Theoretical Approach to the Problem of Macro-Micro Relationships in Secondary Chemistry Teaching: A Proposal Based on Observation and Inference

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Abstract. The aim of the present study, of elucidative and argumentative nature, is to propose a first draft for a theoretical approach towards establishing well-founded explanatory relationships between the micro and macro levels of chemical knowledge. The establishment of such an aim is done taking into account that "levels" in chemistry are usually regarded as the cause of many misconceptions among secondary students. We first examine the recent literature of chemistry education addressing the "macro-micro problem". We then redefine that problem, using the aid of the philosophy of science and the specific philosophy of chemistry, in terms of observations and inferences. We draw attention to the theoretical-empirical, explanatory-descriptive, abstract-concrete, general-factual nature of chemical concepts in science education. Finally, we derive some instructional guidelines that intend to be coherent with currently established knowledge in chemistry education research. We indicate some clues for the design of instructional sequences, laboratory practices, and technology-mediated teaching activities that follow the spirit of our theoretical approach.

Keywords: Secondary Chemistry Education, Macro and Micro Levels, Observation and Inference, Theoretical Approach, Philosophy of Science.

1 Introduction

The theories of Piaget, Bruner, Gagne and Ausubel on how individual experience influences learning emerged more than half a century ago as a new paradigm in education, and they are still widely used to support science teaching. Constructivist learning theories emphasize the importance of experiences, and one of the most crucial aspects of those experiences is observation [1]. For instance, the model of learning

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through discovery, as proposed by Jerome Bruner [2], describes an approach that requires students to draw conclusions from their observations. Observation, which is an indispensable element of the scientific research process, is also a basic skill that is effective in traditional and in technology-mediated science classrooms [3].

Although there are many different teaching methodologies that require students to observe, in terms of science education, the first thing that comes to mind are laboratory-based methods. Such methods are effective in achieving learning outcomes through observations, management of prior knowledge, conceptual understanding, critical thinking, developing ideas and skills, and eventually using digital technologies. Perhaps the most established purpose of experiments in science classes in compulsory education is explaining facts using theoretical knowledge [4]. In other words, making accurate inferences by using the available theoretical knowledge to interpret the observations made through experiments. Therefore, school experiments allowing observation and inference –with or without the aid of new technologies– should have an important role in science teaching. The skills of experimenting, observing, drawing conclusions and establishing hypotheses are “exemplar” scientific processing skills, and therefore significant objectives of contemporary science education. On the other hand, the difference between observation and inference within the scope of the so-called “nature of science” should also be taught [5].

In accordance with the previous considerations, the aims of this article are:

1. To draw attention towards the hybrid theoretical-empirical, explanatory-descriptive, abstract-concrete, general-factual nature of chemical propositions.
2. To make some philosophical considerations on the ontological and epistemological characteristics of the levels in which chemistry functions (macro and micro).
3. To sketch the outline of a theoretical approach towards secondary chemistry teaching based on the process of making inferences from observation.
4. To derive instructional guidelines, coherent with current proposals in chemistry education research, in order to design laboratory experience with or without the mediation of digital technologies.

2 Theory and Antecedents

2.1 The Problem of the Macro-Micro Relationship when Making Inferences from Observation in the Chemistry School Lab

Laboratory and experiments play a significant role in chemistry, which seeks to understand the transformation of substances. In this regard, chemistry may be the first field of science that comes to mind when it comes to experiments. As stated earlier, the main purpose of experiments in science education is to enable students to “reach” scientific facts about observed events reconstructed with reasonable inferences based on already learned, structured knowledge. However, empirical and theoretical knowledge on concrete phenomena re-read through experiments is correlated *through processes of observation and inference*. This supposes an additional difficulty for chemistry education.

Relationships between theoretical and empirical knowledge in the chemistry education literature are described in terms of “levels” of understanding –macro, micro and symbolic [6]. Establishing appropriate relations between macro and micro, two *ontologically separate* aspects of the chemical world, is a competence expected from learners. Chemistry develops scientific models that try to explain with micro “phenomena” how the macro phenomena take place. But when these two levels are considered separately in teaching, students face problems in explaining and modelling [7]. It is usually emphasized that misconceptions in chemistry are caused by confusion between levels [8]: the micro-related knowledge students use in explaining their observations *is incorrectly inferred*, i.e. its transport from one level to another is flawed. Solutions to this learning problem depend on the development of a robust understanding of the micro and a correct structuring of the macro (and this of course can be aided by a consistent and well-founded use of digital technologies).

