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EXPERIMENTAL AND MODEL LEVELS IN CHEMISTRY TEACHING: ANALYSIS OF STUDENTS' REASONING

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The knowledge to be taught regarding chemical changes and equilibrium states in the French chemistry syllabus (grade 12) has been categorized in terms of theory, models and reality. The experimental level is split into reality-as-perceived and reality-as-idealised which leads to two descriptions of experiments. The different models that interpret an experimental situation depending on the issues raised are presented. This categorization of knowledge constitutes a framework which is put to the test to analyse students' understanding during teaching sessions. We seek to determine whether this framework enables to characterize the different kinds of knowledge at stake in the classroom and students' reasoning about chemical changes. Two case studies are set out: in the first one the students had to write a chemical equation to predict a chemical change knowing the composition of a mixture whereas in the second one they had to write the chemical equation after having done an experiment. The interactions between the teacher and the students are analysed in terms of concepts attributed to the different levels of the framework. The analyses reveal the students' difficulty to master the chemical equation, to mobilize a kinetic model, to make a proper link between the model level and the reality-as-idealised or the reality-as-perceived.

Keywords: chemistry, models in sciences, conceptual understanding

INTRODUCTION

Chemistry is a science which interprets and predicts experimental facts by means of models. Chemistry teaching uses school science models (Harrison & Treagust, 2000). Students encounter difficulties to use models and to make proper connections between models and reality (e.g. Cooper, Underwood, & Hilley, 2012; Sensevy, Tiberghien, Santini, Laubé, & Griggs, 2008; Tiberghien & Vince, 2005). This study sets out a framework which is the result of an epistemological analysis of the content to be taught about equilibrium states and incomplete chemical changes (grade 12, in France). Then, it is used to analyse the students' reasoning and the different kinds of knowledge at stake in the classroom in a laboratory session. The results are then discussed.

EPISTEMOLOGICAL ANALYSIS OF THE CONTENT

The knowledge to be taught can be viewed as belonging to three levels, the theoretical level, the model level and the experimental level (Tiberghien, Psillos, & Koumaras, 1994). A school science model is adapted from a science model (Adúriz-Bravo, 2013) considered as a set of interrelated concepts (Johsua, 1994) and built to answer some questions about a restricted part of the real world. Applying this reasoning to the French chemistry syllabus (grade 12) about chemical changes and equilibrium states, leads to consider three school science models stemming from two theoretical domains to describe and explain chemical changes which belong to the experimental level (Kermen & Méheut, 2009, 2011). These three levels constitute three levels of knowledge.

Characterising the experimental level

At the experimental level, the description of an experiment in terms of objects and events (Sensevy et al., 2008) is based on the reality-as-perceived (Gilbert, Pietrocola, Zylbersztajn, & Franco, 2000). It involves liquids, solids (and gas) which are objects of this level. The colour may change, a solid may appear or disappear, the value on a pH meter (a technical object) may change; these are events. An example of such visible modifications is reported in Figure 1a.

A chemical change corresponds to a chemical description of the reality-as-idealised (Gilbert, Pietrocola, et al., 2000) involving chemical species which are model-objects (Gilbert, Pietrocola, et al., 2000) derived from real objects by idealization (Fernández-González, 2013). A chemical change occurs if some chemical species appear and disappear after mixing some objects. Namely the amounts of the chemical species vary when comparing the composition of the initial state and that of the final state of the system (Figure 1b).

