Chapter 16
An Empirical View of the Teaching of the Chemical Element Concept

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16.1 Theoretical Background

The concept of a chemical element is considered a prerequisite for the study of chemistry, essential for understanding John Dalton's (1766–1844) idea of chemical change, and therefore, understanding subsequent and more complex concepts, such as: chemical reactions, substance quantity, and all the stoichiometric problems that derive from it. The concept of a chemical element (CCE) is an elementary concept because it allows the diversity of existing ordinary materials to be explained with a few chemical elements, constituting a unitary structure, and on the other hand, the search for this unitary structure makes it possible to explain the material changes that occur in chemical reactions. Therefore, it represents a model structure that supposes the conservation or permanence of those elements in the materials' chemical transformations (López-Valentín 2008).

This concept has been reviewed from several standpoints: philosophical, historical, and conceptual. Historically, several authors have studied the *development* of this concept over time.[1]

From the philosophical perspective, Paneth was the first to review the epistemological status of the CCE in his article titled "The Epistemological Status of the Element's Chemical Concept" (Paneth 2003). This work was considered as the starting point for many studies in the contemporary philosophy of chemistry (Scerri 2009). Paneth argues for the need for a dual conception of the term "element" that distinguishes two different meanings: "basic substance, indestructible" (microscopic

[1] Partington (1948); Holton and Roller (1963); Rocke (1986); Mierzecki (1991); Bensaude-Vincent and Stengers (1997); Brock (1998); Paneth (2003); Hendry (2005); Scerri (2007); Ruthenberg (2009).

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meaning) present in compounds and elemental substances and "elemental substance" (with macroscopic meaning).

The other angle, starting in the 1980s, incorporating some of the difficulties that students have regarding understanding the CCE, was studied and reported in the literature.[2]

On the other hand, the generalized lack of significant learning about any scientific concept, as has been seen in research, must be related to a critical analysis of how it is being taught. It is believed that one of the many reasons why this significant lack of learning in students exists could be because of a lack of knowledge of teachers of the history of science (the *development* of historical models) and the existence of distorted epistemological versions of the nature of science and scientific activity (Furió 1994; McComas et al. 1998; Fernández et al. 2002). Transmission of these distorted visions, specifically in the teaching of chemistry, often manifests itself implicitly in the organization and sequencing of content in textbooks and in the faculty, and it is supposed that they will also be transmitted in the teaching of the CCE. In this work, the focus is on the empiric–inductivist and atheoretical vision. According to Fernández, the empiric–inductivist vision is understood as:

> The role of neutral observation and experimentation, without a priori ideas, is highlighted, forgetting the essential role of hypotheses and the construction of a coherent body of theoretical knowledge. In addition, despite the verbal importance given to observation and experimentation, teaching is generally based on books with little experimental work. Particular emphasis is placed on the atheoretic vision in presenting the learning of science as a matter of discovery or is reduced to practice to processes, forgetting the contents. (Fernández et al. 2002, 479)

For the purposes of this work, the empiric–inductivist idea for CCE is assumed if the operational definition of a simple substance (an elemental substance, which cannot be decomposed) is identified with the theoretical definition of chemical elements at the macroscopic level of interpretation. It should be borne in mind that the idea of a chemical element, from the macroscopic point of view, can be understood as a basic material system designed to explain the composition of various substances that are the empirical referents (elemental and compound substances). The procedural definitions are based on empirical knowledge accepted as evidence in a determined historical model that is incommensurable (Kuhn 1971) with ontological definitions belonging to another historical model that tries to explain that evidence causally.

Thus, it is assumed that the chemistry faculty presents an empirical view of science if he/she identifies the definition of a simple substance with the theoretical definition of a chemical element at the macroscopic level of representation. This error is fundamentally based on the faculty's empirical views, who do not distinguish the procedural definition of a simple substance, which is considered empirical evidence, and the ontological definition of a chemical element proposed in Dalton's model. This identification of reality with the model is usually pedagogically justified

[2] Caamaño et al. (1983); Holding (1985); Llorens (1991); Pozo et al. (1991); Solsona and Izquierdo (1998); Laugier and Dumon (2003); López-Valentín (2008).

when the professor tries to bring the students closer to the transformation of substances into others in the macroscopic world, but then it is only adequate to talk about simple and compound substances. The explanation of these changes is carried out by conceiving a unique structure as in the introduction of the CCE as a group of atoms that are equal in mass and that belong to the microscopic world (López-Valentín 2008).

