HIGH SCHOOL STUDENTS' UNDERSTANDING OF THE QUANTUM BASIS OF CHEMISTRY

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INTRODUCTION

The focus of this paper is an analysis of relationships between quantum concepts in chemistry held by honors high school students. The study investigates how an instructional program, which includes inquiry based learning, collaborative learning logs, concept maps, and use of interactive simulation of quantum phenomena of chemistry, alters student understanding. In what follows, the researchers compare the effects of traditional methods of instruction, i.e. lecture/lab, against the use of student discovery using a variety of methods including computer simulation, on the alternative conceptions of students in quantum chemistry.

The honors chemistry students participating in the study were from three classrooms from a high school located in a suburb of Boston. The observations were prior to, during, and after the students conducted their study of quantum ideas in chemistry. Two classes, of seventeen students each, were engaged in an in-depth program that included formative assessment and used the Quantum Science Across Disciplines (QSAD) materials, which were developed at Boston University through a National Science Foundation Grant. Seventeen students from a third honors chemistry class at the same school were taught by a different instructor using the traditional lecture demonstration method and were monitored by the researcher for comparison.

Student concept maps and interviews were used to find the baseline misconceptions of the student cohort regarding understanding of quantum science in chemistry. The experimental classes continued to modify their concept maps and collaborated with their instructor using learning logs during the six week unit of study. All of the high school students constructed concept maps and were interviewed after the intervention. The student information including concept maps were analyzed, and compared to the information obtained from students that exit a class using a more traditional approach.

There was one instructor for the two experimental classes. While the teacher of the control class used methods of summative assessment similar to the experimental classes, the teacher of the experimental classes used computer simulations, concept maps (Novak, 1997), and learning logs (Audet, 1996) during the units for the purpose of formative assessment. The students in the experimental groups continued to modify their concept maps as their understanding of quantum chemistry developed. For the learning logs, groups of three students were required by their teacher to achieve consensus and write a response to selected issues within quantum chemistry. Students in the experimental classes were also required to investigate quantum phenomena using the simulations and then make presentations. Classmates were encouraged to ask probing questions. Responses included explanations using quantum chemistry to explain measurable phenomena, such as the energies of molecular orbitals, bond lengths, and relationships between them.

Researchers paid special attention to student explanations of the relationships among eight concepts: bonding, color, electronic structure, energy, molecular geometry, periodic trends, polarity and solubility. Average concept map scores approximately doubled, from pre to post intervention, for all three classes. The classes had similar standard deviations. The research team found that the control and experimental groups showed marked increase in forming propositions in the following five areas: bonding to electronic structure, electronic structure to periodic trends, molecular geometry to polarity, polarity to solubility, and color to energy. Chemistry teachers would recognize these topics as traditional subject areas of importance. The experimental classes improved their ability to explain the relationship between five additional pairs of chemical concepts including: bonding to energy, bonding to polarity, bonding to molecular geometry, and polarity to molecular geometry and solubility.

LITERATURE REVIEW

An investigation of the literature on alternative conceptions showed only limited prior research on quantum chemistry. There is a study on student misconceptions on light and energy at the undergraduate level (Zollman, 1998) that points to confusion around the concepts of color, energy, intensity, and amplitude. Moreover, even though high school teachers often use the Bohr model as a simple way to explain atomic structure. they do not explain to their students the shortcomings of the Bohr model with regard to the heavier atoms. Current high school texts include more abstract concepts, which are only useful if students adopt and apply them.

The current secondary chemistry curriculum includes a unit that explains atomic and molecular structure using the qualitative aspects of quantum mechanics. National standards suggest designing science programs that allow students to understand the connections between scientific disciplines. The principles of quantum mechanics (QM) are used to explain certain energy relationships in biology, chemistry, and physics. The qualitative aspects of QM can be represented graphically on a computer. To accommodate the interdisciplinary albeit qualitative view of QM the term Quantum Science has been coined.

Boston University's Science and Math Education Center is developing interactive simulations for students studying the concepts of Quantum Science. The software is intended to help high school students better understand the connections between quantum science and the science curriculum. Quantum science refers to a probability based model that incorporates the idea that energy can only be released from atoms in discrete packets. These packets are known as quanta, and the mathematical model that describes them can be used to make predictions in many areas of scientific study. The developers of the software intend to create materials that will help students use microscopic phenomena to explain macroscopic behavior. The interdisciplinary nature of this topic fits with goals of science education reform. In the conclusion of the article Research on Goals for the Science Curriculum Bybee and DeBoer state, "There is recent and substantial support for the expansion of themes that include understanding of the nature and history of science and technology providing opportunities that blur disciplinary boundaries" (p. 384).