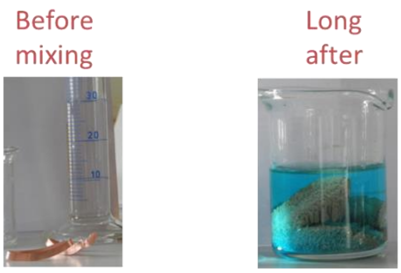

Figure 1a. The reality-as-perceived

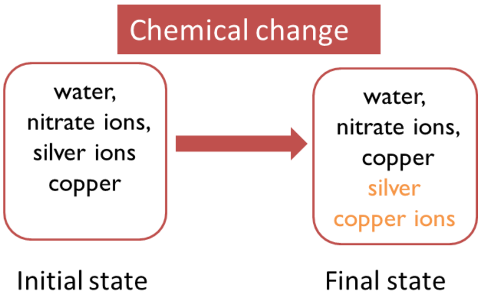

Figure 1b. Diagram of a chemical change

The experimental level is thus divided into two sub-levels, the reality-as-perceived and the reality-as-idealised (see Figure 2). If the same species in different amounts are mixed, several chemical changes occur, which constitute a family of chemical changes. These changes are all modelled by one chemical reaction which is symbolised by a chemical equation (see Figure 2).

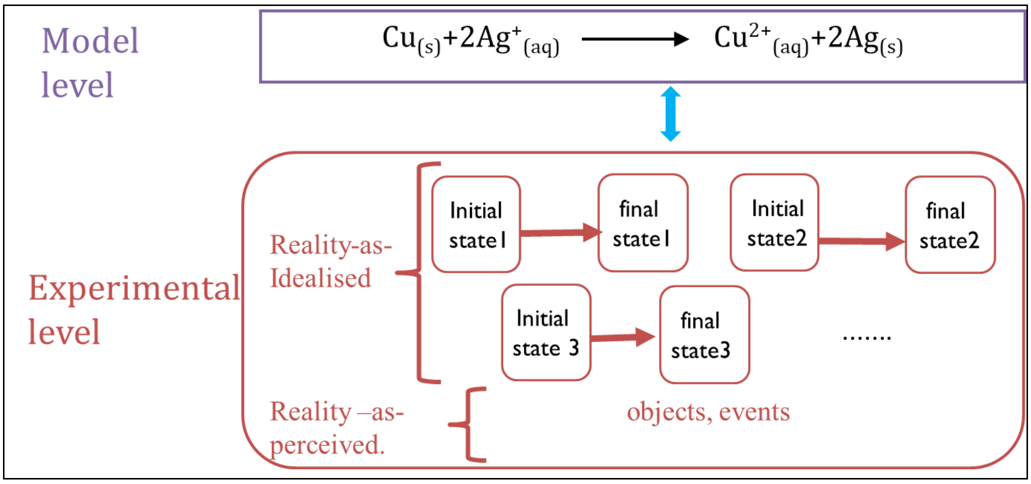

Figure 2. A chemical reaction modelling a family of complete chemical changes

This analysis is valid when the students begin to study chemistry and are confronted to complete chemical changes. An elementary kinetic model involving colliding particles can be added to explain the modification of substances.

Characterising the model level

In grade 12, incomplete chemical changes are studied, and the analysis of the content leads to three general school science models stemming from two theoretical domains (thermodynamics and kinetics) to explain and describe chemical changes.

The thermodynamic model is the most general one and allows the prediction and explanation of the direction of change provided that a chemical equation is known. The chemical equation symbolises a pair of opposing reactions, the forward reaction and the reverse reaction. The functioning of this macroscopic model relies on the comparison of the reaction quotient to the equilibrium constant and is called the evolution criterion.

The kinetic models are explanatory but not predictive. The macroscopic kinetic model comprises the rate of the forward reaction and the rate of the reverse reaction which are different if the composition of the system changes, and are equal at equilibrium state.

In the submicroscopic model, the system is composed of continually moving and colliding entities. During active collisions bonds are broken, electrons are transferred, entities are modified. Thus, substances are modified at the macroscopic level.

Considering chemical changes that concern acidic and basic species a specific model, the Brønsted model, is needed to explain and predict their interactions. Since chemical species are model-objects, they cannot supply any prediction by the direct application of logic because they are idealised empirical objects (Gilbert, Pietrocola et al., 2000). But if they are incorporated in the Brønsted model it is possible to imagine an interaction between some of the species involved. This model allows the foreseeing of a chemical reaction and to write the corresponding chemical equation. Likewise, a specific model is added for redox chemical changes. The connections between these different fields of knowledge are gathered in Figure 3.