The specialized literature focusses on the importance of concretizing micro models for chemical problem solving [6-9]. There are diagnostic studies that determine the conceptual structures, reasoning patterns and extended misconceptions that individuals use at the micro level. Additionally, when school lab experiments aimed at interpreting the micro structure are examined, it is seen that some typified materials, analogies, images and simulations predominate [10, 11]. Current diagnoses portray the problem of the conceptual association of micro and macro in terms of both observing the macro and inferring from the micro.

2.2 Current Approach: Heavy Focus on the Micro

The literature suggests that most research and innovation in chemistry teaching has a micro-oriented approach. Accordingly, different means (scale models, drawings, animations, etc.) are used in order to concretize the theoretical knowledge about micro. However, there are limits to represent the micro through models prepared with concrete materials, analogies with experienced phenomena, images, and digital recreations. Indeed, one of the drawbacks of these representations is the emerging assumption that models are a “replica” of reality [5]. The formation of this epistemologically feeble understanding in the teaching process can lead to new obstacles, instead of eliminating misconceptions. Therefore, it is not surprising that students explain macro behaviors (such as melting or solving) with flawed analogies; students tend to explain the micro level with concepts related to the macro level, instead of the other way round [1, 7, 12]. So, lack of awareness of the use of such tools in activities in the teaching environment may lead to grave conceptual problems. The problem about the micro is basically related to the models used when teaching and the approaches including modelling to reveal the characteristics of central chemical concepts [8, 11]. The process of using concrete models of the micro as proxies of the macro level experience should be supported, and at the same time support, the set of accepted theoretical propositions and inferences based on other formal, symbolic and linguistic representations (formulas, equations, symbols, etc.). Such a complex process requires awareness of the theoretical knowledge and its representations, *and digital mediation, used without care and control, can severely amplify the aforementioned problems*.

On the other hand, available studies show that teachers often prefer to provide "accurate" explanations of the micro, limiting their teaching to "horizontal" relationships at the micro level, and not accompanying their students in the establishment of "vertical" relationships with the macro. Therefore, what is done is the "transmutation" of micro-sized phenomena that do not allow observation to a macro form with concrete (model, drawing, etc.) or digital (animation, simulation) representations. But understanding laboratory experiments is not "enlarging" or "scaling up" the micro pieces involved. Chemical models and their tools are "fictional" descriptions or explanations of the pieces, therefore, the following question is key in chemistry education: what are the "experiences" of students of the nature of the entities modelled, drawn, simulated –broadly, represented? We argue that an experimental approach (which can be made more robust through the use of digital technologies) is indispensable in school chemistry in order to associate the theoretical knowledge about the micro with empirical knowledge about the macro.

3 Discussion: Elucidation and Argumentation

3.1 Analysis of the Problem with the Help of the Philosophy of Science

In order to attack the problem of macro-micro relations, a strategy is to first describe it in some detail with the aid of the philosophy of science [8]. The idea is to identify key aspects of the nature of chemical knowledge to be taught and to establish consistent teaching methods at the secondary level. The philosophy of science has delved into the epistemology of knowledge production and the mechanics of scientific representation (models, analogies, simulations, etc.); these are valuable inputs for chemistry education.

As stated above, chemistry teaching tends to be micro-based and adopts a micro-to-macro orientation. This tendency results in students' conceptual understanding to shift from abstract to concrete. In terms of content knowledge, from theory to observation. The acceptability of using *only* that way is epistemologically and pedagogically controversial: it clashes with what we know of the nature of chemistry. The main reason for this is the epistemological qualities of chemistry. From the philosophical point of view, the problem is related to issues such as emergence, supervenience, holism, part-whole relations, asymmetry, causality, among others [13]. In the discussion in terms of chemical properties, the properties of the part will not be sufficient to understand the properties of the whole, the explanation cannot assume a linear causality between part and whole. In an approach more consistent with the nature of chemistry, we need to take into account the emergence of properties caused by the interaction of the parts, assume a non-reductionist approach to understand the asymmetric relations between whole and part, critically examine the notion of causality, and understand a dynamic and contextual relationship between substances, structures and properties. From this general framework drawn from the philosophy of chemistry, the problem of macro-micro relationship in chemistry is mainly about how to relate observations through inferences. It is the process of inference that reveals new perspectives on the nature of the macro, micro and symbolic dimensions in chemistry education.

