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Exploring Learning Difficulties Associated with Understanding Ionizing By Radiation

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Abstract

What does the word "ionizing" mean in the phrase "ionizing radiation"? This question serves as a litmus test for student understanding on how radiation affects matter. We are doing research on how non-science undergraduates can come to understand the interaction of radiation with matter through inquiry, and we find that the above question helps us determine whether students have a coherent mental model of the ionization process, in which high speed subatomic particles (radiation) knock electrons out of atoms rendering them ionized. We find that substantial pedagogical support is required to get more than a small fraction of the class to develop usable models of ionization. Despite carefully planned instruction on ionization only 12% of students answered this question correctly the first time it was asked two years ago. In response to this problem we have developed extensive support including research-based strategies and a new simulator for ionization by radiation. Although much progress has been made in the number of students who understand the ionization process, approximately 30% of the students still fail to understand this fundamental radiation process. Understanding ionization requires understanding three things: what an ion is, the basic characteristics of radiation, and the process of ionization. Students then must put these ideas together to create a complete mental model of the ionization process. We will identify the learning difficulties and their possible causes, exploring possible ways to resolve them. Mixed methods were used to infer students thinking using data from video, exams, journals, interviews, and homework. This research is part of the Radiation By Inquiry project supported by NSF DUE grant 0942699.

Keywords: Physics Education, Inquiry, Ionizing

1. Introduction

Science literacy is an important element in supporting a democratic and industrial based society.[1] Unfortunately, many of the democratic and industrial populations worldwide have a poor understanding of basic science concepts.[2] Much of the confusion in past and current nuclear disasters such as Chernobyl, atomic bombing of Japan, and Fukushima highlight the need for ionizing radiation literacy. For example after World War II the survivors of the Atom Bomb from Hiroshima and Nagasaki and their off spring were (and still are) discriminated against because of a lack of education in Japan on the effect of ionizing radiation on the body.[2, 3] People feared that Atom Bomb victims carried a "genetic disease", survivors often remained unmarried and their children were denied jobs and social acceptance.[2, 3] After the Fukushima nuclear reactor incident, reports of prejudice and discrimination against Fukushima residents and evacuees emerged due to fear of evacuees "carrying radiation."[5, 6, 7] The need for radiation literacy carries into the medical field. Mubeen et al. 2008 found severe misconceptions among medical students in another country regarding the interaction of radiation with matter.[8] These are a few examples exhibiting the importance of understanding radiation's effect on matter and human health for the civic population. The cause of misunderstanding radiation are many - by examining students ideas, we found students in a survey of physics class who had trouble with ionizing generally had two or more of the following difficulties: a nonfunctional model of atoms, difficulty distinguishing radiation from radioactivity, and scale issues.

To understand ionizing radiation's effect on matter and human health, an individual must know this model: ionizing radiation (subatomic particles) is emitted from radioactive atoms, affecting matter by removing electrons from other atoms that it encounters along its path, thereby breaking apart molecules. Normal alpha, beta, and gamma radiation particles themselves are unable to make matter radioactive which would require transforming nuclei of atoms; they damage matter by destroying molecular bonds between atoms.

Most people are not aware of this model, however, and instead have very rudimentary ideas about radiation. Their initial ideas about radiation can impede the development of radiation literacy and even cause social unrest. To promote radiation literacy we need to solve the education problem of helping people understand the ionizing model. According to Griffith and Preston, the basis of education research is the importance of the concepts students brings into the classroom.[9] Understanding student's concepts about radiation and ionization is an important step in effective teaching.

We are creating and testing inquiry based materials for teaching radiation and radioactivity to non-science majors and high school students. While testing the materials in the class we found that the question, "What does the word "ionizing" mean in the phrase "ionizing radiation"?" serves as an indicator of how students are thinking about the interaction of radiation and matter. In order to answer the question correctly, the students must describe radiation particles knocking electrons away from victim atoms. In 2009 only 12% of students in the Survey of Physics class answered this way after instruction on ionizing.[10] In response to the low understanding of ionizing, three simulators were created that allow students to perform virtual experiments embedded in guided inquiry activities. The simulators are designed to support student construction of a functional model of an abstract atomic world that would otherwise be difficult for students to accomplish and the guided documents help scaffold the experience.[10] The simulators and guided documents for the Radiation By Inquiry (RBI) project can be found at www.CAMSE.org/radiation. With this extra pedagogical support, 70% of the classes as of the Fall Semester of 2011 were able to answer the question sufficiently.[10] While this is an important improvement, the question remains - what is going on with the other 30% who still struggle with ionizing by radiation?