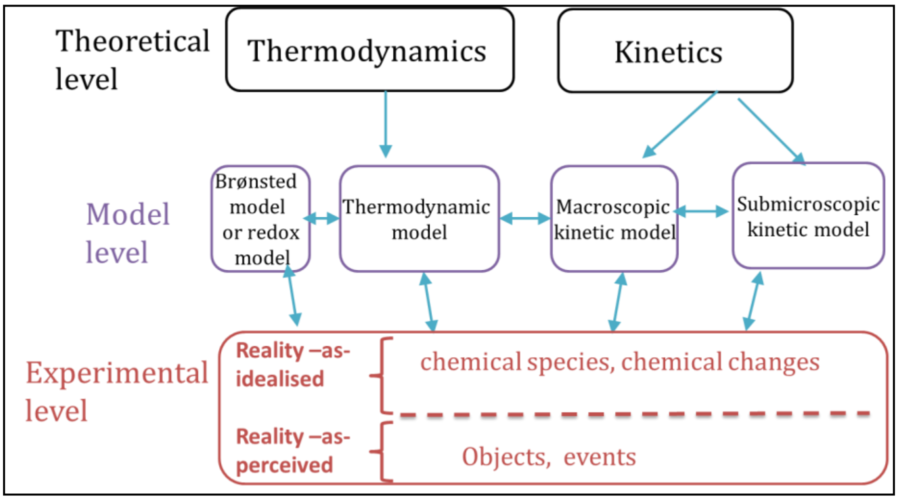

Figure 3. Levels of knowledge regarding chemical changes.

PURPOSE OF THE STUDY

The above analysis results in a framework (summed up in Figure 3) a previous version of which was applied to analyse students' answers to questionnaires (Kermen & Méheut, 2011). It enabled the link to be made between the model level and the reality-as-idealised. In this study we put the framework to the test to analyse the students' understanding and line of reasoning when they encounter an experimental situation in the classroom. The goal of this study is to examine the connections made by the students between the levels and sub-levels. Moreover, we intend to find out what information the use of this framework gives of the students' reasoning and the different kinds of knowledge at stake in the classroom.

METHOD

In a previous study, several chemistry laboratory sessions were filmed to characterise the teacher's practices. Therefore, the students' reasoning and the interaction between the teacher and the students were analysed. These sessions provided a selection of episodes in which the students had to establish connections across the experimental level and between that level and the model level. Two of these episodes were kept because they showed examples of links between levels and a student's difficulty or misunderstanding in connecting two levels. Words and sentences were categorised and attributed to the various levels to determine the level(s) at which the students (or the teacher if necessary) expressed their reasoning and to reveal the connections they made between levels and sub-levels.

Example 1

Teacher: "*these mixtures are somewhat different compared to what we are used to do namely they will comprise the four species we are talking about*"

The mention of the mixtures which are made with colourless liquids belongs to the reality-as-perceived. But when the teacher speaks of species, she moves to the reality-as-idealised and relies on the chemical formulae she wrote on the blackboard. In this sentence the teacher is making a link across the two sub-levels of the experimental level.

RESULTS

First case study

The task to achieve

In the first class, the teacher shows four flasks containing a colourless liquid and tells the students they will make two mixtures of four aqueous solutions (ethanoic acid, methanoic acid, sodium ethanoate and sodium methanoate solutions) at the same concentration and that each solution contains an acid or a base. The teacher writes the formulae of the acids and bases (not of the cationic species which are present in these solutions) on the blackboard (they correspond to two conjugate acid-base pairs). The teacher asks the students to reflect and to write a chemical equation to predict what could happen in the mixtures.

