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RESEARCH REPORT

Undergraduate Professors' Pedagogical Content Knowledge: The case of 'amount of substance'

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This paper documents the pedagogical content knowledge (PCK) of four university professors in General Chemistry for the topic 'amount of substance'; a fundamental quantity of the International System of Units (SI). The research method involved the development of a Content Representation and the application of Mortimer's Conceptual Profile Model to evaluate the way in which participants structured their knowledge of the topic. Five conceptual profile zones were defined: perceptive/intuitive, empiricist, formalist, rationalist, and formal rationalist. These zones were then used as criteria to classify participants' PCK as articulated in the framework of their Content Representations. As a consequence, four different conceptual profile graphs were constructed by plotting the percentage of times that each conceptual profile zone appeared. These conceptual profile graphs revealed the ways in which each professor conceptualised his or her teaching of 'amount of substance'.

Introduction

Shulman (1986) introduced pedagogical content knowledge (PCK) as a specific category of knowledge, one 'which goes beyond knowledge of subject matter per se to the dimension of subject matter knowledge *for teaching*' (p. 9; original emphasis). PCK has been interpreted in many different ways, but central to most conceptualisations is the view that PCK generally encompasses 'a teacher's understanding of how to help students understand specific subject matter' (Magnusson, Krajcik, & Borko, 1999, p. 96). Magnusson et al. (1999, p. 97) offer a helpful conceptualisation of PCK that comprises five components (see Table 1).

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Table 1. Five components of PCK according to Magnusson et al. (1999)

a. Orientations toward science teaching
b. Knowledge and beliefs about science curriculum
c. Knowledge and beliefs about students' understanding of specific science topics
d. Knowledge and beliefs about assessment in science
e. Knowledge and beliefs about instructional strategies for teaching science

While the concept of PCK has been widely debated in the literature (Gess-Newsome & Lederman, 1999), it is generally agreed that the development of PCK is embedded in classroom practice (van Driel, Verloop, & De Vos, 1998). Ideally, teachers should be familiar with students' alternative conceptions and learning difficulties, and be able to organise, arrange, deliver, and assess subject matter. Skilful teachers, it is argued, transform subject matter into forms more accessible to students, adapting it to the specific learning context, thereby developing their PCK. However, attempting to understand how PCK develops can be difficult to research because teachers do not necessarily find it easy to articulate their knowledge about what they do as practitioners. One way of gaining access to this tacit knowledge of practice is possible through Mortimer's (1995) Conceptual Profile Model (CPM), defined as a 'superindividual system of forms of thought' (p. 270), which describes different thinking routes to one concept. This means that one person could have a specific conceptual profile, depending on his/her personal philosophy, beliefs, experiences, and cultural background. According to Mortimer, this model could help researchers to deal with conceptual evolution in the classroom because it represents a change complemented by acquisition of consciousness (Mortimer, 1995, p. 284).

The CPM suggests that there may be different ways of thinking in a specific domain, each one represented by a Conceptual Profile (CP) zone, ranging from common-sense ideas to scientific ideas. Learning science does not involve the replacement of common-sense ideas by scientific ones, but rather the slow and progressive change from one CP zone to another involves developing a more complex level of knowledge of each. In our research, we have used this model to help characterise a pattern in teaching emphasis manifested by a specific professor and found that it sheds light on his/her epistemological and ontological commitments.

With the intention of looking into the nature of the development of PCK, we have employed Loughran, Mulhall, and Berry's (2004) methodology of Content Representations (CoRes) and Pedagogical and Professional-experience Repertoires (PaP-eRs). The first part of this methodology (CoRes) is based on a frame of questions that tries to develop and document the professor's own vision on how to teach the topic of 'amount of substance'. The central concepts or ideas are selected by both the participants and the researchers. The second part of the methodology (PaP-eRs) involves developing a narrative about how professors teach the concept in practice. PaP-eRs explicate different teaching strategies and how they are enacted. We have used this methodology in several previous investigations and have found it to be very helpful in portraying and documenting PCK. In this particular study, we used the specific attributes of a CoRe as a prompt for eliciting participants' understanding of the topic 'amount of substance' by identifying the most important teaching ideas of the specific content. In this way, the participant professors' answers allowed us to explore the nature of their PCK, its underpinnings, and reasons for the way it is conceptualised and actualised in their practice.