The Massachusetts Department of Education has produced a framework for educational change for the teaching of science and technology (Hamos, and McGarry, 1996) It clearly recommends that high school science become an integrated program that would incorporate all three disciplines at the high school level. Throughout each year, students would be exposed to biology, chemistry, and physics. The ideal would be to make students understand the relationships among the concepts not only within each discipline, but also across the three sciences. The frameworks are broad enough to allow teachers some latitude in the methodology that they adopt. Quantum science cuts across disciplines and would be a natural place for teachers to help students make interdisciplinary connections.

Another feature of the new state requirements is an emphasis on "student discovery." However, discovery techniques in chemistry are fraught with problems. Students left to their own devices in the laboratory could be at risk. The teacher's role has always been to monitor safety, but stringent monitoring tends to minimize the student's investigative abilities. The state framework suggests that students follow the scientific method to develop their understanding. For grades nine and ten, teachers are directed to cover the aspects of scientific method and experimentation in strand one: Inquiry (p. 29).

To date, instructors have adopted a combination of static pictures in textbooks and hand waving as a method for teaching the models that scientists use. However, in Quantum Chemistry, the need to visualize the invisible creates an abstraction that presents a problem in the teaching of high school chemistry. The state framework also recommends that students "create and use models to study the structure of atoms" (p. 54). The models used to visualize the microscopic world have proven difficult for students to understand. Scientists use dynamic molecular behavior to explain chemical kinetics, gas laws, and reaction equilibrium. Students have problems relating their macroscopic observations to the theoretical molecular behavior that scientists use to predict properties. For example, when asked to explain gas pressure, the majority of students referred to the force per unit area on the surface of the container. When asked to explain why scientists believe that force occurs, the students do not mention abstractions like molecular collisions.

The instructor of the experimental classes believed that students require sufficient time to make connections among abstract concepts, and that for true understanding to occur, there needed to be connections made by the students to their core of understanding. “To be effective, science curriculum must facilitate knowledge acquisition and comprehension by students” (Schreiber, 1990). Using microscopic models to predict macroscopic behavior allows students to exhibit a deeper understanding of the concepts. Students can connect this new knowledge to the core of their understanding.

Educational researchers have noted several impediments to student learning. It is often the case that teachers are not aware of the preconceptions that are present in the minds of their students. This lack of awareness poses difficulty for the teacher when deciding the particular features that will be included in the curriculum. In the area of quantum chemistry, teachers sometimes assume that there are no misconceptions. It can be very hard for the teacher to change misconceptions that are deep within the students’ conceptual framework. Instructors who rely on textbooks for the principal source of course information for students are often unaware of the misleading and inaccurate statements that are embedded in the texts. “After analyzing eight secondary chemistry textbooks for dissatisfaction, intelligibility, plausibility, and fruitfulness, the books were found to be lacking sufficient amounts of all four. The recommendation was for modifications to future texts and for teachers to expand their instruction beyond the texts” when covering atomic theory (Shiland 1997, pp. 535-545).

There are a variety of concepts covered within a first year high school chemistry course that can be explained by quantum mechanics. In chemistry, the topics of bonding, polarity, solubility, and molecular geometry are a few examples of concepts that are either directly or indirectly related to energy being quantized. Students enter high school chemistry courses with minimal exposure to a variety of chemistry topics. Depending on the circumstances, their understanding of these topics may be either incomplete or in error. Teachers who are unaware of the inadequacy of student preconceptions will not be prepared to adjust the curriculum. As stated in the Common Chapters, The Massachusetts Educational Reform Act of 1993 was adopted to “make systemic change at the school, system, and state level” (p. 1).

METHOD

The community in which we conducted the research has a per capita income of $28,800. Approximately 92% have at least a high school diploma, and 51% have at least a bachelor's degree.

Participating Students

For this report students were chosen from the Honors Chemistry classes of one of the high schools in suburban Boston. Two classes of seventeen students each, and taught by teacher "A", underwent an intervention that focused primarily on student inquiry, while one class of seventeen students taught by teacher "B," was used as a control group and taught using traditional methods of lecture and textbook study. The students were randomly selected to include an even distribution of males and females as well as varying ability levels. The two cooperating teachers used the same textbook (Zumdahl, 1993) and stated that previously they covered the same material in their classes.

Design

The teacher of the control group was instructed to proceed through the material in a normal manner. The experimental classes worked in groups of three on the computers studying electronic structure as explained by quantum chemistry including polarity as explained by charge density and bonding as explained by molecular orbitals. Students could vary the bond length of diatomic molecules and observe the overlap of the amplitudes and the resultant charge densities.

