Making Sense of How Students Interpret Atomic Representations

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Abstract

The objective of this study is to examine students' interpretations and understanding of atomic representations. Students struggle to learn chemistry and in their quest to pass classes they often harbor misconceptions about the atomic theory, misinterpret its representations, and possess a weak epistemology about the topic. Developing conceptual understanding of the particulate nature of matter and atomic theory and its structure is essential to understanding chemistry concepts. This research study took place at the City College of New York as part of a summer enrichment program for rising ninth through eleventh grade students from New York City schools. The program is academically selective. The qualitative data presented here are based on an open-ended questionnaire that was given to the students. The questionnaire had different representations of the atom and students were asked to interpret each of them.

Our data shows that students possess a poor understanding of atomic representations, view the atomic representations differently from experts, misinterpret atomic representations, and have poor epistemological approaches to the atomic representations that are inconsistent with what is scientifically acceptable. They misuse the language of chemistry, and have misconceptions about the nature of atoms, molecules, and chemical bonds. These issues persist and continue with them throughout their college education. Our results indicate that there is a need for change in the way atomic theory and its representations should be addressed in instruction. Based on the data presented here, chemistry topics especially the atomic theory and its structure should be presented with an inquiry-based approach and students should be exposed to the raw data and evidence present at the time, discuss it, and analyze it to arrive at a conclusion. This will give the students the opportunity to construct their own knowledge and understand how chemists reached their conclusions about the atomic representations based on evidence.

Introduction

Identification of chemical vocabulary words about the atom or the ability to solve numerical problems in chemistry does not translate to conceptual understanding of the atomic theory as it pertains to the structure of the atom and its representations. Previous work has shown that solving numerical problems is not equivalent to conceptual understanding (1). Students' lack of understanding or learning of chemistry or structure of the atom could be the result of one or more factors. These factors include: (a) an improper early education where they lacked the proper foundations and fundamentals needed, (b) non-inquiry based instruction because of the way chemistry concepts are presented and taught, (c) lack of historical context and data driven development of atomic structure and representations, and (d) lack of underscoring the importance of epistemology in the development of these ideas. Furthermore, the complex nature of chemistry makes it difficult for students to understand. Johnstone refers to this as the three levels of chemistry (3). Matter and its changes can be described at the macro level (phenomena), the micro level (particle), and the symbolic level (representational). Teachers who neglect to use and relate the three levels in their classrooms, and often teach chemistry at the very abstract symbolic level, will likely find that students have an incomplete conceptual understanding of the subject.

Cognitive research shows that when students construct their own knowledge they achieve a better conceptual understanding of chemistry (4-5). According to Bodner; “Knowledge is constructed in the mind of the learner” (6). When students are actively involved in the learning process such as in inquiry, then they construct their own knowledge and build a more coherent and deeper understanding of the science topics studied. During the learning process, students use their experiences and knowledge to construct an understanding and achieve sense making. This process is facilitated by the interactions they have with their instructors and peers which present conflicts of thoughts and ideas that help students modify their thought processes (7). Concepts that the students build about the atom, its structure, and representations could be aligned with what is scientifically agreed upon or can differ from it. We will refer to those that differ as misconceptions (8). Regardless of those misconceptions, students often rely on algorithms to solve problems.

Students’ understanding of different representations of chemical concepts increases comprehension and retention of chemistry (9). Chemistry textbooks contain a significant number of diagrams, representations and photographs. Students are required to view these diagrams, translate between the three levels of chemistry, visualize a 3D structure from a 2D representation, and use those representations in making-meaning of the topic (10).

Developing understanding of concepts and representations of the atomic structure is essential to understanding and learning of chemistry concepts. The literature contains significant research findings that discuss misconceptions about the atomic theory and atomic structure (2, 11-13). Research in science education has shown that students have several misconceptions related to the atomic theory: misconceptions about the particulate nature of matter where the students view matter as a continuous medium instead of discrete particles that are constantly moving and have empty space between them (11, 14). The National Research Council (NRC) underscores the importance of understanding the atomic theory as a prerequisite for understanding many concepts in chemistry (15). Gabel, et. al. cautioned against presenting chemistry quantitatively before ensuring that students understand chemistry qualitatively because it would lead to algorithmic manipulations of mathematical equations with little emphasis on conceptual understanding (16).