3.2 Observation and Inference

Understanding the relations between observation and inference from a scientific point of view requires epistemological distinctions between descriptive/empirical/concrete/factual and explanatory/theoretical/abstract/general knowledge [14]. The existence of abstract, theoretical knowledge in chemistry depends on a process of *institutionalization of ideas* through the use of technical language. Knowledge is expressed in propositions roughly divided into descriptive and explanatory, respectively aiming at defining the status of phenomena and responding to questions on how and why. Explanatory knowledge, constituted by general propositions about abstract states of affairs involving the identification of causes and consequences, is often simplistically coalesced with theoretical knowledge. If knowledge produced in these processes is obtained directly from the observed characteristics of phenomena, it is usually called empirical knowledge. Indirectly obtained knowledge requires the use of concepts to "reconcile" representations, which point at the unobservable.

Descriptive knowledge can thus be theoretically supported, and explanatory knowledge can refer to empirical sources. However, we usually state, for teaching purposes, that explanations are "general" and description are "factual". For instance, "litmus paper turns red in HCl solution" expresses an empirical conclusion in the form of a description, whereas "litmus paper turns red due to an interaction with the HCl solution" expresses an empirical conclusion in a form that contains explanations produced from observable features. To sum up, the theoretical or empirical nature of the propositions expressing scientific knowledge is more related to the sources of knowledge, while its descriptive or explanatory nature is more related to the aim and intention of the text composed of those propositions [15].

Theoretical knowledge includes terms to describe and explain, produced by the creators of the theory and accepted through consensus. These terms ("theoretical concepts") constitute the "apparatus" of the models of phenomena that appear when using the theory on an empirical domain. For example, when thinking about the boiling point of a liquid, terms such as "van der Waals forces", "induction" or "polarity" are the theoretical concepts that "model" the phenomenon. In the school chemistry lab, empirical knowledge is not sufficient to make sense of a phenomenon observed, theoretical knowledge is also needed. What is observed *is a sign of something else that cannot be observed* (e.g. temperature is a sign of kinetic energy or molecular movement). Further knowledge is needed to understand and explain this "signing", and this includes the list of theoretical concepts. Following the classical ideas by the French physicist and philosopher Pierre Duhem [16], an experiment is accompanied by an *interpretation* relating concrete data obtained by observing to theoretical entities accepted by observers; such an interpretation yields some abstract and symbolic descriptions and explanations. Therefore, each empirical concept is meaningful in a theoretical framework; there are *theoretical structures* to make sense of what is actually happening in a school experiment.

3.3 Moving from Concrete to Abstract

Abstract chemical concepts describe the behavior of substances through resorting to an unobservable particle level. This epistemic move is at the center of the literature of chemistry education. Such a characterization of the knowledge of chemistry can hide the experiential and experimental nature of chemical intervention, and this turns to be an obstacle to understanding the knowledge structure of the discipline. Therefore, although chemistry relies on “unobservable” chemical processes, these are not completely abstract, they are “anchored” in the concrete of chemical interventions to change materials and control such changes. Chemical knowledge consists of *explanations* made by experiencing the phenomenon through scientifically accepted representations, and this is why we talk about moving from concrete to abstract.

As frequently stated in the literature of chemistry education, the three-level (macro, micro and symbolic) understanding of chemical processes [6] requires accepting that the nature of the three levels is not the same. Macro and micro appear to be ontologically separate dimensions, and the symbolic level is *semiotic* (i.e. it deals with the signs). Phenomena occurring at the macro and micro levels are expressed linguistically and non-linguistically through elaborate representations. The macro will be the target of school chemistry lab practices, the micro will be grasped through some theoretical mediators (concepts, representations, scale models, images, spectra, symbols, mechanisms, equations, formulas, etc.). Knowledge of this micro dimension is possible with those epistemological tools produced by science, each element constituting that dimension acts a *semiotic indicator*, having meaning because it refers to macro events. Just because a student writes down a reaction with formulas and symbols, this does not mean that s/he has actually understood the macro change or the micro reaction. The symbolic dimension which of course can be enhanced by digital technologies, should act as a means of establishing satisfactory explanatory relations.