Expected reasoning

The students have studied conjugate acid-base pairs. They are supposed to rely on the name and formulae of species (reality-as-idealised) to resort to the Brønsted model which enables them to propose a chemical equation. At the model level a molecule of acid can donate a hydrogen ion to a molecule of base and conversely a molecule of base can accept a hydrogen ion from a molecule of acid. An acid-base reaction is the transfer of hydrogen ions between an acid and a base. The following equations are expected

$CH_3COOH_{(aq)} + HCOO^-_{(aq)} = CH_3COO^-_{(aq)} + HCOOH_{(aq)}$ or

$CH_3COO^-_{(aq)} + HCOOH_{(aq)} = CH_3COOH_{(aq)} + HCOO^-_{(aq)}$

Description and analysis of the dialog

After a while, the teacher looks at what the students have written and stops at Chloé's place. Chloé wonders how to continue after writing:

$CH_3CO_2H_{(aq)} + HCO_2^-{}_{(aq)} + CH_3CO_2^-{}_{(aq)} + HCO_2H_{(aq)} =.$

Her neighbour Lucile wrote $CH_3CO_2H_{(aq)} + HCO_2^-{}_{(aq)} \rightarrow CH_3CO_2^-{}_{(aq)} + HCO_2H_{(aq)}$. The teacher talks to the two girls. Both have written down an incorrect chemical equation.

> Teacher (to Chloé): yes, this makes four chemical species on the left of the equal sign … and what else on the right? …
>
> Lucile: but why are they all on the left?
>
> Chloé: because one mixes them all?

Then, the teacher has a long dialog with Lucile to determine what she has in mind and resorts to a kinetic representation of the mixture mentioning collisions and active collisions between species. During this dialog the teacher asks: "species that are on the right [of the equation] do they play 1, 2, 3, sun? Do they wait?" Then, Lucile admits that species written on the right side of the chemical equation also continue to react and writes an equal sign (same meaning as a double arrow) instead of a single arrow. At the end of this dialog Chloé who listened without saying anything, asks: "I don't understand if we mix all species together aren't they all reagents?" Lucile answers "no" and the teacher tells her to think it over.

When the teacher asks Chloé what she could write on the left of the equal sign, Lucile shows that she does not agree with Chloé. The teacher and Lucile are arguing at the model level because they question the chemical equation which represents the chemical reactions. Chloé justifies her equation with a reason that belongs to the reality-as-idealised, the chemical species are mixed together so they should be written on the left part of the equation. Until now, she had only encountered mixtures initially composed of chemical species about to react and without the products to be formed. These reagents were written on the left, she just replicates what she is used to do. And she does not know how to determine the products.

The teacher adapted the kinetic scientific school model that involves colliding entities and not species. She may be not fully aware of the specific meaning of both terms. She also used anthropomorphic terms and mentioned a children game[1] (1, 2, 3 sun) to make Lucile realise that chemical entities do not stop moving and colliding which means that species are still reacting. This is an example of a teaching model (Gilbert, Boulter, & Elmer, 2000), a model built by the teacher in the context of the classroom to fulfil a specific need.

At the end of this episode Chloé still gives the same argument, belonging to the reality-as-idealised, but she starts having doubts because she expresses what she believes in an interrogative and negative wording.

Second case study

The task to achieve

In the second class the students performed two successive experiments. First, they mixed a copper sulphate (II) solution and zinc powder (in test tube 2 whereas test tube 1 contained only copper sulphate (II) solution) and then observed. Afterwards they filtered what they had obtained and added a sodium hydroxide solution drop by drop to the filtrate. They had to write down their observations and identify the chemical change in test tube 2.

Expected reasoning

The expected reasoning involves two steps. Two diagrams representing the successive chemical changes specify the line of reasoning the students could follow to identify the formation of zinc ions in tube 2. Figure 4 represents the balance that can be achieved for the first experiment. After filtration, the remaining solution (circled in green in Figure 4) at the end of the first experiment is used to carry out the second experiment.