Backgrounding 'Amount of Substance'

The subject matter of this work is the concept 'amount of substance' and its unit, the 'mole'. This concept was selected for this research due to its importance as a quantity in chemistry, and also because of the well-documented difficulties associated with teaching and learning the concept. (As long ago as the early 1980s, Dierks, 1981, reported that there were 300 journal papers on this topic.)

One difficulty involved in teaching 'amount of substance' may, in part, be attributed to teachers' apparent lack of knowledge about the socio-historical context of this concept and the evolution of its meaning following the adoption of the atomic–molecular theory by modern chemistry. Several key papers on the topic point to the lack of an historical context as one of the main causes of the problems related to the teaching of the concept of the mole (see, e.g., Dierks, 1981; Furió, Azcona, Guisasola, & Ratcliffe, 2000; Strömdahl, Tulbert, & Lybeck, 1994).

In the eighteenth and nineteenth centuries two opposing paradigms were developed as a basis for the study of quantitative chemistry. One was based on the existence of atoms and molecules—the atomist paradigm—that considered as real the possibility of counting atoms and molecules macroscopically. The other one—the equivalentist paradigm—took masses of substances as a launch pad for explaining the proportion in which substances were combined (Padilla & Furió, 2008). The term 'mole' emerged in the equivalentist paradigm due to Ostwald's definition (Furió et al., 2000) of it as a chemical combination weight. Although the equivalentist paradigm emerged with a focus on a macroscopic subject—mass—modern equivalentists have used the mole as a tool to determine 'chemical equivalents', by counting moles of elementary entities; for example, electrons during their transfer in oxidation/reduction processes and H^{2+} ions in acid/base reactions. This situation has created conceptual difficulties for teachers and students because they ought to use 'chemical equivalents' instead of 'moles' of 'amount of substance'. On the other hand, modern atomistic defenders consider 'amount of substance' as the result of macroscopically counting unimaginable elementary units.

In Figure 1 (taken from Furió et al., 2000) the corresponding operative expressions between all variables are indicated. That is, the relations among 'amount of substance' (n), 'mass' (m), 'volume' (V), and 'number of elementary entities' (N) are mediated through the molar mass (M), the molar volume (V_m) and Avogadro's constant (N_A), respectively. (For a more complete description of the variables, see the figure of Strömdahl et al., 1994, p. 23.) This relationship is very important because professors generally do not use it to teach amount of substance, despite their tacit knowledge of it, because as Furió et al. (2000) insist, 'the "amount of substance" is not taught as a

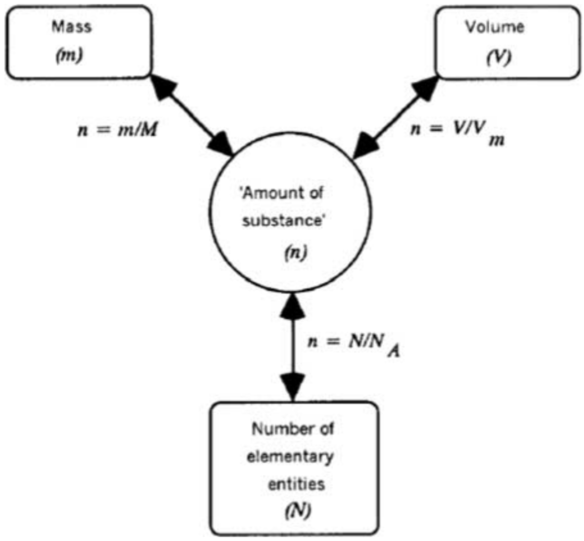

Figure 1. Relationship among the variables 'amount of substance' (n), 'mass' (m), 'volume' (V), and 'number of elementary entities' (N)

new quantity because it is considered to be the mass of substance (the expression "amount of substance" would be synonymous with "amount of matter")' (p. 1302). Generally, both teachers and students make a relationship among amount of substance only to mass, or volume (non-atomistic association) or number of elementary entities (atomistic association) (Furió et al., 2000).