4 A Teaching Proposal

In the light of the conceptual framework given above, some instructional implications can be drawn. Secondary chemistry teaching should act in an integrated fashion at the macro and the micro levels through relating whole and part and expressing the knowledge about these two dimensions with different semiotic tools, including digital technologies in all their potential. Coherent chemical descriptions and explanations should be attempted when conceptualizing the school labs. In this respect, it is possible to divide our instructional proposal into two sub-dimensions: one that is more *ontological*, the relations that we needed to establish between the macro and the micro, and another one that is more *epistemological*, the appropriate theoretical knowledge and representations that we can use to efficiently model those relations.

The history of science has shown that chemical phenomena have been interpreted in quite different ways: it is now commonplace to contrast the explanations for combustion given by supporters of phlogiston and of oxygen. “Making sense of” a phenomenon is done according to the principles of good reasoning and the constraints of theoretical categories. The macro ontological dimension of chemical events is the first step of theoretical reconstruction, which culminates at the micro level with entities that can vary considerably between different theoretical schools. In current chemistry, this sense-making is made by giving properties to the whole through inferring properties of parts, and this requires a whole network of relations. In the philosophy of chemistry, the top-down causality adopted by the holistic approach is more plausible from the epistemological point of view, as opposed to the bottom-up causality adopted by the ontological reduction of the whole (ontological reductionism) approach. Accordingly, in order to explain a chemical phenomenon, the configurational "forces" that determine the relations that are present should be mentioned [13, 17]. Otherwise, stating a chemical causality "piling up" from the micro linearly without emergence can cause misconceptions about properties that cannot be explained.

A perceptible property of a substance, such as odor, is a property depending upon the properties of the particles but it is not explained by an isolated examination of the particles; therefore, it is more appropriate for chemistry to establish an asymmetric relationship between macro and micro with a causality derived from macro properties. In other words, if we seriously consider ideas from the philosophy of science, the starting point in the teaching process should be observable changes of the whole. It can be said that a chemical explanation of a "whole" from this point of departure of "parts" can be put forward more clearly. In this context, instead of giving exaggerate priority to micro representations (models, symbols, technological representations, etc.), the teaching of chemical content should be based on theoretically-reconstructed experiences. It then seems more appropriate to establish an *interactive* relationship by bringing the representations under use closer to the observed phenomenon.

"Projecting" theoretical knowledge onto phenomena requires making *inferences*, i.e. transferences or extractions from models to phenomena. There are different types of reasoning that scientists use when making these inferences to "overstand" (i.e. dominate) facts. In the literature of philosophy of science, a number of theoretical frameworks have been put forward; authors talk about hypothetical deduction, induction, retrodiction, abduction, which are defined as combined, non-formal and therefore non-demonstrative methods [14]. It is often stated that induction and deduction, which are the classical "scientific methods", are not enough in today's understanding of science [18].

Hypothetical thinking is the type of thinking that is essential in science education and forms the basis of a sound method in relation to scientific inference. According to Anton Lawson [14], the process of scientific knowledge formation in the minds of students is essentially neither inductive nor purely deductive. Students reason according to patterns expressed as hypothetical arguments in the form of conditional structures "if… and/but…, then…, therefore…". When effective use of existing theoretical knowledge is required, a hypothetical-deductive form becomes important. Theoretical knowledge and observations related to the phenomenon are linked through an "inference about the case": a fact is observed, a theoretical corpus is deemed appropriate, then an abduced hypothesis provides a reasonable answer. In such a conclusion, two different factual situations can arise. 1. the hypothesis is supported by empirical data, and we have yet another reason for the adoption of our theoretical knowledge, or 2. the hypothesis is not supported empirically, and our theoretical knowledge is deemed insufficient to explain the case: we need to revise. In this "method", as it can be seen, the theoretical knowledge proposed by the teacher is effectively applied and at the same time tested: "ampliative" reasoning is consistent with the notion that scientific knowledge is open to change.