1.1 general difficulties with ionizing:

Students tend to have incomplete and non-functional models of atoms and radiation when they enter the classroom.[10, 11] Vague models of atoms impair student understandings of the simplest radiation processes - emission and ionization.[10, 11] Prather uncovered similar student difficulties with radiation due to incorrect mental models of atoms and radiation at a different institution.[11] He found roughly 60% of students put the electrons, protons, and neutrons in the proper location in the atom and only 20% of students in his study attributed radioactivity to the nucleus of an atom, although they did not always give acceptable reasoning behind their answer.[11] Griffith and Preston found 12th graders in their study overestimated the size of atoms.[9]

We found in previous research that students entered the classroom with vague and poorly organized models of atoms and molecules.[10] In a pre-assessment, 51% of students in the Fall 2011 semester didn't use charges in their explanations of why the inner and outer parts of atoms are held together. When asked, "What is a molecule?" 14% of the class answered, "molecules make up an atom" which indicates a confusion of the roles and relative sizes of atoms and molecules. From 130 students since the Spring Semester of 2010, 25% drew nucleons in atomic orbitals on their pre-assessment.[10] An example is shown in Figure 1.

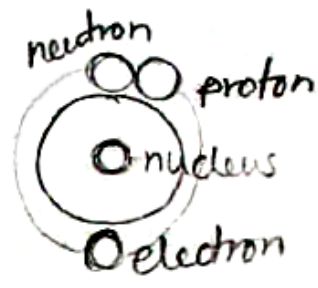

Figure 1. Student's atoms cycle pre-assessment drawing of an atom with nucleons in the orbitals

Even though the materials successfully help a majority of the students understand atoms, some problems persist. A few students still fail to develop a working mental model of atoms. For example, a few students said in order for an atom to balance its charge it will have to lose or find a proton. While this can be imagined, it rarely happens in nature and doesn't allow for a deep understanding of ionizing.

Research has found that distinguishing between radiation and radioactivity is an issue in understanding contamination vs. irradiation.[8, 12] Initially, students tend to describe radiation as "bad stuff", much like a toxin or poison that is harmful to living things.[12, 13] For instance, Millar found students in his study often confused radiation and radioactivity, saying the object contains radiation rather than the canonical view, in which it contains radioactive atoms.[12]

In a companion project we have found that students who have not differentiated radiation from radioactivity tend to use the words radiation and radioactive interchangeably.[13] Students with the undifferentiated view say radiation is radioactive, describe radiation as a contaminant, and think exposure to radioactive sources makes things radioactive.[12, 13] Millar believes understanding the distinctions between radioactivity and radiation is important for understanding the risks and safety measures making it a fundamental part of radiation education.[12] Being able to distinguish radiation and radioactivity is a vital part in understanding the process of ionization by radiation.

2. Setting

The Survey of Physics is an inquiry-based physics class for non-science majors at a mid-west university. Students in this class perform experiments, consider questions, make predictions, and interpret their results like scientists.

The Radiation by Inquiry (RBI) Unit is based on a guided inquiry model. Inquiry has been shown to be much more effective for conceptual understanding than traditional methods. [14] The RBI materials use an inquiry learning cycle - each cycle has a carefully planned sequence of activities designed to initially elicit student thinking, guide and assist students in developing new ideas, and provide closure at the end of each cycle. The RBI materials are divided into four cycles based on the content: Cycle 1: Basic Characteristics of Radiation, Cycle 2: Atoms and Radioactivity, Cycle 3: Interaction of Radiation with Matter, Cycle 4: Nuclear Power and Nuclear Waste. Each cycle has its own pretest to gauge initial student thinking and to set the stage for the oncoming cycle. Post tests were used to assess learning. Our focus is on the outcomes of Cycle 3 in which students were expected to develop understandings of the ionization process.

3. Data and Analysis

We examined the understanding of ionization by radiation of 34 students as expressed in their class work from the 2011 Fall Semester. Student interviews were held up to three weeks after the Radiation by Inquiry Unit was over. Mixed methods were used to infer student ideas throughout the unit.