Historical Perspective of Atomic Concept Development

The history and philosophy of science can play a role in the learning process in the discipline of chemistry (17-18) because it reflects the development of ideas that mirrors the process of science. The discovery of atomic structure and its development is not based on random experimentation where we arrived at the truth, but it is a story of the process of science at its best. For epistemological reasons, students should be engaged in historical accounts and raw data examination of the time of the development of the atomic structure (19). By allowing students to examine raw date obtained at the time and draw their own conclusion, we will be involving them in the construction of their own knowledge and this inquiry engagement is important in science learning (20). This improves the learning process by making the student actively involved in the learning.

Instruction that provides a comprehensive view of historical development based on evidence and a chance examine the data of the atomic theory development provides the student with a clearer understanding of chemistry and the importance of the nature of science. Learning about the history of atomic theory and atomic structure and their development provides useful insights into the scientific reasons for adapting succeeding models of the atomic structure and the importance of discovery, evidence, and the scientific method in the evolution of the atomic theory. The history and philosophy of chemistry in a successful chemistry classroom should provide clear view of scientific research at work with all of its triumphs, failures (21) and controversies (22).

Context

The purpose of the research is to gain insight into students' understanding of atomic structure and its representation after completing one year of high school chemistry. This research study took place in a summer enrichment program for rising tenth and eleventh grade students from New York City. The program is academically selective and students from the top rated high schools in New York City were asked to participate in a summer program. There were 1500 applicants for the program but only 25 students were selected per summer. The students were also asked to have two letters of recommendation from their teachers. Once accepted to the program, which is an all-expense paid program, the student would receive three college credits of chemistry and three of physics upon completion. The participating students were motivated and high achieving and all students have completed a high school chemistry year.

Curriculum and instruction in the summer program are not predicated on covering a prescribed body of information or teaching towards a standardized test. The instructors for the program take this as an opportunity to focus on the scientific process and depth of understanding of an accessible scope of content. This is in contrast to typical academic year high school science instruction in New York City – and most other places where the focus is on measures on a high stakes examination. The contrast results in a great cultural shock for students who are normally accustom to and skilled at succeeding on curriculum and assessment which focuses on memorized facts, prescriptive problem-solving and multiple choice/short answer exams (23).

Each summer since 2004, approximately 25 students have formed a science cohort. The program meets 4 days per week for 6 weeks starting in early July. A total of 4.5 hours per day is formal class time divided equally between a chemistry class and an observational astronomy class integrated with ideas of force and motion. Both classes were delivered in the same inquiry based spirit. In a study conducted on observational astronomy students, it was found that students struggle with scientific justification and thought process and that these skills can be improved by inquiry-based learning of science (23). This paper will discuss only the chemistry class. Quantitative data presented are from the summers of 2005 – 2007 and include all existing data. Data from the previous years are incomplete, but qualitatively there are no substantive differences.

The 6-week class consisted of inquiry-based activities. We define inquiry to be making observations and answering questions by using various sources of information through experimentation, formulating an experiment, collecting data, and analyzing data. Inquiry involves the use of critical thinking and accessing alternative conclusions (24). The activities included various hands-on lessons that were aimed toward fundamental understanding of basic science concepts.

Research Methods

Research Question

The primary research was conducted by handing the students an open ended questionnaire. We presented them with five representations of atomic theory as shown in Figure 1 and asked the following question:

"Consider the following drawings that have been used to represent the atomic structure. For each one on the space at the right, explain how do you interpret the drawing."

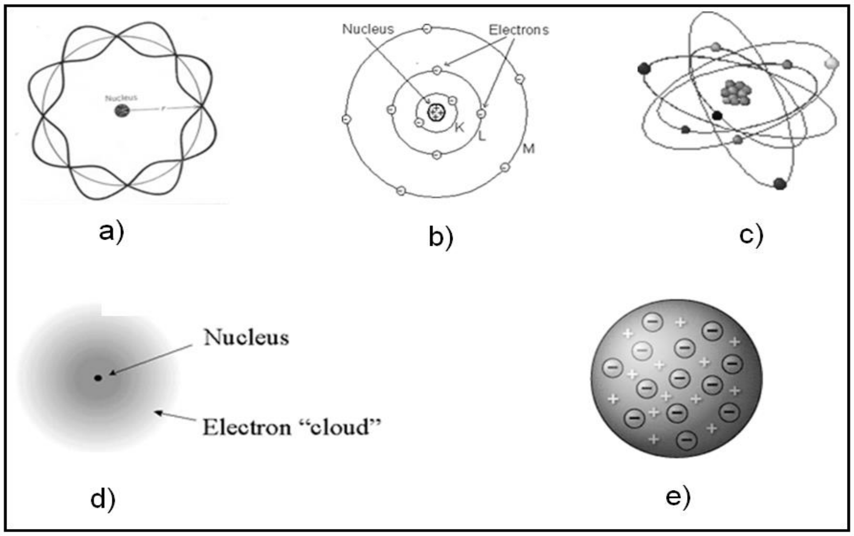

Figure 1 Representations of the atoms; a) De Broglie model, b) 2D Bohr model, c) 3D Bohr model, d) Electron Cloud model, and e) Plum-Pudding model.

