UNDERSTANDING OF THE MOLE CONCEPT ACHIEVED BY STUDENTS IN A CONSTRUCTIVIST GENERAL CHEMISTRY COURSE

C. UTRIA-ECHEVARRIA and M. BRAVO
University of Puerto Rico, Rio Piedras
mlbravo@caribe.net

Abstract

The purpose of this research project was to study the conceptual understanding achieved in a general chemistry course based on a constructivist approach. A group of 28 students participated in repeated measures obtained by means of conceptual maps about the mole concept prepared three times during the course: at the beginning the course, immediately after the concept was studied, and after studying other related concepts. In addition, eight students selected from the group of 28 were interviewed. The interviews were carried out focusing on their conceptual maps. The analysis of the repeated measures indicated significant differences among the three times, especially between the first two. It was evidenced, therefore, that these students obtained a significantly higher level of understanding of the mole concept. The qualitative analysis carried out with students identified a broad range of responses that represent different levels of hierarchical organization, of progressive differentiation, and of formation of significant relations of the mole concept. Some recommendations offered are to develop and implement teaching methods that promote understanding of scientific concepts, and to prepare science professors and teachers to emphasize teaching for conceptual understanding.

Introduction

According to the American Association for the Advancement of Science (AAAS), a fundamental assumption for changes in the classroom is that schools do not need to teach more and more content, but instead should focus on the essence of scientific knowledge and teach this more effectively [1-2]. In the area of science, these reforms in teaching methods become imperative in order to achieve higher levels of effectiveness. The National Science Foundation (NSF) supports initiatives that experiment with ways to change teaching practices [3].

The teaching of science requires clear goals and non-traditional models that use the *inquiry processes*—exploration, based on the natural curiosity of human beings—to promote the development of skills associated with scientific culture [4]. Through these active learning strategies, the objective is to promote the understanding of basic concepts by students, as an indispensable requirement to understand the fundamental theories of science. Conceptual understanding is defined as the student's ability to adequately recognize, interpret, explain, and illustrate the connections among the subordinate concepts of a macroconcept and among these with other related concepts [5].

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In chemistry, for example, the teaching of the core courses should promote students' capability to design their own scientific experiments [6]. That capability requires a higher order understanding of the concepts that make up accepted theories. Consequently, any instructional process that fails to achieve understanding of concepts should be considered ineffective.

There are a considerable number of studies that illustrate the problems students face in developing understanding of concepts and principles of chemistry [7-12]. The problems underscored by this literature are: (1) student learning is predominantly through repetition or memorization, rather than through the active construction of knowledge; (2) students do not know the most important attributes of the concepts nor can they establish the necessary relations among the concepts to understand a macroconcept or a chemistry idea; (3) teaching could fail if it does not offer enough experiences in which the learner can reflect and express the ways in which they are establishing connections.

There is much controversy about what promotes conceptual understanding in a discipline. In chemistry, the relation between solving numeric problems and understanding the concepts has been studied [13]. It is also important to point out the research related to the alternative concepts presented by the students on some chemistry concepts. The studies by Gabel [13], Gabel, Sherwood, and Enochs [14], Anamuah-Mensah [15], and Bunce, Gabel and Samuel [16] indicate that the depth of conceptual understanding usually attained by students is inadequate to solve chemistry problems that require transfer—in other words, chemistry problems in which students must use and relate concepts in a different context to be able to solve them. Likewise, the studies demonstrate that students frequently solve numerical problems only by using an algorithmic approach.

Other studies have shown that traditional instruction in chemistry modifies students' concepts, but not to a great extent [17,18]. Occasionally, instruction creates errors in scientific conceptions or misconceptions. Based on these findings, the need has been identified to explore the effectiveness of instructional strategies designed to promote depth of conceptual understanding. For this purpose, professors and educational and scientific researchers on the secondary and university levels in Puerto Rico carry out educational innovations that seek to promote conceptual understanding. For example, the Puerto Rico Statewide Systemic Initiative (PR-SSI) and the Puerto Rico Collaborative for Excellence in Teacher Preparation (PR-CETP) focus their efforts toward the transformation of science and mathematics education through the development of innovative curricula, and the use of innovative teaching and assessment strategies.