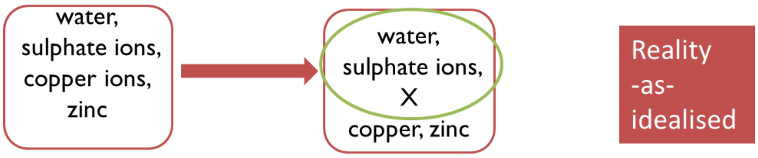

Figure 4: First chemical change

In the second experiment, drops of sodium hydroxide solution are added to the filtrate. A white precipitate appears and then disappears with an excess of sodium hydroxide solution (see Figure 5). These events (reality-as-perceived) should allow the students to identify the presence of zinc ions (reality-as-idealised) in the filtrate if they have previously memorized these facts.

Once zinc ions have been identified, the first chemical change is fully known. A comparison of the initial and the final states can be done to determine which species are reagents and products. It will enable to write the corresponding chemical equation. The students do not need to identify the species that appear in the stages of the second experiment, but they must realise that two chemical changes occurred before and after filtration.

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[1] A child faces a wall and say 1, 2, 3 and turns back when he/she says "sun". The other children can walk when he/she is counting but should be motionless when he/she turns back. If they do not, they have to return at the starting point. The winner is the first one to reach the wall and takes the place face to the wall.

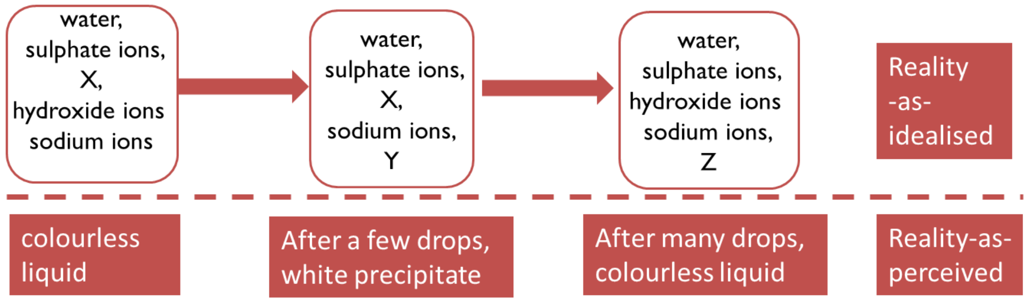

Figure 5: Second experiment and second chemical change

Description and brief analysis of the dialog

To answer the question of the lab sheet, the teacher leads a collective dialog after the experiments are finished. This dialog is quite long, more than 11 minutes, and only a summary of it is reported. She asks them about the role of the second experiment and what species it enables to identify. No student succeeds in recognizing the formation of zinc ions using experiment 2. This reveals a missing link between reality-as-perceived and reality-as-idealised.

Then, she asks them to make an inventory of species in the initial state of the system in experiment 1 and writes these on the blackboard Cu^{2+}, SO_4^{2-} and Zn. Contrary to what happened just before, the students establish correct links between the two sub-levels of reality. The teacher resorts to the law of conservation of chemical elements and the students propose the formation of zinc ions. At that time the chemical description of the first experiment is not fully achieved because the other product is not written down. The teacher carries on with the collective dialog to help the students find out the reagents and the products. When she questions them about the sulphate ions, they answer all together "spectator", which is an evidence of experimental knowledge in reality-as-idealised: the students express the idea that this chemical species does not react. The teacher discards that species from the inventory which keeps only reagents and products. Finally, she writes the chemical equation on the blackboard: $Cu^{2+}_{(aq)}+Zn_{(s)}=Cu_{(s)}+Zn^{2+}_{(aq)}$. This symbolic representation is at the model level. Note that the writing of the chemical equation was not required in the lab sheet, the teacher anticipates the resolution of the following question of the lab sheet (not mentioned in this paper). At that moment, the teacher questions the students once more and shows the chemical equation on the blackboard.

> Teacher: what kind of reaction is this?
> Olivier: precipitation
> Teacher: Fanny?
> Fanny: precipitation
> Teacher: here, precipitation? precipitation relative to soda but I'm not talking of soda here.
> Student: redox

Olivier's and Fanny's answers remind us of what happened in the second experiment. They rely on what they saw, a precipitate which belongs to the reality-as-perceived, whereas the teacher's question is at the model level and about the first experiment. This reveals that some students did not realise that the second experiment does not correspond to the chemical change that was described a few minutes ago. There was no chemical description of the second experiment whilst the description of the first one was detailed.