Johnstone, Morrison, and Sharp (1971) identified the teaching of the mole concept as a source of learning difficulties for chemistry students. As noted above, much research has been published on the concept and the troubles associated with its teaching and learning (Dierks, 1981; Kolb, 1978; Nelson, 1991; Novick & Menis, 1976; Strömdahl et al., 1994). For instance, Furió et al. (2000) found that high-school teachers usually identify 'mole' with a chemical mass and/or with Avogadro's number of elementary entities, and reported that this is consistent with the introduction of the 'mole' concept made in most high-school chemistry textbooks that incorrectly attribute those meanings to it. One of the main conclusions derived from this investigation is that almost all college professors use the 'mole' unit in teaching General Chemistry courses, but the 'amount of substance' quantity remains inexplicably forgotten. In fact, nowadays, the term 'number of moles' is often used, although this is an unacceptable term according to the *IUPAC* (McNaught & Wilkinson, 1997). We suggest that the reason for this omission is related to an 'ahistorical' background of many college professors. Some professors have always taught this concept following an equivalentist paradigm, even if they also believe in the atomistic paradigm (Padilla, 2004), which reveals a contradictory way of thinking. Our view is that professors use a mixture of both paradigms without considering which one is better for the learning-teaching process. This paper then uses the CPM as an analytical approach in order to identify this ahistorical view through Mortimer's profile zones for each participant professor.

Research Objectives and Motivations

The present study attempts to ascertain the knowledge base of each of four college professors from Argentina and Mexico related to the topic 'amount of substance'. This investigation is derived from the development of CoRes (Loughran et al., 2004) and the examination of these CoRes against the five profile zones of Mortimer's (1995) CPM. It will be shown that there are differences between some experienced chemistry professors' uses of language and ways of thinking whilst teaching, and that PCK can be used to classify, construct, and represent the epistemological and ontological commitments of each professor by means of their CP. In this research we have used Magnusson's definition of PCK described in the Introduction section.

The study is based around the following research questions:

- What is the nature of university professors' PCK about 'amount of substance'?
- What are these professors' ways of thinking about this concept as explored through Mortimer's CPM?

The motivation for this research comes from the persistence of problems associated with student learning about the concept 'amount of substance'. The authors hypothesise that the quantity has been inexplicably 'forgotten' by both teachers and chemistry textbooks, which traditionally focus on 'number of moles' and 'chemical equivalent', and that students experience confusion across three aspects: mass, a given number of particles, and a stoichiometric approach to performing chemical calculations.

Methodology

The methodology developed by Loughran et al. (2004) to uncover, document, and portray science teachers' PCK comprises two tools: CoRes and PaP-eRs. Together, these tools are designed as both a methodology for discerning teachers' PCK as well as a way of portraying that knowledge to others.

In this study, we drew on the CoRe as a way of capturing participants' understanding of the subject matter and the particular aspects of that subject matter that they considered influenced their teaching. In using the CoRe, each of the professors was firstly interviewed and asked to provide a set of central ideas related to the topic of 'amount of substance' and its unit the 'mole'. The term 'central ideas' equates with the notion of 'big ideas' of a CoRe and captures participants' views of the major aspects of the topic on which a conceptualisation of that content is based. We understand as central ideas those that are at the core of understanding and teaching the theme; they are the topics that belong to the disciplinary knowledge that the professor usually uses to introduce and deepen the theme.

The research process involved seeking, through interview, the views of each participant regarding what each of them considered a set of central ideas for a specific topic. After analysing the four interviews of approximately 30 min each, and trying to integrate the central ideas obtained from each professor, the researchers presented a revised set of central ideas to each professor separately. This process was continued (i.e., revising, refining and re-presenting) until consensus among the four professors was reached regarding these ideas. Through the aforementioned process, we arrived at consensus in terms of the following six central ideas:

- Fundamental quantities of the International System of Units: amount of substance;
- relative atomic mass;
- mole, the unit of amount of substance;
- molar mass;
- Avogadro's hypothesis and molar volume; and
- number of elementary entities and Avogadro's constant.

Having established these central ideas, participants were again interviewed (approximately 1 hr each) to ascertain how they helped their students understand these ideas, and how they assessed their students' understanding of the ideas. This interview was based on the eight framing questions that shape a CoRe (see Table 2) and are important because of the way they help to uncover the depth of understanding; not only the subject matter itself, but also the ways in which those understandings shape the teaching (i.e., participants' PCK). However, for this research project we adapted the original eight questions by combining the first two and replacing the third and sixth with questions designed to explore new items based on particular aspects of PCK that were absent from the original CoRe prompts (see Table 3 for adjusted CoRe prompts). As Table 3 illustrates, we sought to probe historical, epistemological, philosophical and Science, Technology and Society (STS)-related aspects of the particular content under consideration in this study. These aspects were fundamental to the hypothesis on which this study was based (as outlined earlier); therefore, our changes to the CoRe were crucial to fully meeting our intended research objectives.