Rubric Development

The assessment tool was an in class examination as part of the instruction. The varying understanding of the representations, the limited understanding of the atomic structure concepts, and epistemological approaches that are inconsistent with what is scientifically accepted about the basic models of the atoms were reflected in the written answers that the students provided on the assessment tool. The answers were evaluated on a scale from 1 to 5 based on a rubric that was developed that works well for this type of research.

The final rubric shown in table 1 was finalized after four re-readings of the written exams. Answers with a score of 5 show complete conceptual understanding of the atomic representation and is epistemologically consistent with what is scientifically acceptable about the different representations. A score of 4 depicts an acceptable conceptual understating while a score of 3 is approaching understanding. A score of 2 shows lack of understanding of the representation. A score of 1 represents inadequate conceptual understanding and varied misconceptions. Three researchers independently applied the rubric shown to the entire set of data. The three sets of results agreed over 90% of the time. The responses where the rubric score varied were not different by more than one unit. The three researchers met and discussed the responses that were not unanimous using the rubric until an agreement was reached. The rubric reflects the representative responses that were observed.

Results and Analysis of Student Reponses

Table 1. Rubric used to evaluate student responses to atomic representations.

Rubric Score	Category	Description
1	**Inadequate Conceptual Understanding**	Uses biology or math instead of chemistry to interpret the figure; states that the structure of the model is wrong or incorrect; regurgitates of some "big" words not relevant to interpretation; uses the name of the model incorrectly or states the incorrect model, interprets the figure wrong and uses the physical properties of the figure provided
2	**Lack of Conceptual Understanding**	Literal interpretation, describes the physical properties of the picture, uses general knowledge about basic concepts of chemistry, states that the figure is "incorrect" or "wrong" when the structure does not resemble that of the current model, uses knowledge and statements that contradict the representation
3	**Approaching Conceptual Understanding:**	Shows some conceptual understanding in the interpretation but lacks explanations, provides a description of the atom and the location of its sub-atomic parts, demonstrates familiarity and gives some general chemistry knowledge about the representations of the atoms, does not rely on history of science or epistemology to interpret the representations
4	**Acceptable Conceptual Understanding**	Approaches conceptual understanding, uses prior knowledge but focuses only on the some parts rather than the big picture, provides some explanation about the representations, provides details in the interpretations of the representations, discusses each representation as a model different from other representations, refers to specific experiments that helped arrive at this model
5	**Complete Conceptual Understanding**	Shows complete conceptual understanding and uses their prior knowledge of chemistry and interprets the model with understanding and insight, discusses specific experiments that helped arrive at this representation of the atom, discusses some of the historical developments that lead to the representation, uses epistemology approaches that are consistent with what is scientifically accepted about the representations

Representative responses include:

Figure 1 (a) *"An atom has a nucleus (center). The structure of this atom resembles that of an amoeba. It has no electrons."*

Figure 1 (b) *"The nucleus is the brain of the atom surrounded by a number of electrons."*

Figure 1 (c) *"The following drawing represents the energy around a cell. We can observe the nucleus, and also we can conclude that the lines are the chemical bonds that keep the cell unified."*

The misinterpretations of the atomic representations, inadequate understanding of the atomic theory and atomic structure, and lack of epistemology are shown in the above examples. Students use biology but their answers are also evident in thinking that knowledge lies in the words without recognition as to what the underlying ideas are and where they come from. The confusion between biological entities and the representations of the atom is indicative of focus on common surface features of the two. The first student mentions that the atom resembles an "amoeba" because they see the waves that might conclude that the student is not relying on epistemology to answer a question about the representation of an atom but on prior knowledge from biology. The "brain" of the atom, as stated by the second student, is compared to the nucleus of a cell, which regulates the activities of the cell. The two students have familiarity with the word nucleus but lack a well-developed conceptual understanding of it and have a poor epistemological approach to the topic. As a result, the two students confused the nucleus of an atom and the nucleus of a cell.