The students lack some experimental knowledge, so the connection between reality-as-perceived and reality-as-idealised is missing to identify the presence of zinc ions. Nevertheless, they show other experimental knowledge in recognizing the absence of role of sulphate ions and the formation of copper. The law of conservation of chemical elements acts as a theoretical principle which underlies the model level and the reality-as-idealised and helps to interpret objects and events of the reality-as-perceived.

DISCUSSION

The Brønsted model is not working for Chloé unlike Lucile who wrote a meaningful although incomplete equation. For Chloé, the initial species mentioned by the teacher are the reagents and the left part of the chemical equation may represent the initial state of the system (Gauchon & Méheut, 2007). Distinguishing elements of reality-as-idealised and elements of a model was still difficult for her. The difficulty might have been increased because the same symbols were used to write the chemical equation and to describe the initial composition of the system (part of the reality-as-idealised), and because the teacher did not write down the symbol of the cationic species which was present in the base solution, nor that of water. Thus, Chloé did not think how she could determine what species can react with what other species namely how to use the Brønsted model. For her, the description of reality-as-idealised prevailed over the use of that model. In Lucile’s case resorting to the kinetic model helped to give meaning to what the chemical equation represents. An arrow instead of the equal sign means that species written on the right side of the equation do not interact. An equal sign means that two opposing chemical reactions model the chemical processes, acids and bases keep on reacting. At the end of the dialog between the teacher and Lucile, Chloé’s question revealed her trouble. Since she asked a question, one may think that she began to consider that all initial species were not reagents, an idea that she had not had before. Finally, the use of the kinetic model helped both students to change their mind but not at the same time.

In the second class, the students did not achieve the chemical description of the first experiment. It means that they did not move successfully from the reality-as-perceived to the reality-as-idealised because they lacked specific experimental knowledge about the researched species. This stopped the inventory of species made in the reality-as-idealised and the description of the first chemical change. The teacher’s change of strategy i.e. resorting to a theoretical principle enabled her to overcome this difficulty. The law of conservation of chemical elements is a theoretical principle of chemistry the students had in mind and were able to use. Some students failed to identify the nature of the chemical reaction because they did not realise that two successive chemical changes were involved. They remembered an object they saw, a precipitate (reality-as-perceived) without grasping that it corresponded to the second experiment. The confusion might have arisen because the teacher did not identify the second chemical change she neither describe it nor asked them to. Identifying a chemical species produced in a chemical change by means of another (or several) chemical change is quite widespread in chemistry, it contributes to defining the chemical identity of a substance (Ngai, Sevian & Talanquer, 2014). But here it seems that the students were not able to interpret these experiments in terms of two successive chemical changes, they still needed to be guided for that. While the teacher showed the chemical equation on the blackboard, this answer about the precipitate also shows that these students did not realise they had to reason at the model level with the redox model but not to make a link between the experimental level and the model level.

In both case studies the students knew of the absence of role of spectator ions in chemical changes. This term (spectator) is a habit in chemistry teaching. In both case studies they modelled the experimental situation or used models respecting the law of conservation of chemical elements and the symbols of chemistry. These clues allow us to think that the students adopted the thought style of chemists at least partially and at an elementary level, and that they belong to the thought collective of chemists (Sensevy et al., 2008), which can be viewed as the way chemists see the world through a specific lens.

CONCLUSION

The proposed framework enhanced the importance of a kinetic model that gives meaning to the abstract concepts symbolized by the chemical equation although it is not spontaneously used by the students. Chloé's mistake emphasised the lack of predictive power of chemical species which are model-objects and the need to include them in school science models to provide predictions. The use of the framework enabled to characterize the connections made between levels of knowledge and to interpret some mistakes as a missing link between them. The explicit use of the law of conservation of chemical elements highlights that any modelling (moving from the reality-as-idealised to the model level) proceeds by taking into account the chemical elements that compose the initial substances. All chemical descriptions (moving from the reality-as-perceived to the reality-as-idealised) also follow that principle.