An exam given at the end of Cycle 3 was used as a post-test for the unit. Student responses on the exam were scrutinized for descriptions of ionization. This analysis was done completely independently of the grading process and resulted in an "e-removal exam score". The criterion for a high “e removal exam score” was a clear description of the process of ionizing by radiation, including the removal of electrons by a radiation particle. Students could mention this process once in any of more than three exam questions to qualify as having described electron removal by ionizing radiation. Students were also interviewed at the end of the course on a set of questions that included questions about the interaction of radiation with matter. Student responses to specific interview questions were scored to create another indicator of understanding ionizing. These two ionizing scores were combined to create an overall "electron removal score."

The "electron removal score" was compared with an atom post assessment from Cycle 2 using a linear regression analysis. Another regression analysis was used to see if there was a connection between differentiation and "electron removal score". Excel was used to do the statistical calculations.

3.1 learning targets:

The learning targets for Cycle 3 (in which ionizing by radiation was introduced) are for students to understand the origin of radiation damage as the ejection of electrons from atoms and molecules. Damaged molecules could then lead to cell damage and either cancer (if particular mutations in DNA occur) or acute radiation sickness if the level of damage is high. These latter targets require students to understand how damage at the molecular scale leads to damage at the cellular and organism scales.

4. Results

In the Fall of 2011, 69% of the students in the study correctly answered the "ionizing question" by referring to radiation causing ionization of atoms or molecules. See Figure 2. This result compares favorably with past semesters and suggests that the RBI materials are becoming more reliable at helping students associate the name of the radiation with its effects.

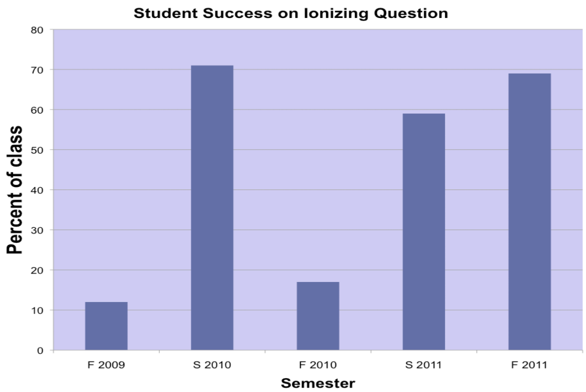

Figure 2. Results on ionizing

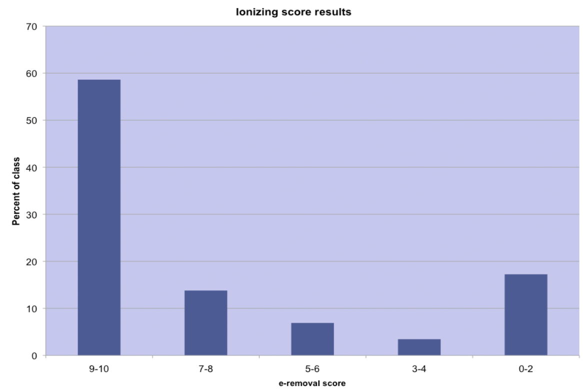

Figure 3. Student e-removal scores

With regard to understanding ionization, Figure 3 shows that 59% of the students rated 9 or 10 (out of a maximum of 10) on the more stringent electron removal score. Again, the RBI materials seem largely successful at promoting understanding of ionization. However, a number of students with scores below 5 out of 10 showed they had poor to little understanding of ionizing by radiation. This group of students is our main concern.

4.1 differentiation vs. ionizing

Separate research conducted at the same time in this class studied student differentiation of radiation from radioactivity.[13] The researchers identified each student's level of differentiation on a scale from zero indicating fully undifferentiated to three which indicated complete differentiation. This was compared with the overall e-removal score from exams and interviews. Figure 4 shows the two measures graphed together. The size of each marker indicates the number of points (students) in that spot. We divided our p value of 0.05 equally between two tests - this test and the atoms vs. ionizing test below. The e-removal and differentiation measures are significantly correlated at the p = 0.025 level, with $R^2 = 0.53$. Thus the data show that differentiating radiation from radioactivity is crucial to understanding ionization.

