, 1992), green chemistry (Cacciatore & Sevian, 2006); amino acid complementary (Vitz, 2005), kinetics in chemical reactions (Toby, 2000; Toby &Tobias, 2003), *et cetera*. We think that the contextualization of concepts which are very abstract is an important tool for teaching. However, we should think about the purpose of context. We agree with Pinto in what implies contextualization, but we also think that in many cases, despite the use of contextual exercises, many proposals are focusing also on the algorithmic process without considering a meaningful concepts' understanding.

Representational

One of the most interesting strategies that are reported in literature is the one related with different kinds of representations to improve learning of Stoichiometry (Arce de Sanabia, 1993; Fortman, 1993; Kashmar, 1997; Roser & McCluskey, 1999; Rohring, 2000; DeMeo, 2002; Witzel, 2002; Chebolu & Storandt, 2003; Haim *et al.*, 2003; Krieger, 1997). In this case we have found the following kind of representations: historical, analogical, visual, analogue maps, lab experiments or demonstrations, molecular models, and material models. In almost all of the above papers, the authors pay more attention to the relations among substance and its molecular representations and how these relationships can help students understand some Stoichiometry ideas; like limiting reagent, mass conservation, amount of substance, and so on. One example of analogy uses "Hamburguer sandwiches" (Haim *et al.*, 2003) where they allow the student to reflect about formulas, chemical equations, mass conservation, limiting reagent. The general idea is to let the students identify those simple mathematical procedures that are needed to solve stoichiometric problems, and lead them to feel the need for new vocabulary. Other analogy is the connection of particles with seeds or clips (Arce de Sanabia, 1993), where the key concept is the relative mass (Fortman, 1993) of the seeds to arrive to samples with the same number of them.

Some authors also include in this category the use of historical cases as a framework for students understanding (Giunta, 1998; Níaz & Rodríguez, 2001; Holton, 2003; Masson & Vázquez-Abad, 2006).

Procedural

Hereafter, we will call "Procedural knowledge" to the knowledge that requires the use of a memorized set of procedures for the solution of a problem, which denotes dynamic and successful utilization of particular rules or algorithms within relevant representation forms.

Most of the literature reports many different strategies to teach Stoichiometry, however almost all of them are focused on the procedure or algorithmic process (DeMeo, 2005; DeToma, 1994; Figueira et al., 1988; Ault, 2001; Kolb, 1978; Arasasingham et al., 2005; Murov & Stedjee, 2001) without considering if students achieve a meaningful learning. In all these reports authors make emphasis in the steps that students should follow to solve in a correct way Stoichiometry exercises. Some of them focus on the use of graph strategies, dimensional analysis, formulas or maps that let them memorize some constant values (like Avogadro's number or molar volume).

Ault (2001) presents several units used to measure an amount (mass, amount of substance, volume, and number of elementary entities) and how to convert one into another; and after that, he gives the way to create a visual representation for the solution of several typical stoichiometric problems (amount of substance to amount of substance, mass to mass, mass to volume, *et cetera*), and the different transformation factors that can be employed in each case.

The law of conservation of matter is a cornerstone in the development and advancement of modern chemistry, as expressed by Paixão & Cachapuz (2000). These researchers propose a very interesting teaching strategy based in history and philosophy, which departs from the combustion reactions and their contemporary economic, environmental, social and political contexts —exploring STSE perspectives in the teaching of science. Its exploration is centred upon the context of oxygen theory discovery. On the other hand, Özmen & Ayas (2003) analyse some misconceptions on the conservation of matter of 150 high school students concerning this topic during a chemical reaction in open and closed systems.

Agung & Schwartz (2007) developed a study to examine Indonesian high school students' understanding of conservation of matter, balancing of equations and Stoichiometry, in 22 schools with 19 teachers that validated the 25-questions survey used with 877 students. In general, student understanding of the fundamental principles in chemistry was low.

Conceptual learning vs. algorithmic problems

In this section the authors will centre on the supposed dichotomy between conceptual vs. procedural knowledge (in mathematics learning it has been summarized by Haapasalo & Kadijevich, 2000). There has been a large number of terms referring to those two kinds of knowledge, as it is described by these two authors in the following set of pairs of knowledge:

• Conceptual vs. practical;

• Knowing that vs. knowing how;

• Declarative vs. procedural;

• Facts vs. skills;

• Understanding vs. algorithmic;

• Theological vs. schematic;

• Deductive vs. empirical;

• Meaningful vs. mechanical;

• Logical/relational vs. instrumental

• Structural vs. operational

One has to recognize that the previous “cavalcade” represent certain polarity of the two knowledge types and can therefore lead to over-simplifications. In the conclusions the authors of this study will give their feeling about this alleged dichotomy.