Figure 1 (d) *"The nucleus seems to be surrounded by an electron "cloud" because of the constant motion of electrons. Since they move quickly in random, unending motion, the electrons seem to form a "cloud" around the nucleus."*
Figure 1 (e) *"The surrounding electron "cloud" hovers over the nucleus like a big mass that is very blurry and undefined. I believe it is saying that within an atom, there are so many electrons that it all becomes a blur."*

These students learned some concepts of chemistry and retained a few vocabulary words from their experience with chemistry. But the students were not able to show their understanding of the concept. One student tries to describe the cloud model of the atom by using the word "cloud." The student does not understand what the "cloud" in the cloud model of the atom means. An expert would think of a cloud as a probability density about the presence of the electron. This student could have developed deeper understanding if they were allowed to construct their own knowledge and not just be informed about it, exposed to the atom from a historical perspective, allowed to construct knowledge based on examining raw data, relied on epistemology to learn science, and question how do we know what we know. Another student uses the name of the atom to define the atom, the student mentions that it is called the cloud model because it "hovers," like a real cloud. Knowing the name of an atomic representation, just like most topics in science, does not translate to conceptual understanding of the topics or the fundamental concepts that the models portray.

De Broglie Model

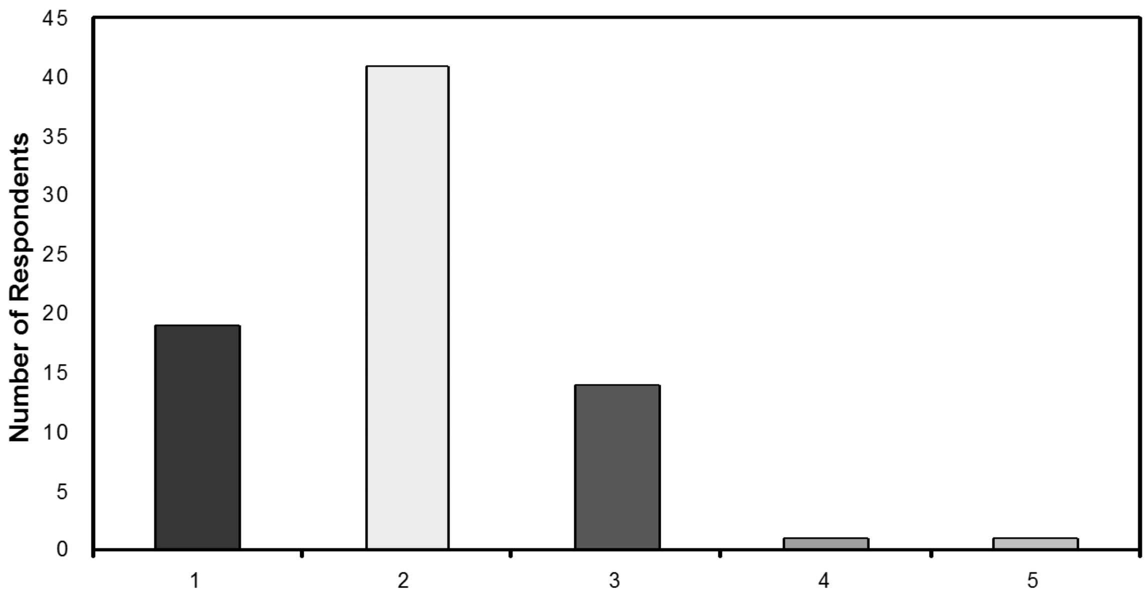

Figure 2 Diagram for <u>question 1a</u> showing the number of respondents for each answer based on the rubric evaluation

Figure 2 shows the number of respondents of the pre-instruction based on the rubric. This figure displays the results for all the students in the three summer programs, which is 78 students. It is noteworthy that 79% of students received a score of 1 or 2. This paper will only present data based on the pre-instruction. The post-instruction data will be published separately because it will examine effect of inquiry-based instruction on the understanding of the structure of the atom. It is difficult for students to understand that a particle can have both wavelike and particle-like behaviors. It is also difficult for students to realize that the electron can act both as a particle and a wave at the same time (25). The De Broglie's atomic representation illustrates an electron standing wave around a nucleus of an atom with integral numbers of wavelengths are allowed.

"The radius of an atom is the distance from the nucleus to the electrons orbitals."
"The nucleus is located at the center of the diagram with r being the diameter of the atomic structure."