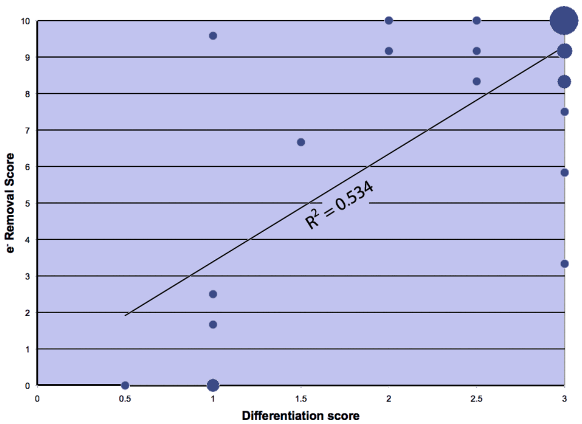

Figure 4. Linear regression chart of the e- removal score vs. differentiation score

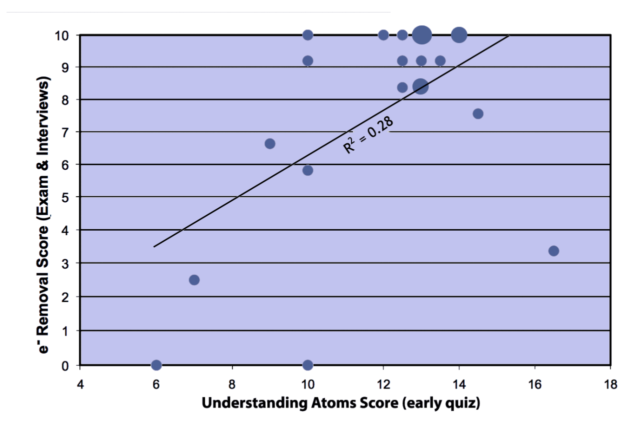

Figure 5. Linear regression chart of the the e- removal score vs. atom score

4.2 understanding atoms vs. ionizing

The post atom quiz at the end of Cycle 2 was scored based on a rubric designed to gauge student understanding. Criteria included whether or not each student had a canonical drawing of an atom, if the student used charges meaningfully in their answers, if student correctly related different size scales, and the degree of relevant details given. The higher the number of appropriate details given in answers, the higher the score. A linear regression was used to compare students' atom score to their ionizing score. A high score on the atom quiz was correlated to a high e- removal score with a P value < 0.02 and R^2 value of 0.28, indicating that a coherent model of atoms is necessary to understanding ionizing. See figure 5.

4.3 identified student difficulties:

We noted that students who had the lowest electron removal scores had particular difficulties. These included assigning ionization to the source atom, the bullet model (see figure 6), vague descriptions indicating lack of a coherent mental model, and confusing the radiation emission with ionizing.

Assigning ionizing to the source atom is not necessarily wrong, the source atom is ionized upon the release of the radiation particle, however; it does not take into consideration the victim atoms in the path of the radiation particle, the soul of radiation literacy as described in the introduction. Thus, students who did not consider victim atoms were not thinking about the whole process of ionization and thus were much less likely to coherently explain effects of radiation on other objects. Students in this category tended to be undifferentiated and continued thinking that radiation causes other objects to become radioactive.

The bullet model theory views a particle emitted from a nucleus ripping through matter breaking apart molecules much like a bullet as the name suggests. Even though the bullet model accounts for damage by radiation to molecules and cells it does not elicit the properties of the particle such as charge and particle type. The bullet model is problematic in the case of gamma radiation - a single gamma can penetrate deeply into matter without causing any damage whatsoever. Only when the gamma finally interacts with an electron does it do damage. A student cartoon of the bullet model can be seen in figure 6. We discuss another problematic aspect of the bullet model below.

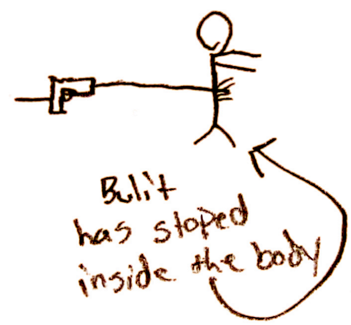

Figure 6. Student illustration of the bullet model of radiation damage

Students who confused radiation emission with ionizing also tended to answer on their exams and in their interviews that ions were radioactive. These students were not distinguishing the radioactivity property of certain atoms (caused by problems in the nucleus) with the condition of being ionized (an imbalance of protons vs. electrons), which often results from radiation's electron removal from victim atoms.

5. Discussion

Our results indicate that the problems associated with understanding ionizing stem from undeveloped models of atoms, difficulty thinking about different scales, and/or persistent preexisting alternate views of radiation and radioactivity. These vague models and alternate views conflict with, or become hybridized with ideas emerging in the class, causing difficulties in student understanding.