Both teachers were instructed to assess their students in their normal manner. For the traditional class, this meant tests at the end of each chapter. They proceeded through chapters on periodic trends, bonding, and molecular orbitals. It was interesting to note that the instructor of the control group was asked by the researcher about the laboratory exercises that were planned for these units. The teacher stated, "There are hardly any lab activities for these units. After we do flame tests and mess around with spectroscopes, the rest of the activities are designed for the students to get extra practice studying the properties of gases." For the teacher in the experimental classes the gas labs were replaced by quantum chemistry activities.

Concept mapping

Prior to the study of periodic trends, the three classes were instructed on the principles of concept mapping by the researcher. The students constructed a concept map from a list of eight concepts, which are listed alphabetically on a hand-out. The eight concepts are: bonding, color, electronic structure, energy, molecular geometry, periodic trends, polarity, and solubility. These particular concepts were chosen as a result of researcher grouping a list of similar codes obtained from interviews during the pilot study. The students were instructed to organize the concepts hierarchically from the most general to the most specific.

Concepts are objects or events. A pair of concepts linked by a phrase that states the relationship between the two forms a proposition that can be scored (Novak and Gowin 1997, pp. 17-19). Students were instructed to identify all of the relationships that they could, including any cross-links or additional concepts that seemed relevant. The researcher used concept maps as a natural way of collecting qualitative data on student preconceptions in quantum chemistry topics. The codes generated by early interviews became the starting point for concept maps. The current interview protocol is now based on these eight concepts: bonding, color, electronic structure, energy, molecular geometry, periodic trends, polarity, and solubility. This method allowed the researcher to come to the interviews with a protocol designed to uncover the misconceptions that students had in quantum chemistry.

One student set of pre and post concept maps from the control group and one from the experimental are included in Appendix "A." Each set consists of an initial c-map and a final c-map, which the student constructed after the study of quantum chemistry. The c-maps were compared to the expert map below, see figure one, to help researchers differentiate between a successful map and one that contains misconceptions.