The relationship between the framing questions with the five components of PCK (see Table 1) and the modified CoRe is as follows. Questions 1–3 are related to component (a) because they reveal the main objectives associated with teaching the idea, but Question 3 is also connected to component (b) because these aspects form

Table 2. Loughran et al.'s (2004) original questions on each of the central ideas that constitute the CoRe

1. What do you intend the students to learn about this idea?
2. Why it is important for students to know this?
3. What else do you know about this idea? (That you do not intend students to know yet).
4. Difficulties/limitations connected with teaching this idea.
5. Knowledge about students' thinking, which influences your teaching of this idea.
6. Other factors that influence the teaching of this idea.
7. Teaching procedures (and particular reasons for using these to engage with this idea).
8. Specific ways for ascertaining students' understanding or confusion around this idea (Include probable range of responses).

Table 3. Questions posed to the interviewed professors, which constitute the CoRe in this research

1. Why is it important for students to learn this idea and what you intend teaching it?
2. From STS and historical context, why is it important for students to learn this?
3. What else you know about history, philosophy, and epistemology of this idea?
4. Difficulties/limitations connected with learning this idea.
5. Difficulties/limitations connected with teaching this idea.
6. Knowledge about students' thinking that influences your teaching of this idea.
7. Teaching procedures for engaging students with this idea (analogies, metaphors, examples, demonstrations, reformulations, etc.).
8. Specific ways for ascertaining students' understanding or confusion around this idea.

part of the scientific content of the idea. The fourth and sixth questions are related to component (c), and the fifth question is clearly related to an exploration of (e). The seventh question is also a part of component (b), but mainly of component (e). Finally, the eighth question was included to probe component (d) of participants' PCK. Hence the modified CoRe (Table 3) serves the same purpose as Loughran et al.'s (2004) CoRe since its structure and use allows researchers to both capture and portray participants' PCK in concrete ways.

After having explained in the second interview the kind of responses we were looking for, the professors were left with the CoRe frame to work on it during two more weeks. The CoRes from each professor were collected, and an array or matrix of cells was constructed with the central ideas in the first row and the questions in the first column (as per the original layout of a CoRe). In that way, an overview of information about the professor's knowledge of lecturing about 'amount of substance' could be portrayed, which in turn draws attention to the ways in which teaching and other pedagogic procedures are used in relation to the specific content.

Conceptual Profile

Through marginally adjusting the prompts that comprise a CoRe for use as a methodological tool for this research project, it became possible to uncover the epistemological and ontological commitments of each of the individual professors through Mortimer's (1995) CPM. Mortimer's model was originally designed to register the progress of students' mental status about some specific topic, but we have applied it to professors in this research. The model is based on a view of learning that requires students to change their conceptual profile; that is, 'conceptual change'. It therefore follows that teaching requires identification of those epistemological and ontological obstacles that students face and to respond accordingly. (Mortimer, 2001, identifies related modes of thinking and ways of speaking in the classroom by means of CPM.)

In this research, to construct the CP about an abstract chemical concept such as 'amount of substance', all of these considerations were taken into account as well as the need to show several zones, each one having categories with more explanatory power than its precedents. The following five CP zones were constructed using the method mentioned in the next section.

(i) *Perceptive/intuitive*. This zone includes ideas about 'amount of substance' that correspond to immediate impressions, sensations, and intuitions, lacking structure or systematisation. The analogy of the 'chemist's dozen' belongs to this zone because of its simplicity (Staver & Lumpe, 1993). Ideas that result from subjective and personal reflection are included in this zone because they constitute simple, everyday life experiences.

(ii) *Empiricist*. Ideas about 'amount of substance' determined objectively and precisely by the use of empirical scales, such as the mass or the volume of a definite quantity of substance, are placed in this zone. 'Amount of substance' may be better perceived by students by means of the determination of either the molar mass or the molar volume, as both concepts are closer to their everyday perception, evidently macroscopic in nature.

(iii) *Formalist*. This zone is characterised by the use of algorithms and mathematical formulae as analytical tools applied without a complete understanding of the conceptual relationships involved. The 'mole', mainly used to perform stoichiometric calculations, is devoid of any clarity about what the corresponding quantity represents.

(iv) *Rationalist*. This includes ideas about 'amount of substance' that imply a closer look at the atomic–molecular level. The discourse is fundamentally built around the nanoscopic view of 'amount of substance' expressed in terms of a 'number of elementary entities' without taking into account the macroscopic understanding of the concept.