On the other hand, if we do not contemplate the development of knowledge, that is, if we do not take into account the history of science, we will not know about its difficulties, and the epistemological obstacles that were necessary to solve them, issues that are fundamental to understanding the difficulties of students (Saltiel and Viennot 1985). This is why it is important to have knowledge of the history of chemistry, because teachers can use this as a tool to define structural concepts (in this case, the CCE), and also as a topic in class where they can analyze or point out the difficulties in its development, conceptual problems, and the obstacles that needed to be solved.

After this brief introduction of the CCE, the hypothesis from which it stems (to detect didactic deficiencies in the teaching of the CCE) is based on the fact that the usual teaching of physics and chemistry follows conventional methods of verbal transmission of scientific knowledge, with the limitations that this implies and that do not facilitate learning. For the purpose of this work, only the empirical vision of science in the introduction of the CCE will be analyzed.

As the teaching received is the external factor that influences learning more, it is important to analyze how this process of teaching is carried out to be able to solve possible didactical deficiencies that could block learning. This is why this work is intended to solve the following question: Do faculty and textbooks present an empirical view of the CCE?

16.2 Methodology

This study was carried out with the participation of 48 Mexican teachers. These individuals had 6–34 years of service and teaching experience at the secondary and pre-university levels. Most had a Bachelor's degree in chemistry. Regarding the chemistry textbooks (CTBs) evaluated, 30 books were reviewed (13 from the pre-university level and 17 from university-level general chemistry).

With the aim of determining if the research question was valid or not, two convergent experimental designs were proposed. The first was oriented to show an empirical view of science of the CCE in teachers and the second one was used to confirm the empirical view of the CCE in chemistry textbooks (a total of five).

The analysis was performed by two independent researchers, and if there was a discrepancy on any item, it was reviewed again, and if it persisted, it was eliminated or an intervention by a third researcher was requested.

16.3 Presentation and Analysis of Results

The objective of this analysis is to corroborate if the operational definition of a simple substance is identified with the ontological definition of a chemical element in the macroscopic level of representation.

The results of the analysis are presented below. First are the results of the empirical view that correspond to the faculty, and second, those related to chemistry textbooks.

16.3.1 Does the Faculty Present an Empirical View of the CCE?

The results obtained by the faculty view of the CCE are shown in Table 16.1.

Question 1 had the greatest number of correct answers. An example of this case is Teacher #21 who distinguished the properties attributed to the CCE and those corresponding to the simple substance. "*The atomic number, atomic weight and valence are properties of the atom itself, but the bonding of atoms forms the "substance called hydrogen.*" *The former characteristics are macroscopic and the latter are microscopic*" (Teacher #21).

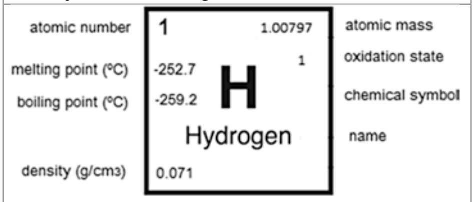
In the case of *Question 2*, the results show that half of the teachers (50%) do not distinguish between the CCE and that of a simple substance on the assumption that simple substances originate a chemical element. For example, the following is a correct answer: "*The element oxygen is a group of atoms that have the same atomic number.*" *Chemical elements are the components of substances; these can be present both in simple as well as compound substances. For example, the simple substance oxygen is represented by O_2, while the element oxygen is present in ozone (O_3); water (H_2O), etc.*" (Professor #31).

Finally, another remarkable answer selected shows the confusion (unusual, although existing) between two terms, allotropes and isotopes, mentioned in the following example: "*Because they are different isotopes*" (Teacher #19).