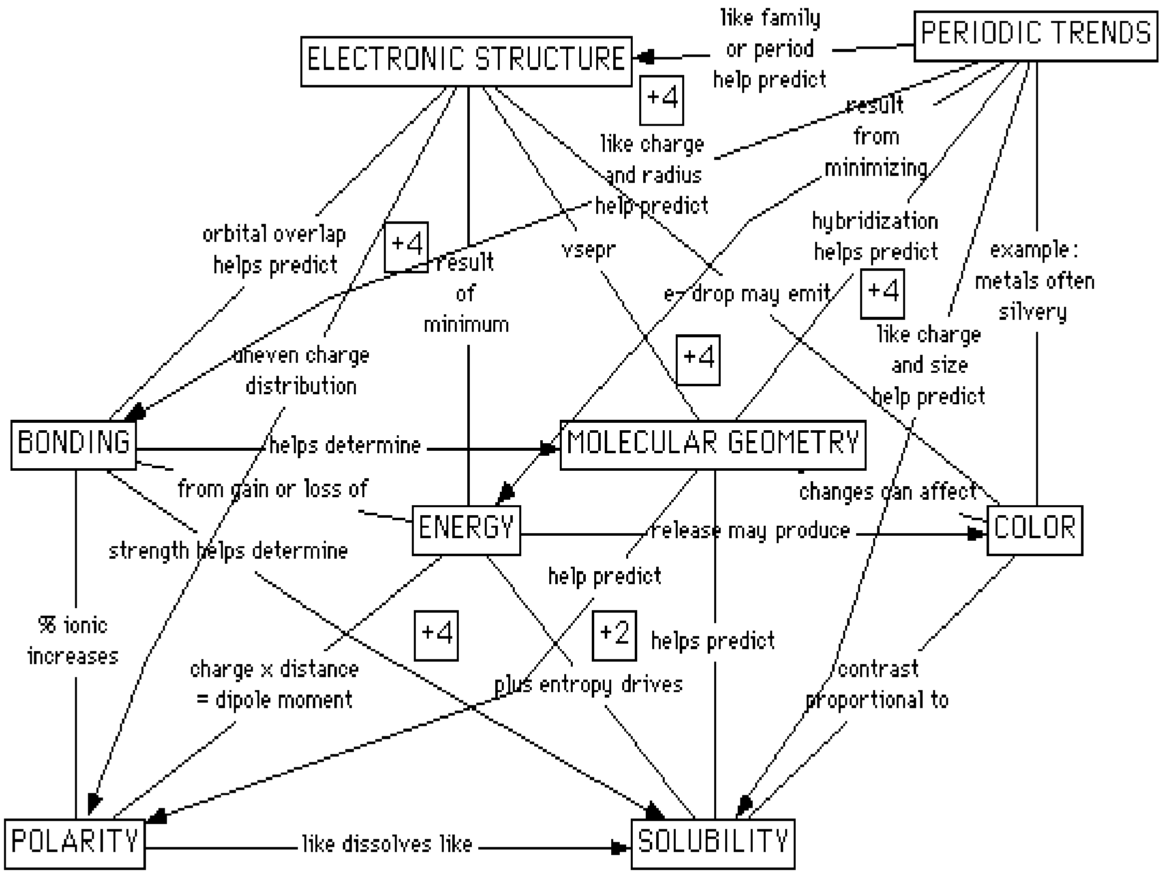


Fig. 1 Expert concept map

An expert concept map was produced by looking for other possible categories and then gradually reducing them into eight major concepts under the heading of atomic structure. Several rearranged listings of the concepts were used in order to decide what topics are the most closely related. One parent map with expert links and cross-links between the eight concepts was completed for comparison. It was important to observe whether students can link their basic molecular understanding to macroscopic events.

The researcher instructed each of the honors chemistry classes in the art of concept mapping prior to their study of the topic of quantum chemistry. Students were presented the categories to see what connections they could make. Four students, two male and two females, were chosen at random for in-depth interviews by the researcher. The interview allows the students an opportunity to present more elaborate explanations regarding their understanding of the material.

The method for scoring the student concept maps was developed by graduate students. The concepts that were successfully linked to form propositions scored one point, the links scored two points each. The scoring procedure for cross-links and deductions for incorrect information on student maps is elaborated in appendix "B."

Computer activities

The first exercise on the computer was for each group to learn how to manipulate the images of the orbitals and charge densities using the atomic explorer. The second activity was to investigate the relationships between energy, orbital overlap, and charge density as they relate to bond length. The groups were also responsible for analyzing the difference between ionic and covalent bonds. The third activity was to investigate the connection of ionization energy to polarity for bonding and anti-bonding orbitals. The fourth computer exercise was for each group to make a class presentation on a topic of their choice.

Each group obtained clearance for their presentation topic by writing an abstract in their learning log. The instructor approved the topics after steering each of the groups to avoid duplication. Groups used class time plus additional time after school to prepare for their talks.

Learning log exercises

Half of the groups were assigned to work on the computers, while the other groups responded to questions in their learning logs. The teacher presented the groups with questions that related to the computer investigation. These groups worked on answers in their learning logs or worked on advancing their concept maps when they were not using the simulations.

The clusters of three students each responded to questions provided by the instructor. They were first asked to comment on the shapes, orientation and relative energy of the various orbitals. When the answers of the groups were assessed to have been sufficiently complete by their instructor they were asked about the arrangement of the nodal surfaces, and whether they could identify any relationships for the number of nodal surfaces and loops within the major energy level.

The groups were then asked to comment on reasons for the different ways the charge density could vary. During the follow-up questions, the groups were asked to explain how wavelength and amplitude were shown in the simulation. The third question asked the groups to explain the relevance of phase to bonding. The final question for each of the groups was to explain the connection of energy to bond length.

Data analysis

After conferring with the target high school faculty, the most difficult topic areas seem to be centered around the categories of molecular bonding, energy, phase, amplitude, the lack of a localized phenomenon and, in general, connecting the concepts to other phenomenology. These topics are in textbooks, but depending on the teacher or the particular group of students, these topics might be skimmed or completely avoided. It is not surprising that students have alternative conceptions.

Coding

The researcher started with an outline that grouped the interview information into possible codes and larger categories. The outline was based on interviews conducted with three chemistry teachers from area high schools. Using the outline as a protocol for five student interviews, a complete list of fifty seven codes were generated. The concept mapping program C-map (Novak, 1989) was used to list the codes obtained from the interviews and then rearranged until they fit comfortably under eight categories: bonding, color, electronic structure, energy, molecular geometry, periodic trends, polarity, and solubility. After the main concepts were chosen, all related concepts were listed. Subsequent interviews and concept maps were focused on the eight main concepts with follow-up questions probing for student understanding of the relationships of the entire set of fifty-seven quantum chemical concepts.

A system of triangulation was used to check the codes that developed. Student concept maps were compared to an expert map derived from the eight categories found earlier in the preliminary interview process. Chemistry class test results from the target school showed that the same areas of misconception prevailed. Student subjects and staff were shown the results as it accumulated. They agreed the conclusions were reasonable.