(v) *Formal rationalist*. In this zone, 'amount of substance' consists of a conceptual network, not merely the result of primitive, immediate, and empirical experience. In this network, aspects of a macroscopic measurement of mass or volume are linked to the counting of a certain number of intangible entities. This zone sustains a coherent and balanced relationship between the macroscopic and the nanoscopic levels of explanation. The formal rationalist zone implies that an accepted scientific model of 'amount of substance' has been acquired.

This analysis of the five CP zones can be restricted since, historically, the concept of 'amount of substance' had been seen, as mentioned, through the prism of two paradigmatic conceptual frameworks: the *equivalentist* and the *atomist* paradigms. Thus, from this historical perspective, the concept 'amount of substance' is basically guided by two ways of thinking reducible to two or three of the conceptual profile zones: the equivalentist paradigm may be reducible to the empiricist profile zone because it has to do with the use of empirical measures (mainly due to its foundation on the concept of mass); and the atomistic paradigm may reduce to the rationalist or the formal-rationalist profile zones because both have to do with elementary entities, the last one in equity with a macroscopic way of counting them.

It may be asserted that both paradigms are incommensurable. The idea of incommensurability was introduced by Kuhn (1970) when he proposed that during a scientific revolution an old paradigm is replaced (in whole or in part) with an incompatible new one. Two rival paradigms are incommensurable if they assign different meanings to key concepts and possess different methods and standards, as is the case with the emphasis on mass in the equivalentist paradigm and that on particles in the atomist one.

Analysis: Classification of sentences of the CoRes into the five CP zones

The professors' CoRes were carefully read line-by-line by the first author to analyse the content and to classify them inside a given CP zone. She read through all CoRes to identify phrases in which 'amount of substance' was related to the use in daily life. She marked all such phrases with a yellow flag to decide afterwards if they could be classified into the first, perceptive/intuitive zone. Similarly, she marked with a green flag the sentences that used 'amount of substance' in relation to a mass or a volume as candidates to be classified into the second, empiricist zone; and with a red flag those sentences that emphasised the use of 'amount of substance' to make chemistry calculations to possibly include them in the third, formalist zone. Finally, she placed an orange flag beside all phrases that mentioned atoms, molecules, or any nanoscopic item to be further classified into the fourth, rationalist zone.

After the first author re-read each of the marked sentences, she developed, through discussion with the fourth author, a specific list of criteria that were used to redefine each of the first four CP zones, and wrote down those of the fifth zone, the formal rationalist. The first author then read through all marked sentences a third time and determined whether the selected CP zone met the written criteria, taking care to identify the sentences belonging to the fifth CP zone. The second, third, and fourth authors reviewed the final decisions of the first author. Once every sentence was allocated to a given profile zone, the number of sentences belonging to each zone was counted and recorded in a table, to allow for the construction of the CP graph.

Participants

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. Participants were anonymised in the research process, hence from here on the use of 'she' occurs regardless of the gender of the original participant.

Professor 1 had 15 years of teaching experience. Her PhD was in Inorganic Chemistry and she performed her postdoctoral work at a renowned European university. Professors 2 and 3 both earned BSc degrees in Chemical Engineering and each had more than 30 years of teaching experience. Professor 4 had a PhD degree in Biochemistry and had almost 30 years of teaching experience.

The following section outlines the results obtained when using the research method described above in order to explicate these participants' conceptual and pedagogic understandings of the concept 'amount of substance'.

Results

The selection of sentences below, taken from the four CoRes, are classified according to each profile zone to exemplify the construction of the CP graphs.

Perceptive/Intuitive

In general, professors have a notable propensity to talk about the 'chemist's dozen'; that is, to relate analogically a numerical quantity to the concept of 'mole'. We have selected the following two quotes from Professor 1, where she advises the use of large amounts such as 'a pile' or 'a bunch' as comparable with a 'mole'. She suggests an analogy to relate the molar mass with that of a dozen objects in the second sentence:

> In general I suggest to students troubled with the concept of mole to try and substitute this word for 'a pile' or 'a bunch' (It would be much easier to illustrate the concept by substituting mole for the cruder as 'a hell of a lot of').

> One of the everyday objects Mexican students count by the dozen are 'tortillas';[1] the analogy of molar mass with the dozen mass seems to work well.

Empiricist

This deals with the tendency to link 'amount of substance' with a mass (Dierks, 1981) as stated in Ostwald's definition, or a volume. Professor 2 pointed out that one of the problems is:

> Making students understand that a mole implies the measurement of elementary entities by the determination of their mass.