Differentiating radiation from radioactivity is crucial to understanding ionization because the differentiated view is based on a vague idea of radiation as material "stuff" rather than on a mental model of subatomic particles traveling at high speed through space. A student who has not differentiated radiation from radioactivity is likely to be confused by images of alpha and beta particles knocking electrons out of victim atoms as students in this class did observe in the Atom Invaders simulator. Those students who did not differentiate and also did not understand ionization apparently did not accommodate the observed behavior into their thinking and continued using a "radiation as material" view. As a result, students who still thought of radiation as "bad stuff" could not answer the ionizing question correctly because they did not think in terms of a specific mechanism of radiation knocking electrons away from atoms. (Note: The Atom Invaders simulator is freely available at http://www.camse.org/sims/invaders)

Differentiation also involves recognizing that radiation does not make other objects radioactive. The RBI materials provide students with multiple reasons to abandon the idea of contamination by radiation, including direct testing of victim atoms that do not become radioactive after being in contact with radioactive disks, and observations of radiation only affecting electrons of atoms, not nuclei which are the sources of radiation. Despite all of these experiences, some students persisted in using the idea of contamination by radiation. It apparently is a very tenacious idea.

Students who persisted in using the contamination by radiation idea did not internalize the radiation damage mechanism that was developed in the class. Instead, these students apparently continued looking for ways that radiation could make other objects radioactive and as a result many did not make sense of the ionizing process. Again, for these students, the representations of ionizing by radiation seen in simulators probably were not relevant or meaningful because they did not match the mental model that these students believed to be true.

5.1 incomplete models of atoms and its association with ionizing:

Those who did not develop viable mental models of atoms also had trouble with ionizing. For instance the post atom quiz asked "What is a molecule in terms of atoms?" and “What holds molecules together?” Students with low scores on this assessment answered, “a molecule is particles that make up an atom” or one student said, “A molecule is the part of an atom with just neutrons and protons, No electrons”. These students did not have well-organized mental models of atoms and we can expect that they would have had difficulty with the ionizing process.

Students with low post atom quiz scores also had a tendency to mix up ionizing and radiation and sometimes said that a positively or negatively charged atom would be unstable and explode, emitting radiation. These students were mixing up characteristics associated with ions with the characteristics of nuclei. Here is an example of a student answer: “If an atom exceeds a certain number of protons or electrons, the atom becomes radioactive and explodes.”

When the answers from 10 of the highest atom quiz scores were compared to answers from the lowest atom quiz scores it was clear that far more of the students with the highest atoms quiz scores used charges to explain what holds the parts of atoms and molecules together while those with the lower atom quiz scores did not invoke charges but instead repeated various words that perhaps sounded appropriate. Without reasoning about charges students had difficulty explaining why electrons are held in atoms, how atoms are held together in molecules, how electrons can be removed from atoms and molecules, and how ionizing radiation accomplishes this.

It is clear that students need to develop a deeper model of atoms beyond naming the parts of the atom. They need to reason about atoms as mechanisms driven by charges in order to be able to effectively understand ionizing.

5.2 zoom scale issues

Our students had difficulty with relating radiation (particles much smaller than atoms) to atoms and molecules, and they had trouble relating atoms and molecules to cells, which are much larger. Understanding relationships and effects across different size scales is called "zoom scale thinking" and it is particularly difficult to develop because it requires connecting multiple mental models across multiple scales.

We illustrate the zoom scale problem with an example taken from the Atom cycle immediately after students had seen simulated atoms emitting various particles at high speed, which would later be identified as alpha, beta, and gamma radiation. During a class discussion the instructor asked if the high-speed particles coming out of atoms in the simulator might be the radiation the class had been studying. One astute student pointed out that once an atom explodes and emits quanta then it is done because it transforms to a different atom. The student was wondering how an atom can be radioactive because it emits radiation only once while the radioactive sources she had seen in the classroom kept on emitting radiation for a long time. The student had trouble relating particles in the atom scale to Geiger counter observations in the room scale. Although this student did a good job of thinking about the atoms and disks she apparently was not considering that the radioactive sources could contain many trillions of radioactive atoms. Follow up instruction on the vast numbers of atoms present in tiny objects apparently helped many members of the class to connect the atom scale to the macro scale.