The students mostly focused on the "r" rather than the entire atom. There were several students that gave similar answers. The students did not specifically look at the picture as a whole. The students relied on the "r" as a tangible value, thus they did not use scientific reasoning to analyze the data provided. Students' poor of use of epistemology and viewing the representations as models is demonstrated in the responses provided. The students' concentration on the radius suggests that they used prior knowledge, the "r", and to interpret the representation. Some took a mathematical approach by focusing on the "r" which seems to indicate focusing on a surface feature that is familiar to them instead of interpreting a representation, demonstrating conceptual understanding of the atomic theory and its representations, and approaching the representations from a good epistemological perspective.

2D Bohr Model

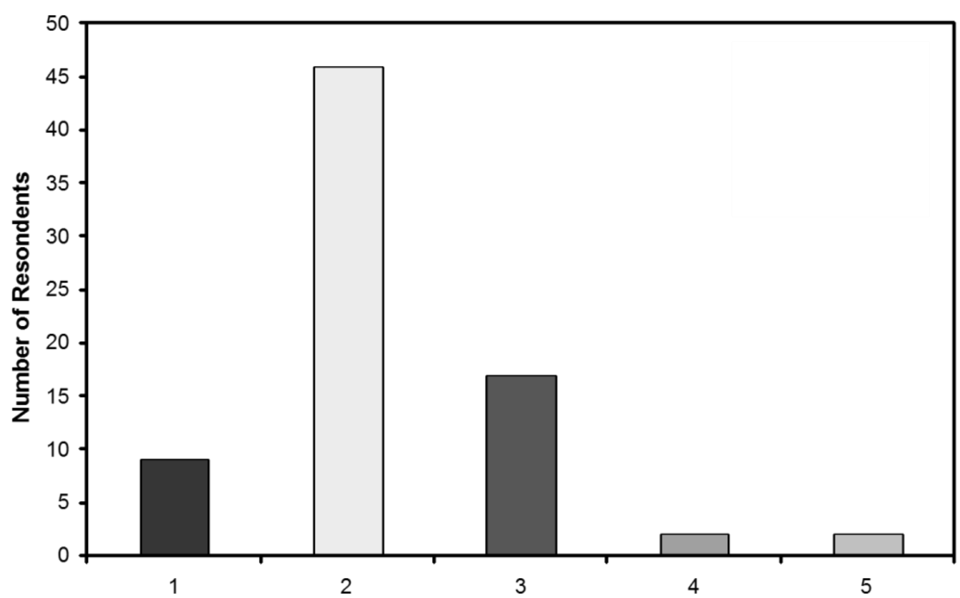

Figure 3 Diagram for <u>question 1 b</u> showing the number of respondents for each answer based on the rubric evaluation

The results about representation 1b based on the rubric scores are shown in Figure 3 and show that 72% of students received a score of 1 or 2.

"The atom is a dense center and electrons are revolving around the nucleus in orbitals. They are like this due to the gravitational pull."

The student compared the nucleus to the sun and the gravitational pull of the sun to the planets. The student found a relationship based on prior knowledge of the solar system and applied it to the representation of the atom. The students might have learned via lecture or reading about the atomic representations, but were not able to process it so what they took away from class was very different than what was intended. The 2D model of the Bohr atom, some students were able to give some insightful understanding of the model.

3D Bohr Model

Some representative responses about representation 1c include:

"This appears to be an atom with a nucleus in the center made up of different particles, and dots which are mostly likely electrons because they are in the atom away from the nucleus, are shown to have elliptical orbits."

"This drawing depicts an atom with some charges in the center and other charges surrounding it. The charges surrounding it are spaced out are in elliptical orbits."