Although its use was limited to two case studies, the framework seems to be relevant to characterise the students' reasoning in the classroom. It needs to be put to the test in other teaching sequences. A future work would be to use this framework to categorise teachers' discourses in the classroom to determine whether the teachers favour a domain of knowledge or do not, whether they promote the establishment of links between these domains or do not and to examine the impact on students' understanding. A simplified version of the framework operating on complete chemical changes (Figure 2 and an elementary submicroscopic kinetic model) could be used to analyse students' reasoning in lower secondary school. And finally, this framework could be presented in teacher training sessions to focus their attention on the specific difficulties the students encounter so that the teachers could devise and discuss strategies to overcome these difficulties.

REFERENCES

Adúriz-Bravo, A. (2013). A 'Semantic' View of Scientific Models for Science Education. *Science & Education*, *22*(7), 1593–1611.

Cooper, M. M., Underwood, S. M., & Hilley, C. Z. (2012). Development and validation of the implicit information from Lewis structures instrument (IILSI): do students connect structures with properties? *Chemistry Education Research and Practice*, *13*(3), 195–200.

Fernández-González, M. (2013). Idealization in chemistry: Pure substance and laboratory product. *Science & Education*, *22*(7), 1723–1740.

Gauchon, L., & Méheut, M. (2007). Learning about stoichiometry: from students' preconceptions to the concept of limiting reactant. *Chemistry Education Research and Practice*, *8*(4), 362.

Gilbert, J. K., Boulter, C. J., & Elmer, R. (2000). Positioning Models in Science Education and in Design and Technology Education. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing Models in Science Education* (pp. 3–17). Springer Netherlands.

Gilbert, J. K., Pietrocola, M., Zylbersztajn, A., & Franco, C. (2000). Science and Education: Notions of Reality, Theory and Model. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing Models in Science Education* (pp. 19–40). Springer Netherlands.

Harrison, A. G., & Treagust, D. F. (2000). A typology of school science models. *International Journal of Science Education*, *22*(9), 1011–1026.

Johsua, S. (1994). Quelques conditions d'évolution d'un objet d'enseignement en physique : l'exemple des circuits électriques [Some conditions for the evolution of a teaching subject in physics: the example of electrical circuits]. In G. Arsac, Y. Chevallard, J.-L. Martinand, & A. Tiberghien, *La transposition didactique à l'épreuve* [the didactic transposition to the test] (pp. 9–34). Grenoble: La Pensée Sauvage.

Kermen, I., & Méheut, M. (2009). Different models used to interpret chemical changes: analysis of a curriculum and its impact on French students' reasoning. *Chemistry Education Research and Practice*, *10*, 24–34.

Kermen, I., & Méheut, M. (2011). Grade 12 French Students' use of a Thermodynamic Model for Predicting the Direction of Incomplete Chemical Changes. *International Journal of Science Education*, *33*(13), 1745–1773.

Ngai, C., Sevian, H., & Talanquer, V. (2014). What is this Substance? What Makes it Different? Mapping Progression in Students' Assumptions about Chemical Identity. *International Journal of Science Education*, *36*(14), 2438–2461.

Sensevy, G., Tiberghien, A., Santini, J., Laubé, S., & Griggs, P. (2008). An epistemological approach to modeling: Cases studies and implications for science teaching. *Science Education*, *92*(3), 424–446.

Tiberghien, A., Psillos, D., & Koumaras, P. (1994). Physics instruction from epistemological and didactical bases. *Instructional Science*, *22*(6), 423–444.

Tiberghien, A., & Vince, J. (2005). Études de l'activité des élèves de lycée en situation d'enseignement de la physique [studies of highschool students' activities in physics classroom]. *Cahiers Du Français Contemporain*, (10), 153–176.