One of the transformed courses through these efforts is the *General Chemistry* course of the University of Puerto Rico, Rio Piedras, which serves as a basis for this study. The study is part of a larger research project that constitutes the master's thesis of the first author of this paper [19]. In this thesis, besides what is presented here, the effectiveness of the constructivist approach adopted through this course in promoting conceptual understanding of the core concepts of *General Chemistry* was evidenced, in comparison with another course taught with traditional teaching methods. The group studied evidenced a significantly higher level of conceptual understanding, compared with another group with comparable sociodemographic and educational characteristics, on a test developed by William Robinson from Purdue University, translated and adapted in Puerto Rico.

The study presented here intends to delve into this finding through a detailed study of the understanding of the mole concept with students taking the *General Chemistry* course based on a constructivist perspective. The professor for this course uses extensive active learning activities. Within these teaching and learning strategies are tasks in cooperative learning groups inside and outside the classroom. Interactive demonstrations based on the process of predicting-observing-explaining, and based on experiments done in the classroom, are also widely used. The professor guides students through a process in which they all predict what could happen in a given situation and which they later research, to clarify their ideas. For example, she introduces the mole concept using an interactive demonstration based on an analogy described by Arce [20]. The professor brings an electronic balance and various matchboxes, each filled with the same number of paperclips, but with different kinds of clips. The thinking process is guided by means of the handout shown in Figure 1. With this interactive demonstration, students "discover" or construct their own understanding of the origin of Avogadro's number before the actual number is known. Later on, another activity carried out in the classroom is the critical analysis of a letter to the editor published in a local newspaper (excerpt shown in Figure 2). In these activities, students work in groups to discuss the problems and agree on an answer. In the letter to the editor activity, students must apply their newly acquired knowledge of stoichiometry and balancing equations to a real life situation in order to understand the important piece of information omitted by the writer.

Interactive Demonstration

Avogadro said: Equal volumes of gases contain the same number of particles.

As an analogy to equal volumes, we have four match boxes, each one containing the same number of paper clips, but with different kinds of clips inside each box.

Box label	A	B	C	D
Mass of box and content				
Mass of box				
Mass of content				

How can we express the ratio of the masses of the clips contained inside each one of the boxes?

How can we define a *clipol*?

Let's weight the mass of a *clipol* of each kind of clip and count the number of clips in each.

	A	B	C	D
Clips in box				
Mass of *clipol* to be weighted				
Number of clips in a *clipol*				

Figure 1. Handout of the interactive demonstration used to study the mole concept.

Can't release more weight than it burns

In my quest for information regarding the coal-fueled Cogentrix ® plant in Mayaguez, I read with interest the article titled "Can't Trust Regulations on Cogentrix®" by professor JB, a fine article that exposes the principal reason to oppose the establishment of this electricity generating plant at its current location.
The main reason used by most against the plant and expressed clearly by JB, is the lack of confidence in the regulatory agencies ability to establish appropriate standards and much less enforce them.
We must require that the appropriate standards are established and must insist that they are the same all over the world.
JB's article, as usual in the printed matter by Cogentrix® oppositionists, has some figures that are grossly exaggerated and cannot be true. In the third paragraph of the article JB states "These discharges include.....15.3 million pounds per day of the "greenhouse" gas carbon dioxide.
As a professor in chemical engineering, JB should not believe this. The little chemistry that I took in college always taught that the molecular weight in a chemical reaction had to remain equal. How about the true weights? Is Cogentrix® going to exhaust more weight than the coal it consumes? How about a free Chemistry class, Prof. JB?

Signed H.L.F, Jr.
Mayaguez

Figure 2. Transcript (only names omitted) of the Letter to the Editor used in the *General Chemistry* course.