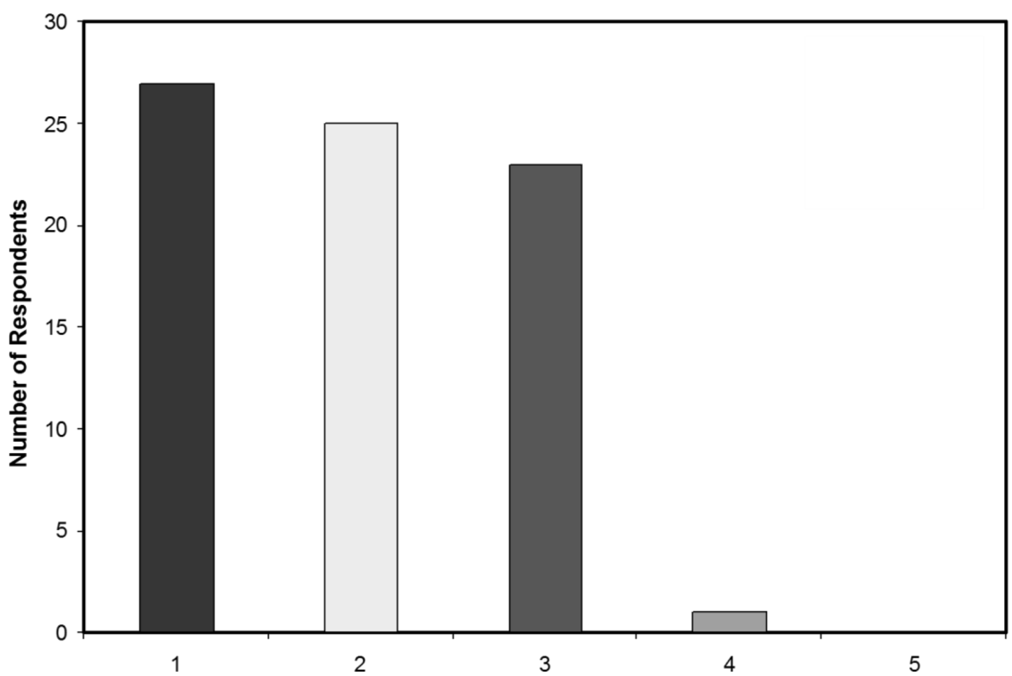

Figure 4 Diagram for <u>question 1c</u> showing the number of respondents for each answer based on the rubric evaluation

The results from the rubric scores for the 2D representation of 3D Bohr Model are shown in Figure 4 and 68% of students received a score of 1 or 2. The students did not realize that this model was a 3D structure of the model from Question 1b which goes to the heart of learning. Developing a good understanding of the atomic theory, applying sound epistemological approaches to learning about the atomic theory, relating the atomic theory to the atomic representations could have provided the students with the tools to see the connections between the two representations.

The students do not use any scientific reasoning because they were not able to see that the two models are the same since both drawings represent the Bohr model with one drawn in two dimensions and the other is drawn to show three dimensions. The students do not realize that the Bohr model is in 3D space because they do not fully understand the concept of the Bohr atom. Overall the Bohr atom was the most recognized atom in the survey. A study done on chemistry textbooks show that older textbooks found Bohr's model of the atom to be more important than that of Thomson and ignore the progress of science and the its process (26).

Electron Cloud Model

Many students answered in simple statements that were correct but did not give a true understanding of the atomic model but also with the correct scientific method. This is not surprising since our data are consistent with science being taught as a static, non-meaningful collection of ill understood pieces of information. The answers often include general information about atom. Students just based their responses on a textbook definition of an atom rather than analyzing the data that was provided. They are not giving specific answers because they do not know what the model is or they believe that the concept that the model portrays is incorrect. The students do not use scientific reasoning in school, but rather memorize textbook facts, which they believe to be correct, and the only answers. One student stated for question 1d, *"This is a diagram that I had once encountered in a textbook and was told that this is how the atom looks…"* The student relied on an authoritarian perspective since much of the science is taught this way. Also, students seem to just state the general facts because they are not taught to figure out the answers, ask how do we know that, but rather told what something is (27). The scoring results for the electron cloud model are shown in figure 5. 68% of students received a score of 1 or 2.