Concept mapping

The c-maps were transferred from student hand maps to computer versions and scored by graduate students. The class averages for the classes prior to the intervention were 14.2 and 13.5 with standard deviations of 5.9 and 3.5 respectively. The control group had a mean score of 9.1 with a standard deviation of 4.0. The post intervention scores for the first two classes were 25.6 and 26.9 with standard deviations of 5.9 and 5.5. The third class improved to a mean of 22.2 and a standard deviation of 6.3. These scores are unremarkable in their similarity, however when the linkages were analyzed, it was noted that more than twice as many connecting phrases were made by the experimental classes after the intervention when compared to the control group.

The number of correct links that were made improved for all three classes as can be seen in the following table. Of the twenty-eight possible links between concepts, the control group only managed significant improvement in four areas (see tables in appendix "C"). This development was marked either by a doubling of correct linkages or by minimum of five correct links where there had been none before. The correct links by this class occurred between the following concepts: bonding vs. electronic structure, color vs. energy, electronic structure vs. periodic trends, and polarity vs. solubility. The graphs included at the end of appendix “C” highlight two relationships. In the first column the student relationships between color and energy are indicated. The graphs indicate that all three classes improved their understanding of this relationship. The Second column shows the relationship between bonding and polarity. Only the two experimental groups improved their understanding of this relationship.

	Links before	Links after	change
a-block	29	114	85
b-block	25	101	75
c-block	12	67	55

Table #1

The experimental groups show greater improvement in c-map relationships than the control group following the intervention (see table #1 above). The experimental classes improved their ability to explain the relationship between five additional pairs of chemical concepts including: bonding to energy, bonding to polarity, bonding to molecular geometry, and polarity to molecular geometry and solubility. During the study, one student, using the interactive computer simulation, increased her score from 3 to 32 for the largest positive change. Without much explanation of the terminology, one look at the initial c-map (appendix "A") for a student from the control class, shows that this student progressed, his final c-map (bottom page 15) shows improvement. On page 16 a student from the experimental group shows significant increase from pre to post intervention. These two sets of maps are representative in that they are close to the mean score from their respective classes.

Most of the students omitted concepts and links that were questionable in their minds. A detailed interview was necessary to ferret out information that enabled the researcher to complete the qualitative analysis of the c-maps. Students were reluctant to make too many guesses. Therefore, only some of the student's alternative conceptions showed up on any of the c-maps (the most any student had was five).

Interviews

Table 1

CODE	WHO	COMMENT
molecular geometry	obs	But is electronic structure related to molecular geometry?
	1	No, it's not.
polarity	obs	Is it related to polarity?
	1	No.
energy	obs	How do you define energy?
	1	You cannot really define energy, there are just different types.
quantum chemistry	obs	What do you know about energy and quantum chemistry?
	1	I know people are trying to quantize electrons and energy levels, but it's really not possible, it's a kind of probability field.
energy transition	obs	What do you know about the energy of an electron within hydrogen?
	1	It can be excited or not excited, Hydrogen is an atom or diatom. I think it can be either. You have the electric potential, and then there's I don't completely understand the other kind of potential that you know energy jumps and releasing photons and receiving those like I said red, but I think that's more of a quantum phenomena, and we don't really say it jumps on micron, you know, closer to the proton and therefore it gives off a proton, it's kind of like an abstract energy jump.
molecular geometry	obs	These things relate to molecular geometry.
	2	Oh, I'm not sure what the molecular geometry is.
bonding	obs	Now, how do you define bonding,

	2	Well bonding is kind of like um, like two atoms um there has like different kind of bonding, I mean, it could be like n electronic, you know the positive and negative...
	obs	OK, so...
	2	Oh, oh, oh it's like mentally they get different kind of bonding, it's like they have um, ah, the positive nucleus in the middle and the electron go float around it just like in orbit.
charge	obs	OK, why does losing an electron make it positive?
	2	Um, because the nucleus has the same charge as the electron outside.

FINDINGS

Baseline data

This paper is focused on the connections that students make or fail to make after having spent time with the basic topics of quantum chemistry. The literature, interviews, and concept maps indicate that there are alternative conceptions present when Honors Chemistry students start the topic in high school. Several misconceptions fall into the definitional level. For example: when asked about polarity, approximately 5-10% of the students in my sample discussed how, "This term refers to how light of a certain type lines up in a certain way." Another 25% believed that the third major energy level could only hold eight electrons and explained that their teacher said, "The periodic table of elements proved this when you counted the third period."

Learning Logs

Student groups were required to write their thoughts regarding the relationship between quantum concepts and observable phenomena. One example is the group explanation for the color that is emitted by a gas discharge tube and the relationship to discontinuous spectra. Approximately 10% of the sample reported that the electron making a transition to a higher energy level is the cause of the color. Close to 30% of the sample continued to confuse the intensity of bright line with the energy of the color released.