To guide the study reported here, the following research questions were posed: Does students' understanding of the mole concept increase after participating in constructivist learning activities in a *General Chemistry* course? What are the characteristics of the conceptual understanding achieved by students in relation to the mole concept?

Method

A mixed method approach was used to achieve a better understanding of the problem studied. The qualitative and quantitative methods were used independently, but simultaneously [21].

The basic research technique used was the concept map administered three times: once at the beginning of the course; again immediately after the mole concept was studied; and then after studying other related concepts. This technique, in conjunction with a rubric, enables the assignment of scores to students according to their performance, and it can be used to guide interviews to obtain qualitative information. A repeated measures statistical analysis of the scores obtained by all students in the concept maps they constructed was carried out (n=28). On the other hand, an individual interview was carried out with eight students selected from among the 28, to inquire about their conceptual work in the three concept maps they elaborated during the course.

Participants – Students who took the constructivist course during the first semester of the academic year were the participants in the study. There were twenty females and eight males with an average age of 19.2 years and an average college entrance GPA of 3.43 (from a maximum of 4.0). The eight students interviewed were selected from among the 28 students. To select them, students were placed in descending order based on the scores they obtained in the second concept map. The students were divided into four equal groups. The highest quarter (highest scores) and the lowest quarter (lowest scores) were selected. In each of these groups, four students were randomly selected. This selection justifies the interest in describing the understanding developed by students who are outstanding in terms of the conceptual understanding they achieve, in contrast with students who manifest difficulty or limitations in their conceptual understanding. In this way, the power to observe a broad range of characteristics related to conceptual understanding is optimized.

Data Collection – The concept map is a procedure developed by Novak [22], based on a theory developed by Ausubel [23] and used in several studies to evaluate conceptual understanding in chemistry [22, 24]. Concept maps are made by establishing a hierarchy and relating concepts through propositions. They are used to allow students to express their knowledge about a concept through their own construction and learning styles.

To collect information, 28 students were asked to construct a concept map of the mole concept three times during the course. Students had 45 minutes to elaborate the conceptual map each time. At time 1, at the beginning of the course (August 2000), each of the students was asked to elaborate a concept map to explore the prior knowledge students brought to the course about the mole concept. At time 2, after the concept of mole was taught in class (October 2000), students were handed the concept maps they had elaborated in time 1, to correct, add, eliminate or re-elaborate according to what they deemed most appropriate. At time 3, a little before the end of the course (November, 2000), after related concepts had been taught, the concept maps created during the two previous times were handed to the students again. They were instructed to make corrections, to add concepts, to eliminate concepts or to establish new relations with other concepts they had studied.

Through the in-depth interviews, the understanding achieved by students was determined. They were asked to explain their thought processes and the ways in which they evidenced changes in conceptual understanding. Questions such as the following were asked: What reasons did you have to establish this hierarchy? Why do you think this relation is important in this part of the map? How do you justify the changes in hierarchy between the first and second maps? Why did you make these changes in the second and third maps? Why do you present a larger number of connections in this map? What examples can you add to these concepts?

Data Analysis – The scoring of the maps was done through the use of a rubric applying the criteria developed by Novak [22]. The score is distributed according to the characteristics of the map, including: hierarchy, propositions, ramifications, intercrossing, and examples. The fundamental base of the scoring scheme is the cognitive learning theory of Ausubel [23].

The researcher scored all students' conceptual maps using the rubric; the final score given to each of the maps for the three times was cumulative. Also, a doctoral student in education with experience in the conceptual map technique independently evaluated all of the maps, using the same rubric. Reliability between the two judges who evaluated the maps was determined through Spearman's statistical *rho* test. Results showed high reliability between the judges for the independently derived scores the three times (Spearman r=0.980, 0.989, 0.995, respectively). In case of discrepancy between scores, the two judges sought agreement regarding the score of the maps, and the scores that were assigned by consensus were the ones used in the analysis.

