PEDAGOGICAL KNOWLEDGE OF CHEMICAL EQUILIBRIUM. A COMPARISON BETWEEN HIGH SCHOOL TEACHERS AND UNDERGRADUATE PROFESSORS

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Abstract: Chemical Equilibrium is a central concept in the learning of chemistry and remains one of the most difficult to teach and to learn. The purpose of this study was to capture and portrait the pedagogical knowledge on chemical equilibrium of four high school teachers and four undergraduate professors for comparing them. The concept of «learning progression» has been used to explain the differences found in the two groups of teachers. The study was made using the content representation of Loughran et al. with a set of consensual central ideas selected by each group of academics. All of the participants are chemistry teachers who have taught chemical equilibrium for several years, so it is expected that all of them possessed a well-developed PCK.

Some of the main differences and agreements that have been found are:

- While in high school chemical equilibrium is grounded on kinetics explanations, in undergraduate it is clearly a thermodynamics topic. As a consequence, high school teachers do not mention either chemical potential or the progress of the reaction as important concepts in teaching chemical equilibrium;
- We have as a conclusion that this represents a learning progression, from kinetic to thermodynamic explanations at each educational level.
- Teachers interviewed of both levels do not clarify a clear purpose of teaching the central ideas and do not manage to differentiate between learning and teaching difficulties.
- At high school level the solution of algorithmic exercises has dominated over the rational domain of concepts, but in undergraduate the last domains over the former.
- Although professors claimed that abstract topics, such as reversibility and chemical potential are difficult for students to understand, they do not mention the use of simulations, animations or ICT as part of theirs teaching methodologies.
- Teachers of both levels do not have palpable ways to make a relation of all of these concepts to everyday phenomena.

Keywords: chemical equilibrium, learning progressions, pedagogical content knowledge, content representation
INTRODUCTION AND THEORETICAL FRAMEWORK

The content representation of Loughran, Mulhall and Berry (2004) to capture pedagogical content knowledge has been applied to four high school teachers and four undergraduate professors on the topic of chemical equilibrium.

This study concludes that exists a learning progression in relation to the learning/teaching of chemical equilibrium (CE). The lecturing focus on particle kinetics by the high school teachers is surmounted in the undergraduate level by a thermodynamics centre of attention.

First, students adopt a kinetic view of CE because in the general chemistry textbooks of high school it is presented as the equality of rates of the two reactions (forward and reverse). That is the way we have found the four high school teachers of this study make emphasis.

This approach is maintained at the general chemistry course at college level, but as students enter to the physical chemistry courses the view changes to a thermodynamic approach, where the professors on charge present the new variables involved, such as entropy, free energy, chemical potential and reaction progress.

Our Research Questions were:

1) How is the influence of teaching and textbooks in the Learning Progression of Chemical Equilibrium from kinetic to thermodynamic approaches?

2) What implications emerge for students learning from each one of these two approaches?

Pedagogical Content Knowledge

Teacher educators and educational researchers have emphasized the need to develop the pedagogical content knowledge (PCK) of the teachers and professors, as a useful tool to enhance students’ outcome. The concept has been recently re-defined in the October 2012 «PCK Summit» at Colorado Springs, CO, USA as “a personal attribute of a teacher and it is considered both a knowledge base and an action”. It is the “knowledge of, reasoning behind, planning for, and enactment of teaching a particular topic in a particular way for a particular reason to particular students for enhanced student outcomes” (Gess-Newsome and Carlson, 2013). This conception of PCK has new elements because it encompasses "action", which was not explicitly mentioned in several of the previous ones (Gess-Newsome and Lederman, 1999; de Jong, Veal, and van Driel, 2002; Hashweh, 2005; Abell, 2007).

PCK “goes beyond knowledge of subject matter per se to the dimension of subject matter knowledge for teaching… I include [in PCK] the most useful forms of representation of those ideas, the most powerful analogies, illustrations, examples, explanations and demonstrations—in a word, the ways of representing and formulating the subject that make it comprehensible to others” (Shulman, 1986, p. 9).

This knowledge is conceptualized as being constructed through the processes of planning, reflecting on, and teaching a specific subject matter, it represents knowledge that is “uniquely the province of teachers, their own special form of professional understanding” (Shulman, 1987, p. 8).
**How to capture PCK?**

Loughran *et al.* (2004) proposed two tools to capture, document, and portray science teachers’ expert knowledge of teaching through the theoretical lens of pedagogical content knowledge: 1) content representation (CoRe) and 2) pedagogical and professional experience repertoires (PaPeRs).