Yarrock (1985) found that only half of the 14 high school students he interviewed were able to represent the correct linkages of atoms in molecules. That represents the difficulties of changing from one chemical level of representation —macro, submicro or symbolic— to the others (Gilbert & Treagust, 2009). The authors consider that Stoichiometric problems can be used to tackle misunderstandings in relation to the constitution of molecules and their formulas. But this implies to go further the algorithmic nature implicit in them.

It has been pointed out that students’ views of the particulate nature of matter are cause of concern (Gabel, Samuel & Hunn, 1987). Instructors of introductory courses know that many students do not understand how to solve problems and frequently resort to algorithmic solutions. In order to solve a problem correctly, the concepts involved in the problem must be understood and must be recalled without prompter. After a preliminary description of the problem is made, the problem needs to be re-described according to the problem solver’s frame of reference. In chemistry, to depict the physical phenomena in terms of the particulate nature of matter is helpful. The authors arrive to the conclusion that the ability to represent matter at the particulate level is very important in explaining phenomena as chemical reactions, changes in state, the gas laws, stoichiometric relationships, and solution chemistry. It is fundamental to the nature of chemistry itself.

Nurrenbem & Pickering (1987) started a series of papers that have been appearing in the *Journal of Chemical Education* related to the handicap that good stoichiometric problem solvers have to face with conceptual problems of basic chemistry. The authors applied some problems of algorithmic nature and some that require conceptual understanding to be solved. They have found students answering problems about gases without knowing anything much about the nature of a gas, or solving limiting-reagent problems without understanding the nature of chemical change. This result is consistent with the work of Yarrock (1985) and Gabel, Samuel & Hunn (1987).

Pickering (1990) goes beyond and asks what happens to the students when they go to other courses in chemistry; organic, for example. Are there two kinds of students, some who possess an ability to do conceptual problems and some who can solve mathematical-algorithmic problems without molecular understanding? Is the distinction between the groups a difference of ability or just a gap in knowledge? He stresses that presumably the instructor's and the textbook's emphasis has caused students to direct their efforts toward problem solving. The ability to solve a problem, while desirable in itself, does not seem to imply much real understanding of microscopic reality, and it is this understanding that is at the heart of chemical science.

Sawrey (1990) repeated the Nurrenbem & Pickering (1987) experiment with a sample of larger and more uniform group of university students. She found that students view the traditional type of questions as mere exercises but the pictorial concept questions as true problems.

The literature contains evidence that novice problem solvers in chemistry usually have greater success with solving problems of an algorithmic mode than problems having a more conceptual base (Bunce, 1993; Nakhleh, 1993). Niaz & Robinson (1992) concluded that student training in algorithmic-mode problems did not guarantee successful understanding of conceptual problems: "algorithmic and conceptual problems may require different cognitive abilities." (p. 54). Mason, Shell & Crawley (1997) worked on the following research question: "How do the general problem-solving procedures used by high-ability algorithmic/high-ability conceptual, low ability algorithmic/high-ability conceptual, high-ability algorithmic/low-ability conceptual, and low-ability algorithmic/low-ability conceptual students compare to each other and to the general problem-solving procedures used by the faculty expert in solving paired algorithmic and conceptual problems?". They conclude that regardless of the students' problem-solving ability, algorithmic-mode problems always required more time and a greater number of transitions for completion than did the paired conceptual-mode problems. However, regardless of the topic, all students correctly solved the algorithmic-mode problems more frequently than the corresponding paired conceptual-mode problems.

Alao & Guthrie (1999) analyse the influence of prior knowledge, use of learning strategies, interest and learning goals on conceptual understanding and the contribution of each one of the factors. These authors used an eighteen items knowledge test to measure conceptual understanding and the "Learning Goals, Interest and Strategy Use Questionnaire" to assess students' intentions to try to learn and understand ecological science concepts. They conclude that all factors are important to knowledge acquisition, but prior knowledge accounted for a significant portion of the variance in conceptual understanding after the contribution of interest, learning goals and strategy use were controlled.