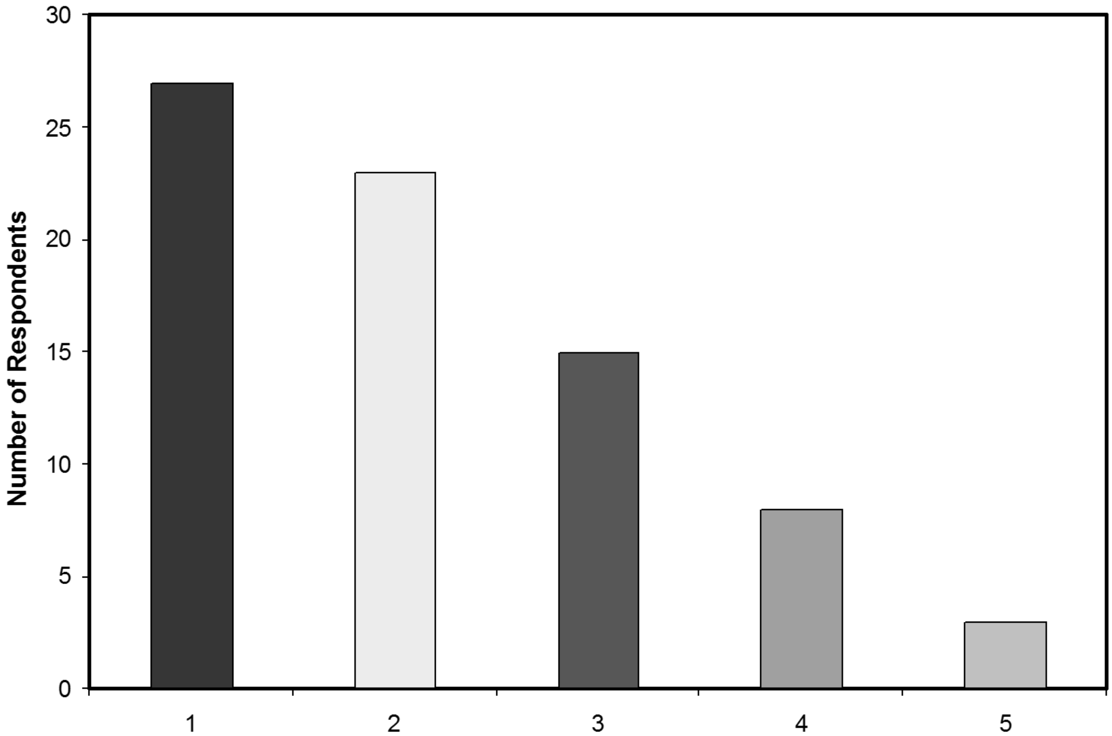

Figure 5 Diagram for <u>question 1d</u> showing the number of respondents for each answer based on the rubric evaluation

> *"This picture of an atom is most realistic and shows the electron cloud that is formed by the electrons moving at such high speeds, that it causes a blur."*
> *"In this picture, I believe that it is establishing the fact that an atom has both positively and negatively charged particles and exactly the same amount of them so that the charge is balanced or neutralized in an atom. It also shows me that the atom's shape is a sphere..."*

The students did not realize that the atomic models are theories, and believes that there are right and wrong versions as compared to representation based on evidence and data available at the time. This goes to the epistemology of learning science and that these models and representations fit the data at the time. Students did not "understand the way in which science has evolved and moved forward, one [students] must understand the trials and tribulations of its past." (28) Students have misconceptions about the "trials and errors" of science. They do not understand that scientists have gone through many experiments before they arrived at a viable conclusion. "Historians and philosophers of any science inevitably pay more attention to successful scientists than to mediocre ones, to important advances than that to dead ones. Similarly, any pedagogical use of historical material tends to focus on success. Thus, the selection of subject material can convey to the student a distorted view of science and scientists, one that gives an unwarranted impression of infallibility." (29) If students were to understand the trials of science they would be able to feel more comfortable with the subject because they would understand that scientists were just as human as them.