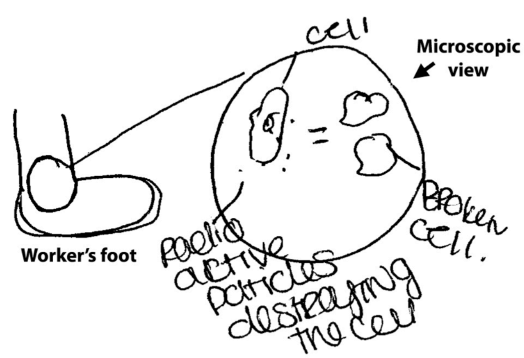

Figure 7. Student drawing of "radioactive particles destroying the cell"

The interaction of radiation with matter involves additional scale problems. Because radiation is composed of particles smaller than atoms, the size difference between alpha radiation and a human cell is approximately a factor of

10 billion. If not for the effects of its charge, an alpha particle could easily slip through the empty spaces inside of atoms, and an atom could easily pass through a cell. Thus radiation does not directly break cells but only damages their chemical contents. On the post assessment, students were asked to describe the chain of events by which a Japanese nuclear reactor worker might get radiation damage from stepping in a puddle of radioactive water. Figure 7 shows a vague model with alternate ideas based on the macroscopic view. The student did not consider the immensely different size scales of radiation particles versus cells, so when trying to explain cell damage the student drew a radiation particle breaking a cell directly.

In contrast, Figure 8 shows a different student's more complete model with details from the atomic scale to the cell scale on how the damage occurred. The student showed an alpha particle breaking apart a molecule in the skin, and included details of how electrons are removed by their electrical attraction to the alpha particle. This student showed a more complete model of ionization by radiation and made an attempt to relate the molecular scale to the cell scale and to damage at the macroscopic scale.

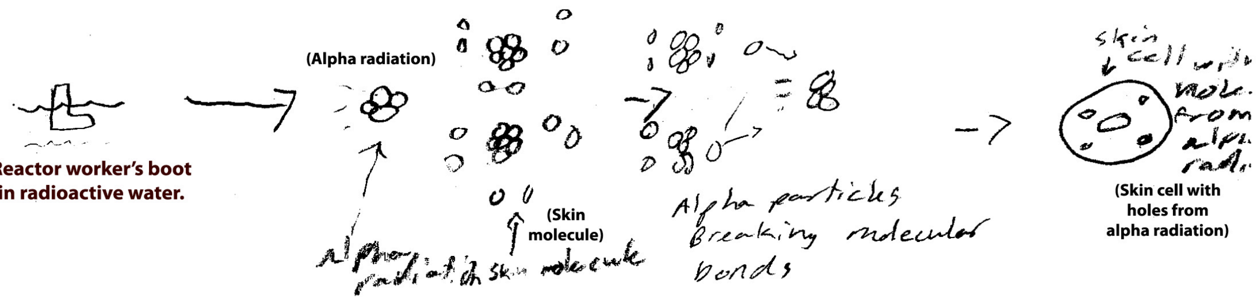

Figure 8. A student's more complete model of the cell damage process via ionization caused by an alpha particle.

In conclusion, we have shown that the majority of students in our trial testing class can learn about ionizing by radiation, but not all of our students accomplished this. There are deep seated difficulties in understanding ionization. We found for students to understand ionization they must think of atoms as "charge machines" in which the electrical charges of protons and electrons play important roles. Students must have viable mental models of atoms. In addition, students must at least partially differentiate radiation from radioactivity so that their thinking is not influenced by incorrect and problematic thinking about the character of radiation. Students must also distinguish between source atom and victim atom so that they can construct a more coherent view of the ionization process, and they must develop and use the idea of radiation particles “knocking” electrons away. Finally, students must be able think about the effects of radiation across many orders of magnitude of size. They must develop zoom scale thinking in this topic.

One possibility for the cause of the student difficulties with differentiation, zoom scale, and ionizing is students with both low post atom quiz and electron removal scores may have tried to use rote memorization to remember information rather than constructing it over and over again in a meaningful matter. So when they took the exam which presented new situations, these students constructed an answer on the spot without the benefit of thinking about the subject repeatedly and constantly constructing relationships between ideas and deciphering what they experienced in class. For example, often students with low atom and electron removal scores answers included information that didn’t have anything to do with answering the question and were vague. In discussions they often wanted what they thought were the answers repeated in order to take notes on, and many of them when discussing a particular problem they were trying to solve where often frustrated they weren’t just told the answers. Bretz and Grove found that students in an organic chemistry course learned differently based on their approach to the learning task along these lines.[15] These researchers found that rote memorization was problematic for understanding particular aspects of organic chemistry. Similar phenomena may well be happening in this course. Further exploration of this theory is the subject of future research.

6. Acknowledgments

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