The prevailing practice at the university level teaching of chemistry consists of lectures by the professor, follow-the-recipe laboratory activities, exercise-solving recitation sessions, and examinations oriented toward algorithmic or lower-order cognitive skills. The lecture format for instruction is incompatible with most higher-order cognitive skills and conceptual learning; and success in solving algorithmic problems does not indicate mastery of the relevant chemical concepts (Zoller *et al.*, 1995).

Science education researchers indicate that many novice learners in chemistry (Nakhleh, 1993; Nakhleh & Mitchel, 1993) are able to apply algorithms without significant conceptual understanding. The authors of this paper want to elucidate if this is due to those who teach introductory chemistry placing more value on algorithmic learning than on conceptual understanding, giving the learners the impression that science is “math in disguise” (Puskin, 1998).

Nakhleh, Lowrey, & Mitchel (1996) present the results of a project reform in the way undergraduate chemistry is taught. This project is set out to narrow the gap between conceptual and algorithmic understanding in freshman chemistry, using the Generative Learning Model of Wittrock (1986). The nature of the assessment in the course moved from a heavy emphasis on mathematical problem solving to a mix of conceptual questions and more traditional problem-solving questions involving the use of algorithms. The results are that special sessions and conceptual exam questions can improve students’ abilities to work successfully with both concepts and algorithms. The special sessions provided diagnostic assessment of strengths and weaknesses for both students and professor.

Lin, Kirsch & Turner (1996) applied Nakhleh (1993) paired type questions (one with conceptual emphasis and the other with an algorithmic objective) related to several topics of the General Chemistry course: gas laws, equations, limiting reagents, empirical formulas, and density. The authors' focus is on the selection on conceptual *versus* algorithmic by students belonging to minorities, arriving to the conclusion that this kind of students are more interested in concepts than in algorithmic aspects of chemistry problem solving.

It has been stressed by Nieswandt (2007) that Conceptual Understanding of science is a complex phenomenon. It incorporates an understanding of single concepts such as 'mass' or of more complex concepts such as 'Stoichiometry' —declarative or factual knowledge— which, following certain rules and models, combines multiple individual concepts —e.g., particle model, mass conservation, amount of substance, equivalent, *et cetera* — results in a new concept. Thus, conceptual understanding comprises declarative knowledge, procedural knowledge —concepts, rules, algorithms— and conditional knowledge —the understanding of when to employ procedural knowledge and why it is important to do so (Paris, Cross & Lipson, 1984).

Recently Salta & Tzougraki (2011) investigated more than one thousand students' (of grades 9^{th} and 11^{th}) performance with problems of conservation of matter during chemical reactions. These authors classified the problems in three types: "algorithmic-type", "particulate-type", and "conceptual-type". All the students had a far better performance in "particulate-type" problems than in the other two. Although students' ability in solving "algorithmic-type" problem increases as their school experience in chemistry progresses, their ability in solving "conceptual-type" problems decreases.

Until now, four different ways of teaching Stoichiometry have been discussed, including a general survey of papers reported in the literature. The authors of this study can say that these are more than just simple strategies, being teaching options that could be used in different moments in the classroom. In this research, as is shown below, we tried to identify all these teaching ways in college chemistry professors.

Methodology

The participants in this study comprised two female and two male professors. All were working full time in either a Mexican or an Argentinean university. We arbitrarily selected as their names Ana, Alex, Alice and Anthony. One of them has 15 years of teaching experience and got a PhD in Inorganic Chemistry with a postdoctoral work at a renowned European university. The second and third professors earned BSc degrees in Chemical Engineering and each one had more than 30 years of teaching experience. Finally, the fourth professor has a PhD degree in Biochemistry and almost 30 years of teaching experience. All of them are considered excellent teachers by their peers and their pupils.

The documenting of Pedagogical Stoichiometry Knowledge of four university professors has been developed using Loughran, Mulhall & Berry's (2004) proposal of Content Representation (CoRe). CoRe tries to find out in professors: their teaching objectives; the knowledge of alternative student's conceptions; the problems that commonly appear when learning; the effective sequencing of topic elements; the important approaches to the framing of the ideas; the use of appropriate analogies, demonstrations and examples; and insightful ways of testing for understanding, among others.

The questions of the CoRe frame that we have selected and adapted are presented in Table 1.