And, in another statement, Professor 2 identified the main hurdle for students as:

> The belief that amount of substance is a given mass of a substance.

To illustrate that the participant professors rarely use 'amount of substance' and that they frequently confuse it with 'amount of matter'[2]—a common mistake made by both secondary and university-level teachers—we selected the following passage belonging to Professor 1:

> It is possible to evaporate different quantities of water in a closed environment of variable volume (such as a balloon) and show that the volume of water vapour is proportional to the amount of matter.

Formalist

One of the professors' main ideas was that the mole concept is only useful to solve arithmetical problems, and to assess how students can develop those procedures without the need for a meaningful understanding of the conceptual framework. Some examples taken from the CoRe of Professor 3 are as follows:

> What they only need to manage is the resolution of arithmetical problems. I evaluated the students' knowledge through simple numerical tests; with this I could notice how much they have understood or where their confusion lies.

Professor 1 insisted on the quantitative relevance of the 'mole' concept:

> It is indispensable for pupils to understand precisely the concept of mole because all stoichiometric relationships are based upon it.

as well as Professor 2:

> It is the central topic of quantitative chemistry; it is involved in the majority of chemical calculations. It is a fundamental unit of measurement of the SI.

Several relatively old papers concur with this assertion (e.g., the initial sentence of Kolb's (1978) paper reads: 'One of the main reasons the "mole" concept is so essential in the study of chemistry is stoichiometry'; p. 728), a concern compatible with the formalist zone.

Rationalist

Professor 1 supplied another approach to this topic. She emphasised the 'mole' as a unit devised to count atoms, not to perform calculations:

> The mole is a unit used on a daily basis in chemistry; instead of counting atoms one by one we chemists count them by moles. Thus, the correct manipulation of this concept is of fundamental importance in the professional training of chemists. I try to enable students to understand the mole in the same way they understand pairs, tens and hundreds; words which identify a precise and finite number of objects. It is not necessary to know the number [of Avogadro]; it is enough to learn that the number of hydrogen atoms in approximately 1g of the gas is the same as the number of chlorine atoms in 35.5g of that substance.

This statement has been classified in the rationalist zone because it draws attention to the nanoscopic view of chemical systems, although it was agreed that the 'pairs, tens and hundreds' part of it should belong also to the perceptive/intuitive zone.

Formal Rationalist

Now we turn to the formal rationalist zone, for which three examples are given to fully characterise it. Professor 3 wisely introduced the equivalentist and the atomist paradigms of the 'mole' concept, when she said:

> I am aware of the transformations the concept of mole suffered when changing from an equivalentist to an atomist point of view … Furthermore, I understand that the concept of mole arose within an equivalentist conceptual framework in Ostwald's lifetime, as 'the mass in grams numerically equal to the molar mass', and that the concept of amount of substance acquired the atomist conceptual framework in 1961, with the definition accepted nowadays. This is a very rare case in which the unit mole was firstly introduced and defined years before its quantity, amount of substance.

Professor 1 correctly insists on the separation of ‘amount of substance’ from the concept of elementary entities. When she teaches ‘amount of substance’ she does not even mention Avogadro’s constant. She wrote:

> In my opinion, Avogadro’s number is an overrated chemical constant. Its numerical value is commonly overemphasized to the detriment of the mole concept. I illustrate chemical formulas through an explanation of the concept of mole, and to do this it is unnecessary to introduce Avogadro’s constant.

In sharp contrast with this point of view, we have selected the following phrase of Professor 3, where she understands that ‘amount of substance’ is related to the ‘number of elementary entities’, but in her teaching she seems unable to discern difference between both terms, employing one for the macroscopic level and the other for the nanoscale:

> The teaching procedures that I use to engage pupils with this idea are based on calculations that allow them to understand the usefulness of counting very small particles such as atoms and molecules, by a macroscopic procedure, with the quantity amount of substance.

Professor 4’s answers have largely been classified mainly in this zone, for example:

> It is essential that the students manipulate the units of the SI. Particularly, the unit for amount of substance is fundamental in experimental activities. I try to help them to learn that the mole allows the counting of elementary entities in an indirect way, from macroscopic measurements.

This statement was classified as formal rationalist because of its consistent and unbiased relationship between the macroscopic and nanoscopic levels of explanation. A long time ago, Novick and Menis (1976) remarked upon the long-sought-after desire for students to elucidate the interactions between macroscopic measurements and nanoscopic interpretations.