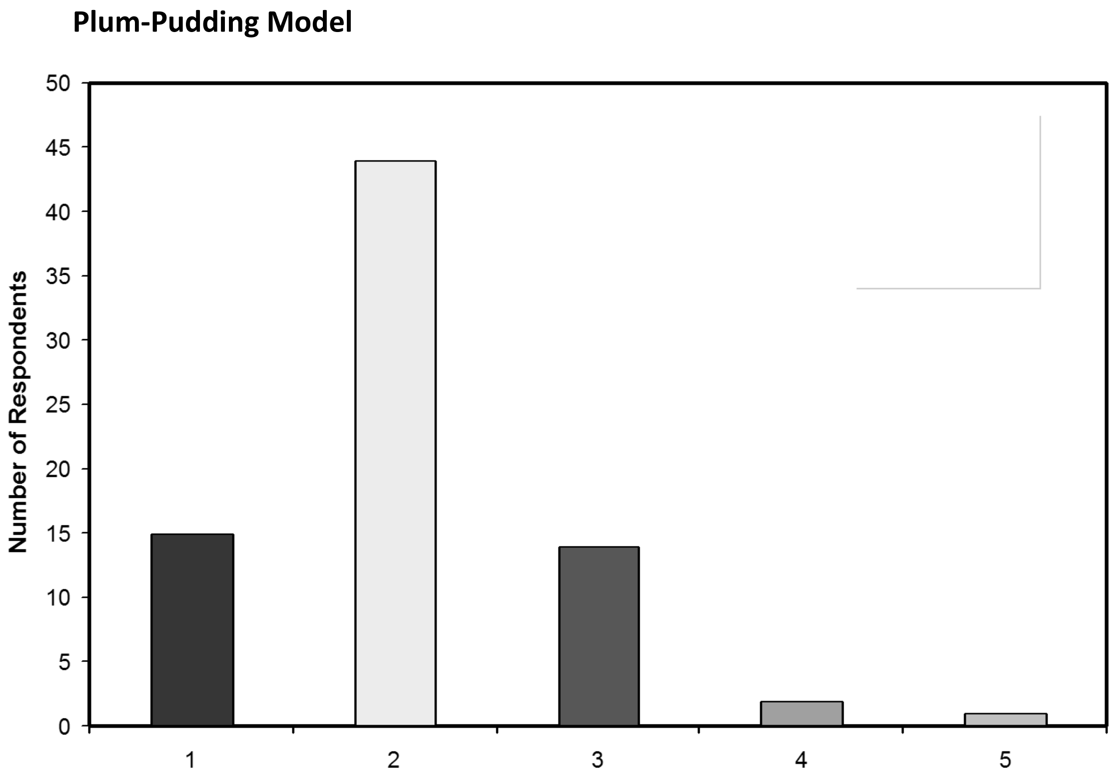

Figure 6 Diagram for <u>question 1e</u> showing the number of respondents for each answer based on the rubric evaluation

The plum-pudding model of the atom was one of the least recognized models on the assessment. The results, based on the rubric that is shown in Figure 6, show that 78% of students received a score of 1 or 2.

> *"The atom is one evenly proportioned mass, like a bowl of rice pudding, with the protons and electrons mixed in a spherical shaped mass."*
> *"This model is the plum-cookie model which has electrons and protons all bunched up together into one single molecule."*

The students did not remember or know the name of the model and guessed the name. Stating the name of a model of an atom does not necessarily mean that the student understands the concept behind the model and its development. Names and pictures are what students are taught in school, students are not taught the concepts behind them. The students form naïve mental models and not a correct conceptual model based on the name (30).

Some of the students memorized models based on images in textbooks.

> *"The nucleus, in the middle, is composed of few particles around the nucleus – they have various shapes and colors – the particles outside the nucleus are moving around along certain orbits or paths."*

This response was from question 1c, where the student had a similar weak response about the atom because the student based the definition on images from a textbook. The student mentioned that particles have color and shapes. This could be due to using modeling kits where carbon atoms are black, hydrogen is white, and oxygen is red or relying on textbook versions of these colors. The student assumed that the atoms in the models have the same colors assigned to them by the modeling kits. This student did not understand that fundamental concept of the atomic models, and the student knowledge based on modeling kits and textbook images was flawed.

Based on the figures, a score of two was the most common rating for the answers provided by the students. A two shows lack of conceptual understanding. The students' analysis of the representations and scan for the concepts they know and not for the things they have to interpret. This shows that students have a weak foundation in analyzing and interpreting atomic representations.

Students struggle to learn chemistry and in their quest to pass classes they often harbor misconceptions about the atomic theory, misinterpret its representations, and possess a weak epistemology about the topic. These types of problems stay with them throughout their college studies and further until addressed through conceptual change. Students often study problem solving for classes to pass exams but do not understand the fundamental scientific concepts (31). Passing scores are often the only achievement standard that is looked at when evaluating whether students know the chemistry that was taught. Sometimes, especially when the assessment tool focuses on algorithmic problem solving, passing scores do not reflect understanding of the concepts that were presented. Once these misconceptions about the atomic theory, misinterpretations of its representations, and the proper epistemological development, are etched into students' minds, students become resistant to change. They do not just struggle with learning representation and developing conceptual understanding, this study is an example of how students lack an understanding of the nature of scientific knowledge.

Conclusion

The misconceptions about the atomic theory, misinterpretations of its representations, and the proper epistemological development, were reflected in the written answers that the students provided on the assessment tool. Our results show that the well-above average high school students, who have completed one year of high school chemistry, have a fragmented understanding of the atomic theory, atomic structure, its representations, and epistemology, which is attributed to the way science in general and chemistry in particular is taught. Students learn to become "Algorithmic problem solvers" to succeed in chemistry while lacking any understanding of the deep important concepts such as the atomic theory and its structure (1). These issues persist and continue with them throughout their college education. Our results indicate that there is a need for change in the way atomic theory and its representations should be addressed in instruction. Based on the data presented here, chemistry topics especially the atomic theory and its structure should be presented with an inquiry-based approach and students should be exposed to the raw data and evidence present at the time, discuss it, and analyze it to arrive at a conclusion. This will give the students the opportunity to construct their own knowledge and understand how chemists reached their conclusions about the atomic representations based on evidence. Furthermore, teachers, college professors, and textbook authors should make it clear to the students that the atomic representations are just models that fit the data at the time. The atomic theory keeps improving those models as more data becomes available.

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