To start with our research, professors and authors discussed about which could be the central concepts or ideas related to teaching Stoichiometry (a crucial component of the Loughran *et al.* CoRe). We understand the central ideas as those that are at the core of understanding and teaching the theme; they are the topics that belong to the disciplinary knowledge which the teacher usually uses to split their classes. The clue is that those ideas sharply reflect the most important of the topic, maybe including some of its precedents.

Table 1 around here

After a long set of conversations, professors and authors arrived to the consensual agreement that the six central ideas that are involved in teaching Stoichiometry are:

a) Ratios and proportions,

b) Purity of substances,

c) Composition,

d) Empirical and molecular formulas,

e) Balancing chemical equations, and

f) Expressions of concentration.

Then the professors received the frame of Table 1 and were asked to answer the questions for each one of these central ideas; and to do it at home, without any pressure.

Based on researches reported in literature (Mortimer, 1995; Padilla, Ponce, Rembado & Garritz, 2008), we decided to use the classification of four conceptual profile zones that we chose to be the same as those mentioned in the section "Stoichiometry teaching categories" of this paper (although we have written there an extended explanation, a short description of how to decide the classification of phrases in each of the conceptual profile zones has been included), to start our analysis of what professors mentioned in their CoRes:

- **Conceptual**: Phrases related to the importance given by teachers to try students understand the fundamental concepts before start doing problems; to employ inductive and deductive reasoning and to the recognition that some ideas generate confusion among students because they are difficult to understand.
- **Contextual**: Sentences that use everyday problems or references that help students to contextualize the subject and make it closer to them. It also includes learning by doing or by applying and cooperating.
- **Procedural.** This zone is characterized by remarks on the use of algorithms and mathematical formulae as analytical tools applied without a complete understanding of the conceptual relationships involved.
- **Representational.** Comments on the use of ways for representing the topic, such as: historical narratives, analogies, demonstrations and laboratory work, metaphors, stories, web-based teaching, controversies, *et cetera*.

Each one of the authors did the classification of phrases in the CoRe answers to the questions of table 1 for the main ideas that are fundamental to teach Stoichiometry, by marking them in four different colours, each one corresponding to a conceptual profile zone, and discussing and solving the differences existent between their viewpoints. Then, the authors counted the number of times that each one of these profile zones appeared for each one of the professors and characterized them and expressed it as percentages.

Results

The result of counting each one of the responses belonging to each one of the conceptual profile zones is presented in figure 1 for our four professors.

Figure 1 around here

It is interesting to notice that all teachers show similar percentage of use of conceptual strategies, despite they do not have a similar complete profile (except perhaps Alex and Alice). It is interesting, because we have said how important is that students learn in a meaningful way, which means that students should understand those ideas in a qualitative way. The general profile of four teachers is quite different if we analyse each profile zone; for example, it seems that Anthony points out the importance of procedural knowledge to teach Stoichiometry ideas, in spite of the use of a conceptual way of teaching. At the same time, Anthony is somehow representational and contextual. Alice and Alex have a very similar profile because both of them are cognitive and representational. They make use of procedural knowledge almost in the same proportion (Alex a little more than Alice, but as we will discuss below, in a different way). Ana uses the same proportion of cognitive and procedural knowledge, and at the same time she uses contextual and representational ways of teaching, giving more importance to the first one. What it is important to notice is that, despite some of them seem to have almost the same profile, the main differences are in the kind of phrases they show in their CoRe, and that will be revealed below.

An analysis of each one of the four professors' answers is now developed.

Ana

To start with the analysis, we have selected four sentences of Ana, each one belonging to one of the profile zones, just to give examples of how they were selected. It is highlighted by the authors in italics some portions of the professor's CoRes that take us to the decision of categorising the whole phrase in a given profile zone.

Ana's procedural sentence is: "*It is fundamental* that students *know how to calculate* substances elemental composition from the chemical formula and *vice versa*. What I want is that *students learn how to do the process*, understanding each mathematical step involved."

She also mentions the following conceptual phrase, which alludes to the: "[students'] difficulties to *understand the meaning of formula subscripts*, because they change them while making the chemical balancing, without being conscious that those changes affect the *nature of the substances involved*".

The authors selected the following sentence of Ana as included in the Representational profile zone: "The *difficulties are based on the superposition of representational levels*: macroscopic, microscopic and symbolic".