Regarding *Question 3*, only four teachers (13%) did not have an empirical view of the text, as seen in the following answer: "*Presenting an element in its pure state implies the generalization that all elements are substances. Since it introduces the phrase with the word 'some,' it is assumed that the rest of the elements are found in the form of mixtures; in other words, it associates the idea of a chemical compound with that of a mixture and that of an element with a pure substance, as if a compound could not form a pure substance. Only an element always forms a pure substance, therefore it doesn't make sense to say it is present in a pure state. Here it associates the idea of an element with that of a substance*" (Teacher #14).

As seen in this answer, Teacher #14 solves the *empirical vision of chemistry*, as in the first two lines he identifies that in the cited text, the word *substances* should be mentioned instead of *elements*. On the other hand, this educator also reflects on

Table 16.1 Objectives, questions, and results obtained for the empirical view of the teachers regarding the teaching of the concept of a chemical element (CCE)

Objective	Question	Correct responses (%) (*N* = 48)
Identify whether teachers differentiate the properties attributed to the CCE and those corresponding to the simple substance	1. The following figure shows some of the information of the element hydrogen that is usually found on the periodic table  Regarding this information, a teacher says: "*The density, boiling and melting point are properties of the simple substance called hydrogen; while the atomic number, the atomic mass and the valence are properties of its element*." Argue whether you agree or disagree with this statement	58
Confirm the teacher defines oxygen as a set of atoms with the same atomic number, and therefore distinguishes between the chemical element and a simple substance	2. Atmospheric oxygen and stratospheric ozone are simple substances that have different properties. How do you explain to your students what the element oxygen is?	50
Verify that the teacher identifies chemical elements as elemental substances that may occur in nature	3. The concept of chemical elements, like all scientific concepts, has a validity range that depends on the definition given and the theoretical context in which it is introduced. Comment on the validity of the following expression found in a chemistry textbook: "*Some of the elements have been in a pure state in nature for thousands of years*"	13

the implicit association that "could be made in the text" of the association between the compound and mixture; and finally, comments on the erroneous redundancy made when the pureness of substances or of chemical elements is mentioned.

On the other hand, 23% of the sample considers the text invalid, but the faculty do not express practical reasons to justify them, such as: "*I consider that this statement does not have all the validity since the native elements are found in nature in pure state, not thousands of years ago, but since our planet was formed*" (Teacher # 4).

This teacher focuses his comment on the time factor as an error, as it is considered that the expression "for thousands of years" should be greater, that is to say, "since our planet was formed," so this expression is not valid philosophically. He explicitly identifies *native elements* with *pure simple substances*.

When reviewing the results of the three questions together, it is confirmed that the faculty has an *empirical view* by identifying the ontological definition of a chemical element with the operational definition of a simple substance, as the maximum number of correct answers obtained of 58% for Question 1 was similar to that of Question 2 (50%). This can be explained by the degree of difficulty being the same, as question 1 (differentiation between the properties attributed to the CCE and those corresponding to the simple substance) and question 2 (defining the element oxygen as a set of atoms with the same atomic number) are apparently easier to answer than question 3 in which the percentage obtained was 13%, because in the latter, teachers needed to criticize the error when identifying a chemical element with a simple substance in a given text. This can indicate that the faculty, in general, does not have a clear idea of these concepts, as when they answer the direct question (question 1) they are "careful" of their answer, but when they have to identify the error, they seem not to see it.

To close with the analysis of this section, the great abundance of teachers who do not solve this empiricist vision is striking, because 12% of teachers leave the answer without responding.

16.3.2 Do Chemistry Textbooks Show an Empirical View of the CCE?

To continue the analysis of the *empirical view of science*, two questions were applied to the CTB. The results are shown in Table 16.2.