The scores attained by the students in the conceptual maps the three times were statistically analyzed calculating the mean and standard deviation for each administration. To evaluate differences among the three measures, the statistical test MANOVA (SSPS) was used.

For the qualitative analysis of the data gathered through the interviews, the constant comparative method was used. Through this method, the coding of information in deductive and inductive categories is combined at the same time that all the units of meaning are compared among themselves [25]. The use of a computer program for the qualitative analysis, *The Ethnograph* version 5.0, facilitated the grouping of the fragments corresponding to each category in thematic files.

Results

The first question that guided this study focused on the increment in conceptual understanding attained through the course. The inspection of the means of the repeated measures obtained through the maps suggests that there was an increase between scores for times 1 and 2, and they continued to increase, although to a lesser degree, in time 3 (see Table 1). The MANOVA test for repeated measures identified significant statistical differences among the concept maps of the three times (F=57.24, gl=2, p=0.000). Differences between times 1 and 3 were identified in the same way (F=80.09, gl=1.27, p =0.000) and between time 2 and the mean of times 1 and 3 (F=14.16, gl=1.27, p =0.001). From these results, it is concluded that students evidenced a progressive improvement, and a statistically significant one, throughout the different times of measurement, which indicates that their conceptual understanding of the mole concept increased considerably as the learning process advanced in the constructivist course.

Table 1. Mean and Standard Deviation of the Repeated Measures.

Times	Means	Standard Deviations
Time 1	1.536	1.934
Time 2	12.250	7.511
Time 3	15.536	8.500

Regarding the characteristics of the conceptual understanding achieved by students of the mole concept, the second research question of this study, data was analyzed through coding in categories based on the cognitive learning theory of Ausubel [23] and the studies by Novak and Gowin [26]. The selected categories are processes described by Ausubel that characterize the achievement of conceptual understanding, including hierarchical organization, progressive differentiation, and integrative conciliation. These categories were divided into subcategories that allowed the discovery of gradations or levels within each of the processes.

Results are illustrated below with examples of the answers given by the students interviewed. Examples included evidence of the different characteristics of conceptual understanding that were observed. The answers correspond to the participants from the two groups of students in the sample—that is, students with high scores and those with low scores at time 2.

Hierarchical Organization – According to Ausubel [23], the cognitive structure is organized hierarchically. A sound hierarchical structure for the understanding of a concept begins with broad, inclusive concepts and later follows with more specific and less inclusive concepts. The characteristics associated with hierarchical organization that characterize conceptual understanding attained by students are the following: (1) general or concrete conceptual relations; (2) conceptual relations without a clear distinction between general and concrete concepts; (3) simple high or low level conceptual relations; and, (4) complex high and low level conceptual relations. These characteristics denote progress in the conceptual understanding achieved by students.

In the analysis of the information from the interviews, it was observed that students with low scores in the maps had a tendency to form only general or concrete conceptual relations (45%). In an equal proportion, students formed conceptual relations without clearly distinguishing between general and specific concepts (45%). In the group with high scores in the maps, a tendency to form high and low level conceptual relations, simple as well as complex, was observed, although the latter occurred to a lesser extent (64.7% and 17.64%, respectively).

An example of a general conceptual relation is a statement by Beatriz (the names used are pseudonyms, those beginning with an "A" are used to identify students from the group with high scores and those with "B" to identify those from the group with low scores). She establishes a hierarchy with very general concepts. Although she also mentions specific concepts, Beatriz does not express a coherent relation in her conceptual hierarchy. She also explains the reasons that led her to establish the hierarchy shown in the map:

> When I thought about a mole I thought that it could be about elements as compounds, ... and in fact I am thinking that in a mole of an element there is the same amount as there is in a compound... and ..... that what this tells me about a mole.... In a mole of a certain amount, there are certain grams or 6.02 by 10 to the 23 units of a mole.