In this study we have employed the CoRe, which is a framework with several questions that pretends, for each one of the central ideas the teacher declares, to capture the:

- Teaching objectives.
- Knowledge of alternative students’ conceptions.
- Troubles that commonly appear when teaching and learning.
- Effective sequencing of topic elements and important approaches to the framing of the idea.
- Use of appropriate analogies, demonstrations and examples.
- Insightful ways of students’ assessment.

The central ideas to teach CE were discussed by each group, and both arrived to those mentioned in Table 1.

**Table 1. Consensual central ideas for each group of academics**

<table>
<thead>
<tr>
<th>High school teachers</th>
<th>Undergraduate professors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background concepts: dissolutions and their concentration, chemical reaction, stoichiometry and reaction rate.</td>
<td>Spontaneity, reversibility and equilibrium</td>
</tr>
<tr>
<td>Reversibility and dynamic equilibrium.</td>
<td>Stoichiometry ( (\upsilon_i) ) and reaction progress ( (\xi) )</td>
</tr>
<tr>
<td>Equilibrium constant ( (K_c) )</td>
<td>Thermodynamic properties ( (S, G) )</td>
</tr>
<tr>
<td>Factors that modify CE.</td>
<td>Equilibrium constant ( (K) )</td>
</tr>
<tr>
<td></td>
<td>Chemical potential ( (\mu) )</td>
</tr>
</tbody>
</table>

The questionnaire followed by Loughran et al. has been shortened and rewritten with the following five questions for each one of the central ideas selected by the two groups of teachers and professors:

1. Why do you consider important for students to learn this central idea and what do you intend by teaching it?
2. Which are the difficulties and limitations connected with learning this central idea?
3. Which are the difficulties and limitations connected with teaching this central idea?
4. What teaching procedures or methodologies (analogies, metaphors, examples, demonstrations, re-formulations, experiments, etc.) do you use to engage students with this central idea?
5. How do you assess students’ learning in relation to this central idea?
Learning Progressions

Learning progressions (LP) were described by the NRC (2007) as the successively more sophisticated ways of thinking about an idea that follows one another over a broad span of time and are based on educational research about how people learn, existing pedagogical content knowledge in the area of interest, as well as on the critical analysis of the structure of the associated disciplinary knowledge (Sevian and Talanquer, 2014). It is important to keep in mind that the notion of LP does not imply a specific time frame for learning specific ideas and it is helpful to assume that learning progress is a trajectory of development rather than a series of discrete events (Heritage, 2008).

LPs are ordered descriptions of students’ understanding of a given concept. They represent a promising framework for developing meaningful assessments, allowing both large-scale and classroom-based assessments to be grounded in models of how understanding develops in a given domain. (Alonzo and Steedle, 2009).

LPs are generally viewed by researchers as conjectural or hypothetical model pathways of learning over periods of time that have been empirically validated. In these pathways, the learning progress is considered continuous and coherent, an incremental sequence from novice to expert performance, and mediated by instruction.

The notion of LP for teachers is consistent with descriptions of what expert teachers are able to do and the stages of teacher development. These descriptions are of teachers’ skills and based on comparisons of novice or inexperienced teachers and expert or teachers with years of experience. Some as a characteristic of learning progressions also includes alignment with curriculum. One approach is the idea that learning progressions are bounded by assumptions regarding students’ initial ideas at one end and by what is expected at the other end of the progression. In this context, it is important that science teachers on-going educative support as they learn how to create effective science learning environments with their students (Schneider and Plasman, 2011). To think about teachers’ learning across their careers implies thinking about how ideas and skills of teaching become more refined over time.

Recently, one of the authors has edited an issue of a Journal entirely on learning progressions (see Educación Química in the references).

CHEMICAL EQUILIBRIUM

“There seems to be no topic in freshman chemistry that presents more difficulties to students than chemical equilibrium.” (Hildebrand, 1946, p. 589)

The introduction of this concept challenges the conception about chemical reactions that students have derived from previous education. A complete review on the topic appeared in Van Driel and Gräber (2002).

On the other hand, there are many few articles about the PCK of chemical equilibrium (Van Driel, et al., 1998a and b; Harrison and de Jong, 2005b; Rollnick et al., 2008; Mavhunga and Rollnick, 2011).

QE is a topic in which there are a lot of analogies analyzed (even multiple analogies as in
Harrison and de Jong, 2005a), and one has to realize that knowledge is part of PCK (Raviolo and Garritz, 2009).