There was additional confusion between the energy of the orbital and its size. Some students (7% in this study) had difficulty with the idea that orbitals could have different energies when they were around different nuclei. This led to confusion around the idea that only orbitals of certain energies could overlap appropriately for bonding. The class had productive responses around the topic of charge density and enumerated correctly, several possible reasons for why the density could vary after experimenting with the software and class discussion.

DISCUSSION

Causes

The qualitative and quantitative results can only be related to similar populations. There is evidence of a variety of areas in which students' misconceptions are produced on entering, during, and after the study of quantum science. First, students that have only seen two-dimensional representations or mathematical models that repeatedly build to a climax of the atomic model with the Bohr description of the atom. Second, some students have an inability to visualize a scientific model in three-dimensional space. The students who had problems with polarity highlighted the above deficits. Their difficulties arose from the students' inability to rotate the three dimensional model in their mind, a lack of depth perception, or limited sense of perspective.

The student who is not a visual learner or has problems thinking in three-dimensional space is at a disadvantage. Also vague wording of some text material leaves students unable to discern the correct definition for a particular condition. Other misconceptions relate to the cognitive level of the student and what degree of abstraction is understood. Some individuals have difficulty relating to models at an atomic scale.

Students' continue to misinterpret the sign of the energy. An example of the energy problem occurred during one of the presentations. The student group was discussing the energy of the valence s-orbital and had produced a bar graph to show the trends. The group had left out the negative sign on the energy levels and therefore the s-orbitals proceeding down family one had a trend with s-orbitals of less energy at the bottom of the family. When asked about the trend the presenters stated that of course the energies were exothermic, but the audience was confused.

Lingering Behavior

The science education literature has many references to the durability of student misconceptions in science. Novak points out that although it can be difficult to positively affect many alternative conceptions not all are intractable (Gabel, 1994). We have evidence that an interesting concept met with considerable resistance. It was noted by the researcher during the preliminary study that students often misinterpreted the signs on ions and also on energy values, such as transition energies when a photon is released or when bond energies are evaluated. The symptom is manifested when students use a number line interpretation of the sign when evaluating endo- or exothermic situations. In addition, students were found to continually misinterpret the meaning of (+/-) ions by adding electrons for plus and subtracting electrons for minus. Even after the instructor emphasized the correct analysis of each of these concepts 5-10% of the students continued to misinterpret the data.

The relationship between bonding and electronic structure was the only connection that approximately half of students in each class made prior to the study. This can explained when we took into account the fact that the students used the octet rule as an explanation for bonding. The additional relationships that the experimental groups were able to express appear to be connected to the type of activities. Their increased ability to explain the relationships among bonding and other concepts could be a direct result of the work with the bond explorer. In addition the time spent with small group discussion, preparing for presentations, and writing learning log entries seems to have had a direct benefit.

Shifts in Student Behavior

In this study, students were allowed to make predictions about the macroscopic world based on their understanding of the microscopic. When the content is rich enough, students absorb themselves in study leading to the development of judgment in the area of scientific prediction. In chemistry, concepts learned in one unit become the foundation for the next. The mindful instructor needs to be alert to typical student errors before these misconceptions get in the way of further learning. Students investigated bonding and anti-bonding in the Diatomic Explorer prior to reading about them in the textbook. The teacher noted that students successfully used their information on molecular orbitals to predict why the formation of some bonds (e.g. He_2) are not favored.

It has been noted that the two intervention classes managed to make twice as many links when compared to the traditional class. Increased awareness with respect to the relationships among bonding, molecular geometry, polarity, and periodic trends allowed the students in the intervention classes to make scientifically accurate predictions regarding chemical behavior. During interviews students from the experimental classes more often shifted from the electron dot structure/Bohr model of the atom to a molecular orbital/charge density model of the atom.

More of the students from the experimental classes shifted to a more appropriate scientific model when confronted with a problem that is difficult for the old models to explain. Students from the intervention class explained the difference between ionic and covalent bonding as a continuum and based their answers on the shift of charge density that they had observed while using the computer simulations. Students interviewed about resonance or expanded octets drafted their explanations using a quantum chemical basis and appeared to be less thwarted by the inconsistencies and limitations of the initial models that they had been taught.

Future Study

The information gathered on student alternative conceptions in quantum chemistry will help to improve both curriculum content and teacher presentation. The findings of this effort are being used to design and implement activities that foster understanding of the conceptual relationships that were not made by students as of this study. In addition, there remains a question as to whether the directional components of the relationship between concepts as stated by the students has meaning?

REFERENCES

Audet, R. H., Hickman, P. & Dobrynina, G. (1996). Learning logs: A classroom practice for scientific sense making. Journal of Research in Science Teaching, 33 (2), pp. 205-222.