In these expressions, it can be observed that the relationships between concepts do not incorporate hierarchy. At first instance, she relates the mole concept with elements and compounds without reaching a greater degree of specificity of these concepts. Later, she relates the mole concept with grams and with the Avogadro number, evidencing a leap between the first level (elements and compounds) and the second level (grams, Avogadro number). This is to say, the general concepts on one hand and the specific or concrete concepts on the other.

Alfred establishes a simple hierarchical organization. He defined the mole concept in first instance. From this definition, he starts to relate concepts, keeping in mind the general and inclusive ones, as well as the specific and non-inclusive one. He commented:

> Well, from the mole to the most explicit, defining the mole as the quantity of substance and from there each concept leads to the other... it became normal in other words...it was pretty easy for me to go from the lower definition to compound, and from compound to element, and from there to molar mass... the definitions take us there... the higher one, I really guide myself by the higher one.

These expressions evidence a logical way of organizing the compounds. Defining the mole concept allowed the student to acquire a broader view about the relationships he established. This shows a better understanding of the set of relations between the mole concept and the ones that are subordinate to it. On the other hand, it is important to keep in mind that the creative students are capable of finding new ways to represent relationships and conceptual hierarchies [26].

Alice establishes hierarchies with conceptual relationships considered complex. Her hierarchical organization begins with the definition of the concept, and later establishes relations with broad and inclusive concepts and continues with less inclusive and more specific concepts. In the hierarchical organization of the maps of the second and third times, a greater degree of specificity of the mole concept is observed. About this she comments:

> Mole is a unit that represents a quantity of a substance whether of a compound or of an element. .. because the elements are the simplest and the compounds are beyond. The compounds and the elements are represented by the chemical formulas and from here you reach the stoichiometric calculations to determine atomic mass, molar mass.. atomic mass is expressed in u.m.a. ... molar mass is in grams by mole of molar mass I can reach the Avogadro number which is equal to 6.02 by 10 to the 23 molecules, ions and other things.

From the findings, it can be said that students with lower scores in general present an insufficient understanding of the concepts related to the mole concept which is clearly manifested in the lack of hierarchical organization that is evident in their answers. This is consistent with studies by Herron [27] and Abraham [28]. These researchers point out that the students present difficulties of understanding the mole concept due to limitations in their understanding of the related concepts and the use of rules and memorized algorithms. On the other hand, students with high scores presented definitions of the mole concept based on other concepts that are consistent with the findings from previous studies [29-32]. These researchers point out that a clear indicator of sound understanding of the mole concept in students is that they express a clear definition of the concept. Also, they can relate it with other concepts such as stoichiometry, molar mass, and solution concentration, among others.

Progressive Differentiation – The Ausbelian principle of progressive differentiation establishes that significant learning is a continuous process, during which new concepts reach higher significance as they acquire new relations [26]. Therefore, concepts are "never totally learned," but are always being developed, modified or becoming more explicit and inclusive as they continue to differentiate progressively.

Among the identified characteristics associated with progressive differentiations that characterize students' conceptual understanding, are the following: (1) assimilation of the meaning of concepts; (2) recognition of new conceptual relationships; and, (3) reorganization of the cognitive structure.

The observed tendency in students with low scores is mostly in the assimilation of the meaning of the concepts (64.28%). In the group with high scores in their concept maps, we found the tendency toward differentiation of the mole concept is to recognize new concepts (40%) and to change or reorganize their cognitive structure (52%). The following is an example of assimilation of the meaning of concepts expressed by Beto:

> Mole is the quantity of something... it is the quantity of substance, molecules, atoms... it's very confusing to relate it because it is so abstract, the stoichiometry, all that... it confuses and one has to understand it well.

From these expressions, it can be said that although Beto has internalized the meanings of the given definitions of the mole concept, he is not able to relate new concepts to those already existing in his cognitive structure. The differentiation he makes of the concept is limited. To a great extent, it could be because he did not establish specific new conceptual links. These conceptual links are relatively precise indicators of the degree of differentiation of a concept that can be attained [26].