The law of mass action is presented since high school, but the equilibrium condition is attained from thermodynamics courses:

$$\Delta_r G = 0 \text{ where } \Delta_r G = \left( \frac{\delta G}{\delta \xi} \right)_{T,P} = \sum_i v_i \mu_i$$

The sum of chemical potential times the stoichiometric coefficients of products minus reactants equal to zero is the equilibrium condition.

For a simple reaction such as $v_R \text{ R} \leftrightarrow v_P \text{ P}$ this implies a relationship between the two chemical potentials of the involved species:

$$\mu_P = (v_R/v_P) \mu_R$$

**METHODOLOGY AND RESULTS OF APPLYING THE CoRe FRAMEWORK**

We selected four high school teachers of the baccalaureate system of our university (UNAM), lecturing to students from 15 to 17 years old, and four university professors of the thermodynamics course of third semester at college level, giving lectures to students from 19 to 21 years old (see tables 2 and 3 for a brief description of the selected academics).

<table>
<thead>
<tr>
<th>Teacher</th>
<th>Gender</th>
<th>Age</th>
<th>Teaching experience (years)</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Female</td>
<td>36</td>
<td>11</td>
<td>PhD student</td>
</tr>
<tr>
<td>B</td>
<td>Male</td>
<td>50</td>
<td>15</td>
<td>Master in didactics</td>
</tr>
<tr>
<td>C</td>
<td>Female</td>
<td>51</td>
<td>25</td>
<td>Master in didactics</td>
</tr>
<tr>
<td>D</td>
<td>Male</td>
<td>42</td>
<td>20</td>
<td>Chemical sciences master</td>
</tr>
</tbody>
</table>
### Table 3. Undergraduate professors’ description

<table>
<thead>
<tr>
<th>Professor</th>
<th>Gender</th>
<th>Age</th>
<th>Teaching experience (years)</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Male</td>
<td>33</td>
<td>3</td>
<td>Chemical sciences master</td>
</tr>
<tr>
<td>B</td>
<td>Male</td>
<td>59</td>
<td>37</td>
<td>Chemistry degree</td>
</tr>
<tr>
<td>C</td>
<td>Male</td>
<td>48</td>
<td>10</td>
<td>PhD in organics</td>
</tr>
<tr>
<td>D</td>
<td>Male</td>
<td>65</td>
<td>39</td>
<td>PhD in chemical engineering</td>
</tr>
</tbody>
</table>

A comparison of teaching methods was done within these two groups by analysing their individual PCK for the topic of CE, obtained by the Loughran et al.’s CoRe methodology.

The following concepts are common in the two sets of central ideas, so one finds related answers:

- Reversibility and equilibrium
- Stoichiometry
- Equilibrium constant

But there are also contrasting phrases in those points (as will be seen). And there were contrasting central ideas also:

- In baccalaureate they selected “reaction rate”, and
- In undergraduate level several thermodynamic properties (such as S, G, K and $\mu$).

For example, with respect to the central idea on “reversibility and equilibrium”, phrases of similar character are expressed at both levels for the question on teaching and learning difficulties (at the beginning, it is included a progressive number for each one of high school (HS) teachers or undergraduate (U) professors):

- P2 HS in teaching difficulties: “one-way misconception of chemical processes is deeply rooted in students”.
- P4 U in learning difficulties: “students reason that reactants must be totally consumed”.
- P1 U in learning difficulties: “students are used to say that reactions occur in a complete manner until the limiting reactant is consumed”.

Nevertheless, related to the same central idea on “reversibility and equilibrium” contrasting phrases are found within different objectives:

- P3 HS in objectives: “a CE process may not be understood without the previous understanding of what is a reversible process”.
- P3 U in objectives: these concepts “are important to predict the behavior of a system and the direction in which it will evolve”.
- P2 U in teaching difficulties: “student’s intuitive ideas on the colloquial meaning of these words must be eliminated”.
With respect to the central idea on “stoichiometry”, phrases of similar character are also expressed at both levels:

- P3 HS: “students have difficulties understanding the proportionality between products and reactants”.
- P3 U: “stoichiometry is the basis of the definite and multiple proportions law, so the proportion in which elements combine might be known”.

But also contrasting phrases:

- P3 HS: “the most common conflict occurs in the balance of a chemical equation because there is confusion between the meanings of coefficients and sub indexes”.
- P2 U: “the problem is the previous way in which students learn stoichiometry; like a thumb rule (called cross-multiplication)”.

Related to the central idea on “Equilibrium constant”, there are also similar phrases:

- P3 HS in objectives: it is important to “understand that the concentrations of reactants and products are not equal to each other [a common alternative conception], but constant with time”.
- P1 HS in objectives: “this constant is important for students to understand the equilibrium concept, not only qualitatively but also quantitatively, comprehending the way how it might be modified”.
- P2 U in objectives: it allows the quantitative calculation of equilibrium concentrations and to visualize qualitatively the spontaneous direction of the reaction and to predict the reaction progress”.