One of her sentences in the contextual profile zone is: "In the STS context *those concepts can be applied to food, medicines and cleaning products*".

Ana recognizes the importance of mathematical calculations, but she emphasizes that it is quite important that *students understand each mathematical step* taken, which do not means that students already have had a meaningful learning. Because, in many cases they just learn algorithmic procedures for some style of problems and if they have to solve a slightly different one they do not know how to proceed. However, in her conceptual sentence she points out the importance for students to understand the chemical formula and the meaning of the subscripts, which implies that they must comprehend the concept of amount of substance. In the representational category, Ana was the only one who made emphasis in the three representational levels proposed by Johnstone (1993). It has been demonstrated that the relationships among them are the most difficult ideas to be understood by students in all educational levels (Gilbert & Treagust, 2009). Finally, she pointed out to her students that Stoichiometry is a subject that is used in many other matters_related to chemistry, and mostly in those of chemical industry.

Alex

Alex has showed to be quite consistent in his teaching strategies. He is making use of almost the same percentage of conceptual and procedural strategies. However, it seems that he makes emphasis in Representational strategies but pay little attention to Contextual ones. Examples of Alex answers for each category are the following:

> "In general, the process of *calculation and unit conversions in concentration problems could be mechanical*. Students could be efficient to do calculations in some way; however *the logic behind the process is still dark to them*" (Procedural).
>
> "At this point, to illustrate the idea of percentage mass/mass and mole fractions I always *use the traditional analogy of cakes* (with different masses) cut in slices sometimes of the same size and other times different" (Representational).
>
> "The concentration idea is something quite intuitive for students, because they have made lemonade at least once; that is why *I tried to represent those many*

> *ways to quantify the amount* of lemon juice, water and sugar using different ways to express chemical concentrations" (Contextual).
>
> For balancing chemical reactions Alex said "this is important not just from a conceptual view (like those factors that could affect the chemical reaction yield), but also when students have to study complicate subjects like chemical equilibrium (Conceptual)."

In these phrases, Alex is recognizing that students could be very efficient on Stoichiometry calculations; but, at the same time he is saying that sometimes this problem solving process could be dark to them, because they do not understand the logic behind. Besides this, when we analyse his CoRe it seems that he does not make emphasis in students' reflections related to the qualitative comprehension of these ideas. In the representational sentence, Alex makes use of analogies or material models to teach Stoichiometry concepts. This does not means that Alex strategies were not important, however we think that those levels of representation presented by Johnstone (1991; 1993) should be taught to students in a comprehensive way at the same time than the use of other models. One strategy used by Alex to teach relative masses has been implemented as a practical experience in the general chemistry lab work at our School of Chemistry (during the first semester). This representational strategy makes use of nails, nuts, screws, etc. to try students get a better comprehension of what are relative masses and why they are used in chemistry.

Respect to the conceptual category Alex is considering the importance that students get a meaningfully understanding of balancing chemical reactions, which means to understand what amount of substance is and why it is used for in chemistry, and this is one of the most complicated and important subjects, because teachers have different conceptions of amount of substance as Padilla, Ponce , Rembado, & Garritz (2008) have shown.

Alice

Alice is the professor with more phrases on the Representational profile zone, because she uses a lot of historical comments on her CoRe:

> "I know the transformations that these concepts have had, from *two visions: equivalentist and atomist*. I understand that mole concept first appeared in the equivalentist conceptual framework, with Ostwald, a denier of the atomic hypothesis.
>
> "A great problem to understand these concepts is the frequent changes they have had, so a *deep knowledge of history is necessary to understand them* until what we know now. It is a strange case this in which *the unit (mole) is first defined and explained and afterwards appears the magnitude (amount of substance).*
>
> "I know that amount of substance is accepted as a fundamental unit of the International System of Units, first by IUPAF and later on, in 1965, by IUPAQ. This moment was a breakthrough that started in Richter times at the end of XVIII Century who thought *in Stoichiometry as a way to "mathematize" chemistry to quantify chemical reactions*."

To the authors, historical evolution of chemical ideas is quite important for teaching and in some cases fundamental to students to recognize them because it will lead them to understand qualitative ideas and to comprehend them much better. In our CoRe the second question is about STS and historical ideas; however, just Alice uses the historical ones to "represent" how this subject has evolved from its origins as equivalentist paradigm to now, where atomism is the predominant paradigm. It is interesting to analyse the last sentence given by Alice in this category where we could reflect about how Stoichiometry was conceived as a way to mathematize chemistry, which is taken so literal for some teachers.