An example that evidences the recognition of new concepts is Alfred's explanations:

> I can not say that they are a conversion measure at the start if I don't give the definition of mole to understand it more... because that helps to understand what a mole is, all the definitions and relations of the mole are important to point out in the map... it is important to know for what it is used... how it relates, for example to atomic mass, molar mass, grams of a compound.. it is important to know that there is a basic number that is called Avogadro because he was the scientist who knew that there was an exact number, although he didn't know exactly which, but he knew.

In Alfred's answers, we observe the importance he gives to the definition of mole. He also makes reference to its use and how it relates to other concepts. Alfred's differentiation level of the concept is in evidence. On the other hand, his expression of a preference to understand the concept better, serves as an indicator to affirm that his level of differentiation is in continuous development.

Alba, for her part, in explaining the relations that she establishes in her maps, makes a differentiation between the atoms and molecules of a compound. She also differentiates that the molar mass is defined as the quantity of grams per mole. An example of the conceptual links and differentiation Alba makes is:

> When I look at the periodic table and I see hydrogen and it says that it is 1.008 I have to be aware that it is a quantity that I have of hydrogen in a mole...when you analyze the composition of hydrogen you find that it is the atoms that form a molecule and the Avogadro number lets you know that a mole of any substance is 6.02 by 10 to the 23 atoms of that specific substance... and that molar mass is defined as grams per mole and that atomic mass is measured in u.m.a.

From Alba's explanations, it can be observed that one of the characteristics of conceptual understanding of the mole is to be able to differentiate it. This means to be able to reach higher levels of specificity through which the student internalizes the meaning of the concepts. Also, to be able to establish more differentiated relations of the mole. Alba's explanations are consistent with Novak and Gowin's study in which they showed that high differentiation in concepts in the cognitive structure of individuals is an indication of sound conceptual understanding [26].

Integrative Conciliation – Novak and Gowin establish that there is a sound understanding of a concept if the learner recognizes new relations (illustrated through the interconnections in a conceptual map) among related sets of concepts in hierarchical levels [26]. They also sustain that when understanding of a concept is achieved by the student, he/she is capable of solving conceptual conflicts in meaning.

Among the characteristics associated with the integrative conciliation related to conceptual understanding attained by students about the mole are the following: (1) relationships with non-appropriate concepts; (2) memory relationships; and, (3) significant relationships.

In analyzing the information from the interviews, a tendency to establish relations between non-appropriate concepts was observed in the group with low scores (54.5%). Another characteristic was the establishment of relations based on memory (40.9%). On the other hand, four students with high scores in their maps established mainly significant relations among concepts (87.5%).

Bernie explained erroneous or poor connections. He had difficulty in relating the subindex of chemical formulas with the appropriate number of atoms. An example of these relationships is the following:

> Well, if you have an element then you can associate that such an element is equivalent to a mole..it is an association that you make that in this element there is a mole.. if you had an element such as hydrogen (H^2) then you would have about two moles.

Bernie's explanations are consistent with the findings of Yarroch [12]. This researcher found that students do not make appropriate distinctions between the coefficient that precedes the formula in an equation and the subindexes of the formulas of either compounds or elements.

Belkis and Beatriz presented erroneous conceptions when they defined the mole. Belkis defines the mole as follows:

> The mole is... it is like the atomic mass in which grams of the elements and compounds are found... that is the mole.

In this definition, it is clearly shown that the relationships established are not appropriate for the mole concept. This is consistent with the findings of Staver and Lumpe which show that one of the most frequent mistakes made by students is that they define mole as a mass expressed in grams [30].

Beto, for his part, establishes new relations among related sets of concepts, but does not explain how or why a determined conceptual link is important. The relations he establishes are based on memory. An example is:

> I do not know the real importance of the relation (mole and u.m.a.) ... I placed what I understood about mole... I really didn't want to put it all together... one thing has nothing to do with the other... I know that the Avogadro number is equal to 6.02 by 10 to the 23 particles, I don't know what relation all this has, I just put them together, that's all.