But also contrasting phrases:

- P2 HS in objectives she adopts a kinetic focus on CE: “it is important for the student to use the kinetic molecular model to explain the dynamic nature and the equality of rates in both directions of the reaction, at a nanoscopic level”.
- P3 U in teaching difficulties adopts a thermodynamics focus on CE: “I show examples that relate the equilibrium constant to the thermodynamic potentials (ΔG, ΔH, ΔS) and its physico-chemical interpretation.”

The sentence of P2 HS make evident that for the high school teachers a kinetic approach to CE. Here it is emphasized that point with a second sentence: P1 HS: “the teaching [of CE] from the Le Châtelier’s principle point of view, implies that students are clear in other concepts such as chemical kinetics, endothermic and exothermic reactions and ideal gases, among others.

Meanwhile, the undergraduate professors insist in a thermodynamic foundation of CE.

- P1 U: “calculation of the equilibrium state is based on the following second law results:
  “1) in a closed and isolated system the equilibrium state corresponds to one of maximum entropy;
  “2) in a system at constant temperature and pressure, the equilibrium state corresponds to that of the minimum Gibbs energy.”
- P4 U: “this is evaluated with problem solving, with the question related to the amount of products and reactants needed in a reaction that reaches the equilibrium condition, besides its relation with the equilibrium constant and Gibbs free energy”.
CONCLUSIONS

From the analysis of the CoRes of teachers and professors at both levels, we may conclude that there are two teaching perspectives:

- A kinetic one in high school level.
- A thermodynamic perspective in the undergraduate level.

In high school there is no mention of important concepts such as reaction progress and equalization of chemical potential. The CE condition is based only on the equality of rates for forward and inverse processes and the law of action of masses.

At the undergraduate level, CE revolves around the understanding and management of thermodynamic parameters such as entropy, free energy, reaction progress and chemical potential. Through the free energy change of the reaction is set the Equilibrium Condition.

This situation propitiates that the pedagogy of teaching the CE concept be different at each level.

Duschl and collaborators (2011) have mentioned that LPs have a beginning point and an ending point that can span months, semesters or years. This is the case with this LP on CE from a kinetic to a thermodynamic point of view. “Taking science to school refers to the beginning point as the ‘lower anchor’, which represents the knowledge children bring with them to school. This beginning knowledge is often grounded in sensory-based observations of commonly occurring natural events. In this way the lower anchor disciplinary concepts of LPs are said to be accessible to learners since they have some awareness of the phenomenon. The ‘upper anchor’ represents the expectations we have of students learning at the end of the LP. That is, what students should know and be able to do (p. 150-151)”.

At the high school level there are some additional troubles because:

- There is mention of neither reaction progress nor chemical potentials.
- It is incorrect not to discuss the thermodynamic foundation of CE.

At both levels some troubles are:

- Teachers interviewed do not clarify a clear purpose of teaching the central ideas and do not manage to differentiate between learning and teaching difficulties.
- At High School level the solution of algorithmic exercises has dominated over the rational domain of concepts, but in Undergraduate the last domains over the former.
- Although professors claimed that abstract topics, such as reversibility and chemical potential are difficult for students to understand, they do not mention the use of simulations, animations or ICT as part of theirs teaching methodologies. There is a sub-use of ICTs.
- Teachers of both levels do not have palpable ways to make a relation of all of these concepts to everyday phenomena.
- The frequent use of Le Châtelier’s Principle in spite of the troubles mentioned (Quílez and Solaz, 1995).

It remains to be answered our second research question: “What implications emerge for students learning from these two approaches”?\"
Schneider and Plasman (2011) indicate in their analysis that it is helpful for teachers to think about learners first, then to focus on teaching, and points out the essential role of reflection for teachers to rearrange their ideas in ways that develop their PCK.

Understanding how science teachers learn and continue to learn about teaching science is essential to creating programs to meet their needs at each stage of their careers. Learning progressions—although proposed as a framework to guide our thinking about student learning—can guide our thinking about how teachers’ knowledge progresses over time. For science teachers, a learning progression framework means considering teachers’ ideas and how they develop as teachers continue to learn about teaching science. Pedagogical content knowledge (PCK) is a construct to aid our thinking about what teachers continue to learn as they study their practice. To begin to understand how science teachers’ learning progresses, the research literature relevant to science teachers’ pedagogical content knowledge was reviewed.

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