Implications for Teaching

We include here two of the topics highlighted several times by all professors as important implications for teaching, and because these two topics are considered by all of them as basic to understand amount of substance.

Relevance of Relative Masses to Teaching ‘Amount of Substance’

In the CoRes of our professors, the concept of relative mass appears most important because it represents the key for counting elementary entities by weighing. If a silver atom weighs nine times a carbon atom, a sample of silver that contains the same number of atoms as that of carbon will weigh nine times as much. That is why a mole of carbon has a mass of 12 g and a mole of silver 108 g (= 12 g × 9). The following sentence was provided by Professor 2:

> I think that without those concepts (relative mass and absolute mass) it would be very difficult understanding amount of substance … I use an analogy that has been very

> fruitful, I select different kind of seeds or other objects to determine their relative and absolute masses. At the end, it is possible to obtain almost the same number of seeds when the experimental relative mass is taken as weighing reference.

Professor 1 says:

> The mole concept is easier to illustrate with relative mass without talking of Avogadro's number. I like to illustrate the mole concept using nails, nuts and screws demonstrations in class.

As has been previously noted by Ainley (1991), problems exist among students with the use and meaning of the word 'relative', perhaps because it is the first time that they have seen such a word attached to a mass. To resolve this situation, the use of analogies with commonplace objects, as suggested by Professors 1 and 2, seems an appropriate course of action.

Suitable Use of All the Variables Involved

A second implication for teaching from this study is the recommendation for proper handling of the different variables that constitute each topic, several times mentioned in the CoRes of our professors (see Figure 1). For example, Professor 3 says:

> The Avogadro's hypothesis is really important because through it we can establish a relationship between a gas's amount of substance and its volume.

Professor 1 expressed the following:

> Once the mole concept is understood, it is easier to understand molar mass, which contains the Avogadro's number of atoms, molecules or ions. Masses are almost always different but not the number of particles that are contained.

Conceptual profile graphics. It can be argued that the percentage of times a professor's response was allocated into a specific CP zone represents a pattern of thought. The present study found that there are at least two opposing ways to teach the topic 'amount of substance'. These range from the equivalentist paradigm—represented by Professor 1 in Figure 2, armed mainly with an empiricist way of thinking, sustaining all her arguments on the fact that the relative atomic masses provide the same number of particles for any two samples of different substances, no matter what that number may be—to the atomistic paradigm—a formal rationalist zone represented by Professor 4, for whom 'amount of substance' is a conceptual network that involves macroscopic measurements of a mass or a volume, and simultaneously the counting of a finite and defined number of elementary entities.

Professor 1 seeks to teach 'amount of substance' through concepts such as mass, volume, and others associated with perception. However, she does not mention the concept at the nanoscale—as was the case with Ostwald's definition of 'mole'—or use Avogadro's constant. Professor 4, on the other hand, delivers a class in accordance with the atomist paradigm. She perceives 'amount of substance' as based