The conceptual relationships (interconnections) that Beto establishes are essentially based on memory. This finding from this study coincides with Herron's [27] and Abraham's [28] statements that one of the barriers to successfully solve chemical problems that deal with the mole concept is the use of rules or memorized algorithms. An example of the significant relations is what Alicia expresses:

> The atomic mass is the mass of an element but expressed in u.m.a.... it is the same as if I could use the example of the oxygen element which is 16 u.m.a. as it is the same for the molar mass but expressed in grams.

It is considered significant because the student explains adequately how and why a particular conceptual link (interconnection) is important in the map. This description provided by Alicia agrees with the studies by Staver and Lumpe [30] who point out that there is a connection among the students' definitions of mole, and their explanations of the numerical identity that exists between the atomic mass and the molar mass of a substance.

Discussion

A progressive increment in the understanding of the mole concept throughout time, as evidenced in repeated measures on concept maps, was observed in students from the *General*

Chemistry course taught through a constructivist approach. The design of this study does not enable us to conclude that the changes were solely due to the constructivist approach. However, it evidenced that a significant increase in conceptual understanding was attained, thus suggesting that the teaching strategies used in this *General Chemistry* course might have been effective for this purpose. The understanding of concepts in chemistry is important for students to comprehend the scientific processes inherent in this discipline in a significant way. Moreover, good instruction in chemistry should modify students' comprehension of concepts [17-18]. Feasible and effective instructional models are needed for promoting the understanding of chemical concepts [24,33].

The study also evidenced the characteristics of the understanding of the mole concept achieved by students, as observed during in-depth interviews. We noticed that students, particularly those who obtained low scores in their conceptual maps, established general or specific conceptual relationships about the mole concept. For this reason, a hierarchical organization of the concept was not observed in their conceptual structure. This finding is consistent with the studies of Novak and Gowin [26]. These researchers determined that the meaning a student has of a particular concept depends on first instance on the hierarchical level of the conceptual relations they establish. On the other hand, it was identified that some students, specifically those who obtained high scores in their maps, established high-low level conceptual relationships, some simple and others more complex. These relationships reflect an organized hierarchical structure of the mole concept.

This research also evidenced that one of the characteristics of conceptual understanding achieved by students is that of relating new concepts with previously existing ones in their conceptual structure. This was illustrated in the continuous differentiation of the mole concept evidenced by students in their conceptual maps and in their explanations of the changes they made between the first map (before instruction) and the second one they developed (after instruction). This finding illustrates the statement by Osborne and Cosgrove who pointed out that each student has previous knowledge and that through the teaching and learning process, prior knowledge gradually progresses [34].

The establishment of significant relations of the mole concept by students is another characteristic, no less important, that was documented through this study. These relations evidence the knowledge structure acquired by students and are an indication of the sound understanding of a concept. This finding is consistent with the results of Novak [22]. This researcher indicated that significant relationships show the mutual connections of the concepts as well as their hierarchical order for the transformation of knowledge by students.

Another important finding highlighted by this study is the persistence of inappropriate relations among concepts in some students, specifically those who obtained low scores in their maps. This was observed in the explanations they offered to the ideas included in their conceptual maps in the three different times, in spite of the instruction received. This means that even though the constructivist teaching-learning methods were effective for most of the students in changing their initial levels of conceptual understanding, the establishment of inappropriate relations persisted with some students. A study by Cros, Castrette, and Fayol points out that erroneous concepts are difficult to eradicate even through effective instruction [17]. This finding constitutes a challenge for faculty and researchers in the teaching of chemistry. It reinforces the need to continue seeking ways to modify these erroneous concepts in some students.