Alice also makes use of analogies, where everyday objects are always present:

> "Usually we go to the market to buy grapes by their weight not by their number. Of course that is the same with rice or beans, which are not bought by the number of grains. Only the great fruits can be bought by their number.
>
> "I use an analogy between the mass magnitude, its unit the kilogram, and the magnitude amount of substance and its unit mole."

Or demonstrations:

> "Classroom demonstration that allow students to understand the difference between to measure amounts or masses of diverse objects or substances, for example to have a dozen of flowers or 10 g of copper."

In these analogies and demonstrations Alice is trying that her students understand the difference among measuring big objects and tiny objects. In this way she wants to exemplify differences among mass and amount of substance helping students to comprehend these differences. One problem in her last phrase is "to have a dozen of flowers or 10 g of cupper" because the chemistry dozen is a return of considering amount of substance's unit mole, as a number, which is mistakenly used by teachers as well as in textbooks.

Anthony

This professor has a dominant procedural profile zone. Here we have some examples of their sentences classified in that category in his CoRe (the authors have emphasized the procedural portion of the phrases with italics):

> “I first let the students use the *procedure they feel experts on* and then I make them use *conversion factors* to solve the same examples.
>
> *“It is the mathematical model*, besides the conservation of mass law and the mole concept *what makes possible balancing equations to coincide with what happens in a real chemical process.*
>
> “I propose them to solve *a lot of exercises* of all kinds. This is enough to achieve good results.
>
> “The main difficulty in teaching Stoichiometry is to make students understand the relation between concentration and density, —in physics or chemistry units (here Anthony is doing a distinction between mass and volume, as physical units, and amount of substance, which he consider a chemical unit , as is the case with some other teachers that make a distinction between physics and chemistry magnitudes and units of measure). The second is to *convince* [students] that these *concentration expressions* are intensive magnitudes, calculated from quotients of extensive ones. Once these two obstacles are surpassed understanding goes better.
>
> In reactions where there is not change in oxidation state of the substances involved *it is enough for balancing the trial or algebraic methods*.”

All these phrases make special emphasis in how Anthony teaches Stoichiometry. He left students making a lot of exercises; it means that if they get a correct result they learn Stoichiometry. He handles the idea of *convincing students* instead of *helping them* to understand meaningfully these ideas. There are many teachers like Antony. Those who considered that left students to make exercises implies that they are doing "problem solving" when what they are really doing is solving algorithmic problems. In this sense, it could be interesting to reflect on what " does problem-solving mean". Solving problems go much farther from just follow a sequence of steps. It really implies that students can take decisions, can use the information in a correct way, as well as have the capacity of interpreting the results got. According to the authors, this process is quite related to a conceptual way of teaching. While teaching Stoichiometry, teachers pay more attention to the procedural process without considering the importance that students conceptualize basic ideas like amount of substance, concentration, limiting reagent, chemical balancing and chemical formulas.

Anthony has lower percentages of representational profile zone; nevertheless he, like Alice, makes use of historical representations; one of his phrases of this kind is the following:

> "The processes to purify substances come from alchemists' time, which in their eagerness of transforming metals into gold developed almost all purification processes that are used until now."

In his profile Anthony almost doesn't show sentences related to the contextual profile zone, however in the next sentence we could distinguish contextual and conceptual ideas.

> "I asked questions to know if they could distinguish among substances and mixtures, I used daily life products like food, drinks, medicines, etc. (contextual).

> To bring misconceptions from everyday world is almost always the reason of their confusion" (conceptual).

In this last phrase Anthony said that some ideas, brought by students from their everyday context make them get confused. This could be explained in terms of chemistry as a subject which is present in all everyday activities, however is not so easy to explain chemical facts and students may build some explanations using the knowledge learned in previous courses.

Conclusions and possible impact on teaching

A discussion has been set taking advantage of the four proposed ways of teaching Stoichiometry, but mainly on two of them: conceptual and procedural. We think that the profiles got in this research are very particular, because all teachers have almost the same level of conceptual profile zone, at the same time they have different percentage in the other categories. Alex and Alice use the same percentage of representational phrases, however the kind of "representations" used by them are quite different. Alex is more analogical, and Alice is more historical. What we can notice through all the literature and in this research is that Stoichiometry teaching tends to be more procedural because the ontological meaning and origin of this subject. As Alice said, this subject came from a "mathematization" of chemistry, and this idea has permeated in time chemistry education.