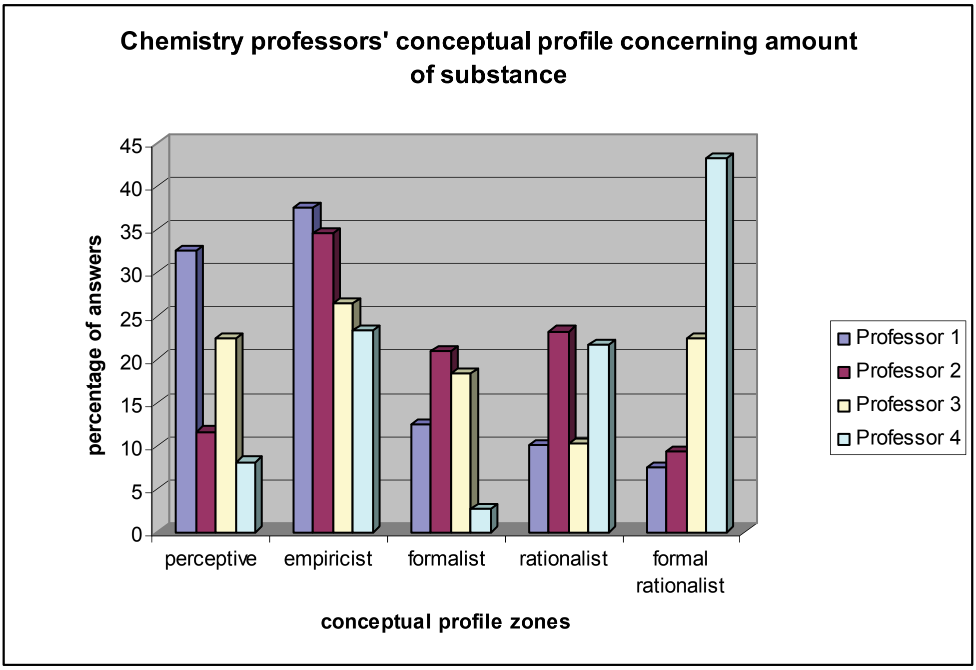

Figure 2. The four CP graphs, expressed as the percentages of answers from each professor on the CP zones; from the mainly empiricist (or equivalentist; Professor 1) to the mainly formal rationalist (or atomist; Professor 4)

fundamentally on counting nanoscopic entities based on measurements—of mass and volume—made in the macroscopic world. She almost always appeals to the scientifically correct concept, although sometimes she shows a tendency towards empiricism whilst avoiding any mention of 'amount of substance's' relationship with stoichiometric calculations—the formal zone.

In the middle of the classification lie two of the professors (Professors 2 and 3) that demonstrate a tendency towards empiricism, with shades of the formalist and the rational formalist zones. More specifically, Professor 2 shows a clear tendency towards empiricism whilst her teaching strategies seem also inclined towards the formalist and rationalist zones, as she sometimes made reference to the nanoscopic way of thinking when talking about the 'mole' concept. Professor 3 possesses the most heterogeneous way of thinking. She scored an intermediate position in all five CP zones.

Conclusions

This work is a sample of how the PCK of a specific topic ('amount of substance') can be documented, analysed, and better understood and follows Abell's (2007) call for 'More studies need to focus on the essence of PCK—how teachers transform subject matter knowledge of specific science topics into visible instruction' (p. 1134). As we have demonstrated through this study, Loughran et al.'s (2004) methodology for capturing PCK offers an interesting way of documenting and portraying the construct and, as also illustrated in this study, Mortimer's CPM looks to be a useful tool for sorting the epistemological and ontological statements of individuals.

Both methods can be used to efficiently characterise PCK and can therefore be useful in discussing divergent ways of teaching. The classification of these professors' CoRe statements into CP zones represents a valuable new tool in educational research on teaching performance, especially in the classification of professors' ways of thinking and acting in the classroom. We suggest that the combined use of both methodologies represents a unique and novel way of compiling and analysing PCK. Related to the research question on the nature of university professors' PCK about 'amount of substance', we have found two frames of teaching ideas, one centred in the empiricist profile zone and the other in the formal rationalist.

A second categorisation related to the history of chemistry has been proposed by framing the knowledge base of these professors into two incommensurable paradigmatic frameworks that stood in direct opposition during the whole nineteenth century: the equivalentist—related to the empiricist CP zone—and the atomist—corresponding to the formal rationalist CP zone. As this study has illustrated, this dichotomy similarly exists amongst these four professors. As a consequence, an aspect of understanding the foundational aspects of these participants' PCK is that it is perhaps easier for (these) professors—and for (their) students—to visualise 'mass' or 'volume' instead of 'amount of substance', because those two quantities are closer to their everyday life and intuition.

One important conclusion able to be drawn from this research project is that, in relation to a teacher's conceptual understanding, in order to grasp a fairly clear comprehension of 'amount of substance', the teacher must distinguish between this concept and the concepts of mass, volume, and number of elementary entities, as well as know the relationships between them. Further to this, teaching the relative mass concept to understand how 'amount of substance' is used to count a certain number of intangible entities is also important.

However, this kind of qualitative research has some characteristics that may be considered limitations. They are summarised as follows:

- The selection of phrases from the CoRe inside the diverse conceptual profile zones may vary depending on the researchers' biases.
- The selection of conceptual profiles is made in a subjective form. In this case it was based on the epistemological obstacles of the students as well as on historical facts. Each selection of CP zones is critical to arrive at meaningful research results. This methodology is not appropriate to portray the unlimited universe of teaching strategies, since it is an in-depth analysis of some ways of thinking and teaching, and its findings should not be extrapolated to all professors.

Nevertheless, despite these limitations, there is one stronger point. The methodology proposed is a tool useful to characterise different teaching methods and ways of thinking.

Notes

1. A thin Mexican pancake made with corn flour, usually eaten hot and filled with almost any kind of food, as a substitute for bread.
2. One has to recall that the term used in French for 'amount of substance' is '*quantité de matière*'.

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