Regarding *Question 1*, most textbooks do not solve the *empirical and atheoretical view of science* or in another way, only four texts (13.3%) "warn" the reader about the possible confusion (very common) of understanding the idea of a chemical element as a basic or fundamental substance with which "real" substances are formed and that can be considered empirical referents. The rest of the texts do not

Table 16.2 Objectives, questions, and results obtained on the empirical view of the CTB in the introduction of the CCE

Objective	Question	Correct responses (%) ($N = 30$)
Identify whether the text makes the emphasis needed to avoid confusion when using the operational definition of a simple substance as the theoretical definition of a chemical element at the macroscopic level of interpretation	1. The text explicitly or implicitly presents that a simple (or elemental) substance is not the same as a chemical element	13.3
Discover if an element is identified with a simple substance as a mixture of two simple substances	2. The textbook presents, at least, some of the possible difficulties that can occur when identifying a simple substance	10

advise about this detail, and what is worse, superimpose the concept of chemical element with that of elemental (or simple) substance.

The following is an example of a positive valuation where the idea of an element as a material formed by a particular class of atoms (Daltonian model) and the elemental substance is implicitly differentiated:

> When a species of matter is represented by a particular class of atoms it is called an *element*. All pure substances can be divided into two classes: elemental and compound substances. *An elemental substance is that consisting of atoms of a single class. A compound is a substance consisting of atoms of two or more different kinds* […] Thus, an elemental substance is composed of an element; a compound of two or more […]. (Pauling 1961, 76)

However, strictly speaking, in this example a macro–micro overlap can be seen as it needs to be added that the (compound) substance is composed of "particles" or "molecules" all the same, because if they cannot be confused at a microscopic level (mixture and compound concepts). This identification between element and elementary substance was very frequent when the Periodic System was introduced as an empirical synthesis of the results obtained by chemistry in 1864. An example is the following paragraph of a text:

> The Russian Mendeleev obtained the most impressive result in 1869, when he generated the periodic table. You can find a modern version of the periodic diagram on the back cover of this text. In it, you can see photos of the elements that make it clear that those in the same column have a similar appearance. (Garritz and Chamizo 1994, 144)

In short, the textual quotation suggests that the chemical element is the elemental substance, when in fact, it is not, transmitting a certain epistemological obstacle by not being able to differentiate between the atomic–molecular model conceptualization of the chemical element and, the interpretation of the operational definitions of a simple substance and compound introduced in the Empiricist Model (eighteenth century).

To conclude the analysis of this question, I refer to the paragraph shown in Table 16.3 and discuss some of its erroneous ideas:

Table 16.3 Quoted paragraph by Hein (1992, 5)

1	"*Modern chemistry developed slower than astronomy and physics,*
2	*it started at the beginning of the XVII and XVIII centuries when Joseph Priestley (1773*–1804) who*
3	*Discovered oxygen in 1774, and Robert Boyle (1627–1691), started to record and*
4	*publish the results of their experiments, and to openly present their theories.*
5	*Boyle, who has been called the founder of modern chemistry, was one of the*
6	*first to practice it as a true science. He believed in the*
7	*experimental method. In his most important book. The Skeptical Chemist, he clearly*
8	*distinguished between an element and a compound or mixture. Boyle is better known today*
9	*because of the law of gases that has his name. A French chemist*
10	*Antoine Lavoisier (1743–1794), put chemistry on a firm foundation with*
11	*experiments in which he used a balance to perform quantitative measures of the*
12	*the weight of substances that formed part of chemical reactions*"

In this text, Hein presents diverse aspects about the nature of chemistry that show the empirical–inductivist view of the author as follows:

- One of these clues is when the author cites in line 5 that "Boyle was one of the first to practice chemistry as a true science." In this paragraph, he states that in this era the theoretical body of chemistry was established, when actually, historians indicate that this is when chemistry began as a science (Holton and Roller 1963). Therefore, we can doubt the existence of a theoretical body in Boyle's time. What this author did was contribute the introduction of the empirical conceptual model that allowed the classification of material systems using an operational definition into "mixtures, not perfectly mixed bodies (simple substances) and perfectly mixed bodies (compounds)" (López Valentín 2008).
- On the other hand, lines 7 and 8 seem to use the terms "compounds" and "mixtures" as synonyms, which induce the reader to a conceptual error (although this could also be attributed to the translator of the text). Coherently, in lines 7 and 8, the concept of *element* is explicitly identified with the empirical idea of a *simple substance*, which is in opposition to the concepts of "mixture or compound."
- The author states his empirical vision explicitly (lines 6 and 7) when he associates science with the experimental method, as if the scientific method could be reduced to only the performance of experiments (Fernández et al. 2002).
- Last, the birth date of Joseph Pristley "(1773*–1804)" is incorrect, as it is not possible that he discovered oxygen at 1 year of age. The correct date should be 1733–1804 (Biografias y vidas).