We considered that it is central to understand how procedural knowledge and conceptual knowledge relate to each other. It seems appropriate to underline that these two types of knowledge must be somehow related when the learning process is our focus. However, the variables in the assessment of this process promote or obstruct possible qualitative and quantitative links between the two knowledge types. One must take into account the complementary presence of both kinds of knowledge while learning; that is, the necessity of having both, procedural and conceptual components, in teaching science; a perspective similar to the "complementary" considered in the Middle-American and Oriental Worldviews.

The pedagogical approaches that derive from the enhancement of procedural vs. conceptual knowledge (or *vice versa*) cannot construct a modern view of teaching and learning, because both extremes mean a conventional teacher-based, behaviourist instruction of concepts and/or procedures.

Which factors in our education —or perhaps in the whole of society— are important for the development of our thinking abilities and multi-modality in human brains? This basically calls upon and considers the representations taught to follow the questions: do I know that (conceptual), do I know why (contextual and representational), do I know how (procedural) and do I know how I know (metacognitive).

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Table 1. Questions used into the CoRe frame to document chemistry professors' Stoichiometry PCK

1. Why is it important for students to learn this idea and what do you intend teaching it?
2. From STS and historical context, why is it important for students to learn this?
3. Difficulties/limitations connected with learning this idea
4. Difficulties/limitations connected with teaching this idea
5. Knowledge about students' thinking which influences your teaching of this idea
6. What representations do you use to engage students with this idea (analogies, metaphors, examples, demonstrations, reformulations, *et cetera*?)
7. Specific ways of ascertaining students' understanding or confusion around this idea

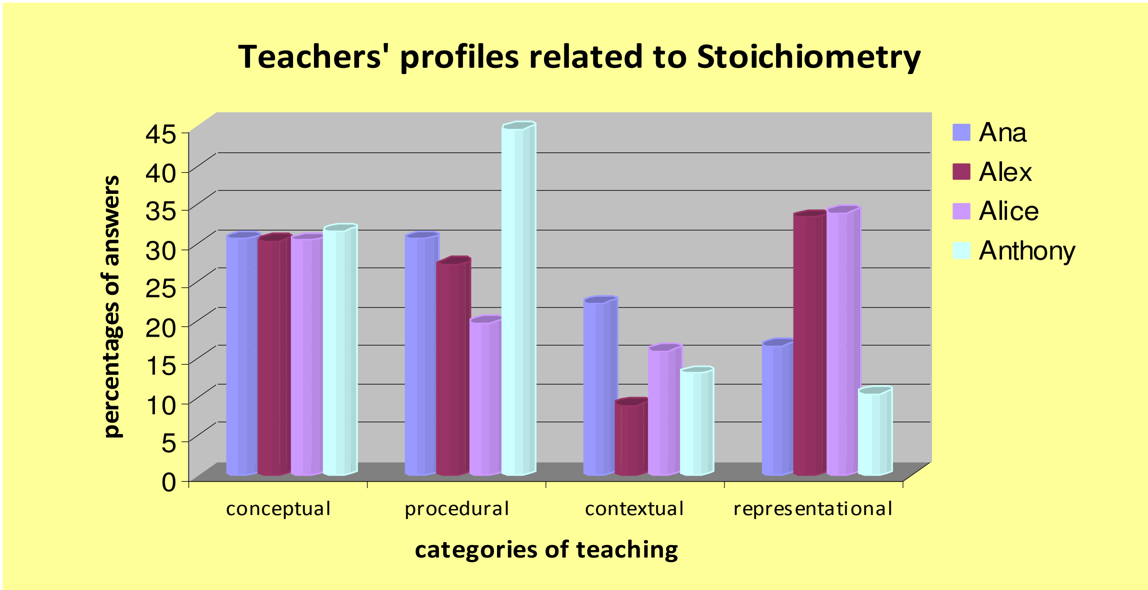

Figure 1. Professors' profiles related to Stoichiometry teaching. As was pointed out at the Methodology section of this paper, the authors have selected arbitrary names to maintain the confidentiality on the real ones.