In our proposal for chemistry teaching, a crucial point of the hypothetical method is providing meaning for empirical knowledge. When interpreting a lab experience, there is *production* of testable hypothetical propositions within the framework of theoretical knowledge institutionalized in class. In this context of school chemistry, relationships between the macro and the micro are established through an interactive process that "comes and goes" between observation and theory with the intervention of inferences. Here, of course, technological mediations can give new dimensions to the process. An overview of that interactive process that we envisage is presented in Table 1.

Table 1. Proposal of an interactive process between the macro and the micro for secondary chemistry teaching through lab experiences.

Dimensions and stages	
A. Working in the macro dimension	A1. Observation of an experience in the school lab, with or without technologies A2. Transition from observation to inference
B. Working in the micro dimension	B1. Theoretical representation of the experience, with or without technologies B2. "Making sense" of the phenomenon
C. Working in the macro and micro dimensions	C.1. Comparing and "editing" inferences C.2. "Abduction" of hypotheses C.3. Test of hypotheses, with or without technologies C.4. Extraction of conclusions

5 Final Remarks

An initial evaluation of our teaching proposals in terms of the corpus of science education research can be done under some general "headings". Instructional activities generated with our framework are in accordance with the "inventive route" strategy of proposing and testing hypotheses. Current well-known "active" teaching methods, and adequate supporting new technologies, can be inserted at the different stages of our proposal (see Table 1). For example, when students face the macro experience in the lab, teachers could use *computer-assisted* labs, *remote* labs, *virtual/simulated* labs or *animation-based* labs. On the other hand, when a dimension of "prediction" is incorporated as a preliminary stage, prior to the transition from macro observations towards micro explanations, the whole lab experience can become a prediction-observation-explanation cycle, a method favored in the specialized literature.

In the stages where the micro is being examined, a wide variety of digital technologies (animations, mobile apps, augmented reality, *and even search engines and* *social media*) can be profitably used to enrich teaching and assist learning. The stage where students are required to infer can be organized as the construction of *school scientific argumentations*, and further argumentative texts can be elaborated to connect the different stages of our proposal. Argumentation leads the students to justify their own conclusions with the use of multiple representations such as pictures, graphs, scale models, multimodal and hypermedia texts and even gestures [19].

The fact that our teaching proposal is adjusted to methodological approaches currently favored in innovative chemistry education and at the same time to epistemologically valid views on the nature of scientific processes is salient. The use of Lawson's proposal [20] of hypothetical prediction and argumentation warrants that our suggestions for secondary chemistry classrooms are aligned with conceptions of the nature of science shared within our research community [21]. Activities designed under the guidelines that we have discussed can potentially support scientific thinking and reasoning skills in students. *Affordances* and *constraints* introduced by the mediation of digital technologies at this point of our cycle need to be further investigated in chemistry education.

The conceptual approach proposed in this work focusses on establishing epistemological articulations between observation and inference; it is thus inscribed, as it was said before, in the line of research and innovation around the nature of science, or NOS [21]. Further NOS ideas that can be explored with our proposal are the differences between law and theory, the nature of models in chemistry, the logical structure of chemical knowledge, the nature of idealization or the role of representations. The spirit of our proposal intends to create awareness among students of the empirical, theoretical, descriptive, explanatory, factual, general, concrete, abstract nature of chemical propositions.

In terms of innovative chemistry education, a proposal structured around inferences may contribute to the "eradication" of misconceptions. Many misconceptions on the particulate structure of matter have been related to a lack of understanding of the use of the micro dimension to "account for" the macro dimension. Reconciliation of the pieces of theoretical knowledge that in principle can explain results obtained in the school lab is the keystone of our proposal and a way of "working with" students' conceptions in a more comprehensive way, looking for possible integrations and re-significations.

Finally, we think our approach should be tested in actual technology-mediated implementations in secondary chemistry classrooms with the aid of analytical constructs from philosophy of science and science education. In its state presented in this article, it should be considered a set of recommendations or guidelines derived from currently accepted knowledge in the discipline of chemistry education.

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