Bybee & DeBoer, Gabel, D. L. Editor (1994). Research on Goals in the Science Curriculum. Handbook of research on teaching and learning. New York: Simon and Schuster and Pr4entice Hall International. p 384.

Gabel, D.L. (1994). Handbook of research on teaching and learning. New York: Simon and Schuster and Pr4entice Hall International.

Hamos, and McGarry (1996). Massachusetts Department of Education Frameworks for Science and Technology. pp. 29-54.

Hickman, P. (1994). Interactive-collaborative-electronic learning logs. Belmont High School, Belmont, MA.

Massachusetts Educational Reform Act of (1993). p. 1.

Noh, T. & Schamann, L. C. (1979). Instructional Influence of a Molecular Level Pictorial Presentation of a Matter on Students' Conceptions and Problem Solving Ability. Journal of Research in Science Teaching. 34(2). pp. 199-217.

Novak, J. D. (1989). C-map program: version 1. Ithaca: Cornell University.

Novak, J. D. & Gowin D. B. (1997). Learning how to learn. Cambridge: Cambridge University Press.

Schreiber, D. A. (1990). Scoring Student-Generated Concept Maps in Introductory College Chemistry. Boston University Press

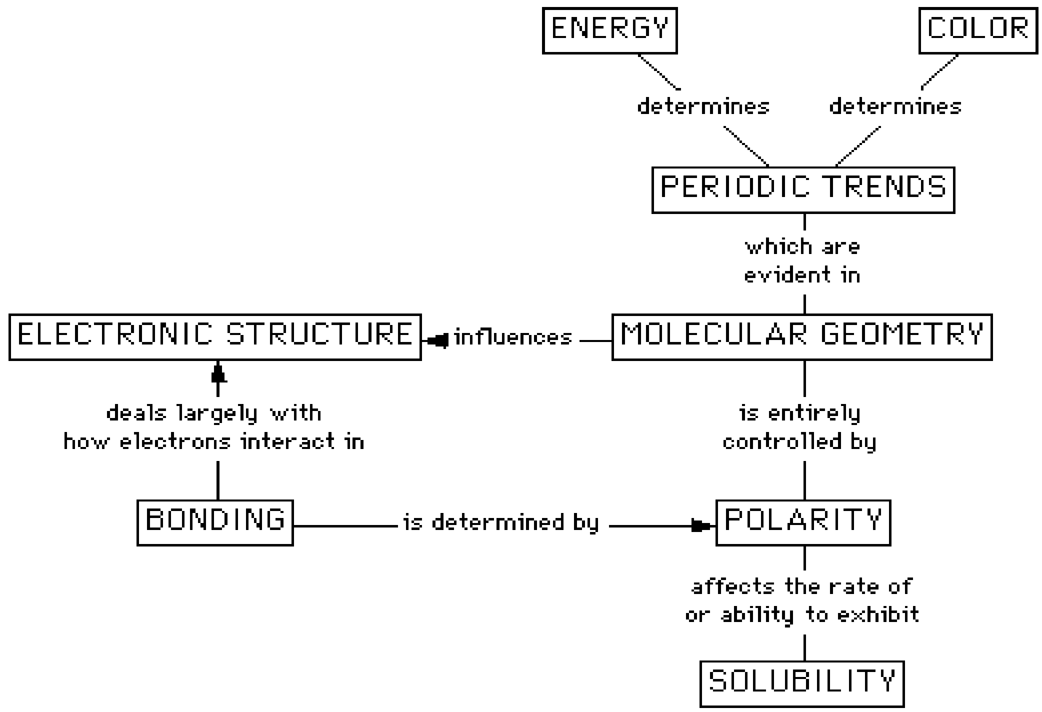
Shiland, T. W. (1997). Quantum Mechanics and Conceptual Change in High School Chemistry Textbooks. Journal of Research in Science Teaching. 34(5). pp. 535-545.

Zollman, D. A. & Rebello, N. S. (1998). Creating a modern physics course: visualization and computation for undergraduate physics majors. www.phys.ksu.edu.perg/vqm/working/mmprogrep.html#ideas

Zumdahl, S. S. (1993). Chemistry, Third Edition. Lexington: D.C. Heath and Company. pp. 279-431.