Regarding the results that correspond to *Question 2*, only 10% of the CTB make a comment about the difficulties that resulted from the introduction of various definitions of the chemical element and, specifically, identify an element with a simple substance. Table 16.4 shows an example:

When the author mentions that "compound substances are those formed by two or more simple substances (lines 2 and 3), the conceptual error of identifying an element as a simple substance, and later, defining a compound formed by two or more elements or simple substances, that is, as a mixture of substances, can be

Table 16.4 Quoted paragraph of Feo and Izquierdo (1976, 211–212)

1	"*Simple substances are those that cannot be divided into simpler ones.*
2	*Hydrogen, sulfur, oxygen, zinc, etc., are simple substances.*
3	*Compound substances are those formed by two or more simple substances, with these*
4	*being divided forming simple substances, and obtaining, when grouped, simple substances*
5	*that form them. Water, hydrochloric acid, calcium carbonate, etc., are compound substances.*
6	*Since matter is formed by atoms, which are individual units*
7	*of matter, whether a substance is simple or compound will depend*
8	*Only if it is composed of equal or different atoms*"

introduced. This is the confusion that must be avoided in teaching, even more so when we consider that it is much generalized among students who are starting to study chemistry (Furió and Domínguez 2007).

On the other hand, the text does not introduce Dalton's concept of element as it implicitly identifies it with a simple substance when it states "since matter is formed by atoms, which are individual units of matter, whether a substance is simple or compound will depend only if it is composed of equal or different atoms" (lines 6–8). This empirical idea eliminates the idea of an element as it is identical to that of a simple substance. It is convenient to remember, historically, that Dalton introduces in his proposition the concept of an element as a group of equal atoms and that according to the rule of maximum simplicity, the simple substance is formed of equal atoms because "compound atoms" (molecules) cannot be formed. This is why Dalton was opposed to the results obtained by Joseph Louis Gay-Lussac (1778–1850) especially, the explanation of the experiments of gas reactions performed by Amedeo Avogadro (1776–1856), in which the hypothesis that molecules of simple substances were composed of more than one atom was introduced.

To complete with the analysis of the CTB, most textbooks (86.7%) do not go beyond an empiricist view of science, because they do not "alert" the reader about the possible confusion of understanding the chemical element and the simple substance (very common). Only 10% of the books comment on the possible difficulties when introducing several definitions of the chemical element and, in particular, the identification of an element with a simple substance.

16.4 Conclusions

The teaching of the CCE is actually empirical. Teachers do not know the philosophy and history of science and do not have a critical view of the development of chemistry. On the other hand, in textbooks there is an absence of topics concerning the history and development of the CCE.

The development of historical models plays an important role in the origin and development of chemical knowledge (Justi and Gilbert 2000), and especially in the construction of the concepts of chemical and elemental substances. Similarly, knowing the history and philosophy of chemistry helps to understand better the nature of science (Matthews 1994). Regarding the didactic implications that this may have for chemical education, I consider that this is a good topic that teachers should know and that should be taken into account in training courses for teachers. It is well known that teachers must not only have a good knowledge of the subject to do their job well, but they also need to know the history and epistemology of scientific constructs beyond the contents of chemistry. In addition, knowing chemical epistemology provides the teachers with the necessary tools to learn, to discuss, and to reason in chemistry, which means being able to establish suitable relationships between, for example, the macroscopic and microscopic levels of representation in chemistry. In this case, it means being able to explain the specific properties of substances, the characteristics of the macroscopic level of representation from the properties of atoms and molecules, entities from the microscopic or submicroscopic model of matter (Gabel 1998; Erduran and Scerri 2003; Treagust et al. 2003).

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