In view of the findings of the present study, the following conclusions can be reached: (1) The constructivist approach apparently contributed to promote an increase in the understanding of the mole concept in a *General Chemistry* course; (2) the understanding of the mole concept progressively increased in students who took the researched course, evidenced through the analysis of understanding before studying the concept in class, as they finished discussing it, and some time after the discussion; (3) a broad range of answers was identified which represent different hierarchical organization levels in the understanding of the mole concept—this encompassed the presentation of general or concrete conceptual relations alone, to the establishment of high level conceptual relations; (4) a progressive differentiation of the understanding of the mole concept developed by students was identified—this progressive understanding was evidenced in several forms, that is, including the assimilation of the meaning of concepts themselves, through the recognition of new relations about it, and through the reorganization of their cognitive structure; (5) the formation of meaningful relations using subordinate concepts of the mole concept, was characteristic of the integrative conciliation process among students; (6) even though most students increased the level of their conceptual understanding after participating in constructivist activities, the establishment of inappropriate relations among the concepts persisted with some students.

From the experiences and results of this study, the following recommendations are made: (1) the teaching of science should focus on the promotion of understanding of scientific concepts; (2) science professors and teachers should be prepared to implement teaching and learning processes that promote improved conceptual understanding among students; (3) they should also be prepared to adequately assess conceptual understanding (concept maps and interviews are alternatives); (4) special attention should be given to the development and implementation of effective strategies to help students substitute erroneous or incomplete concepts; (5) courses in which teaching methods are being transformed should be studied to learn about the educational value of such efforts.

As in all research endeavors, the present study has strengths as well as limitations. The use of a multi-method approach allowed access to broad and precise information, as well as depth to the obtained findings. This is evidenced by the fact that the quantitative changes observed in the repeated measures could be described in more detail and understood in depth through the interviews carried out with the students. Because of this, one of the contributions made through this research for educational practice is to offer a multi-method approach that represents a useful option for the study of understanding of any concept in science. The mixed methods approach in this study was based on the use of concept maps, a technique used in multiple research projects by authors such as Easley [35] and Novak and Gowin [26] to study changes in cognitive structures. In the present study, the usefulness of concept maps to detect these changes was confirmed. The participation of an external evaluator, besides the principal researcher, to score the maps, the high reliability of their independent judgements and the calibration of their scores with each other was also a strength of this research. Moreover, the development of a rubric to score the maps, applying Novak's criteria but with a different population and scientific concept, and in conjunction with the high level of agreement among judges, adds evidence to the validity of the rubric. For this reason, the rubric might be used by other researchers interested in studying the conceptual understanding of students on different levels. Professors and teachers could also use it to assess the conceptual understanding achieved by their students at different times in their learning process.

On the other hand, a limitation of the study was that the principal researcher was the only person who carried out the categorization of data obtained in the interviews. Nevertheless, the elaboration of the categories integrated the input of three professors from the University of Puerto Rico and of a doctoral student of the Program of Curriculum and Teaching of Science, who participated as an external evaluator in the scoring of the concept maps. A more important limitation of this study is the absence of a comparison group and appropriate controls to be able to conclude that the observed changes in the understanding of the mole concept were due to the constructivist teaching strategies and that the levels of change observed were higher than would have been observed using more traditional teaching approaches. Studies of this kind are needed to convincingly reach these conclusions. However, results from another part of the larger research, on which this study is based, suggest that that could be the case. It involved a quasi-experimental design in which students from the constructivist course targeted in this study were compared to a group taught through traditional teaching methods; the groups were similar in sociodemographic and educational characteristics and did not differ in their pre-test scores. The experimental group showed a significantly higher level of conceptual understanding than the comparison group on a test, developed by William Robinson from Purdue University, that assesses concepts covered in a general chemistry course, including the mole concept. ■

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Bio

Carlos Utria-Echevarria is Professor of Chemistry at the INEM University Miguel Antonio Caro, at Baranquilla, Colombia, and Advisor to the Research Centre of the Universidad Autónoma del Caribe, in Baranquilla, Colombia.

Milagros Bravo-Vick is Professor in the College of Education at the University of Puerto Rico, Río Piedras, and Coordinator of the Evaluation Component of the Puerto Rico Collaborative for Excellence in Teacher Preparation (PR-CETP).

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