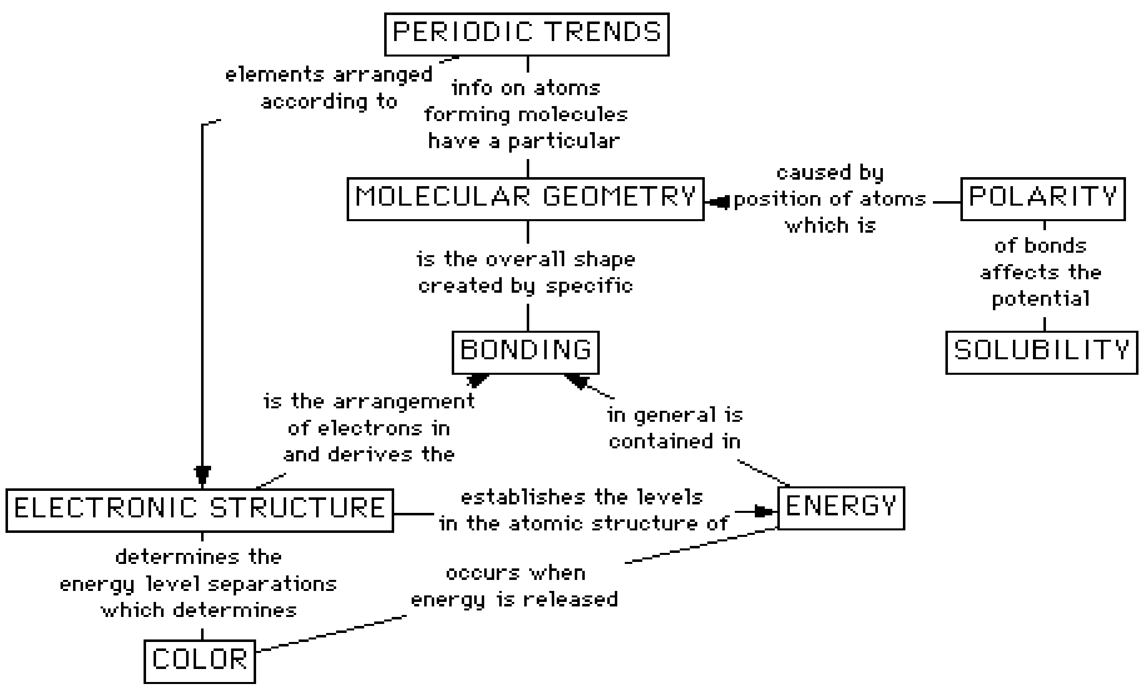
APPENDIX "A"

Traditional Class Concept Map: Student #8e Prior to Study



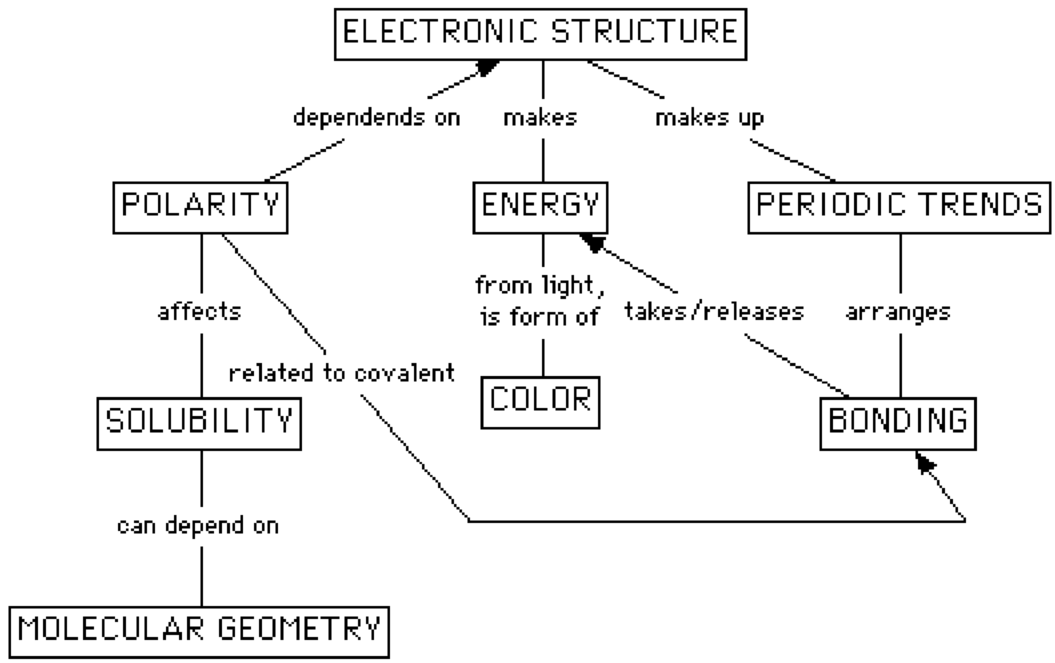
Net score = 7 points (5 for concepts, 5 for links, 0 for cross-links)

Traditional Class Concept Map: Student #8e After the Study



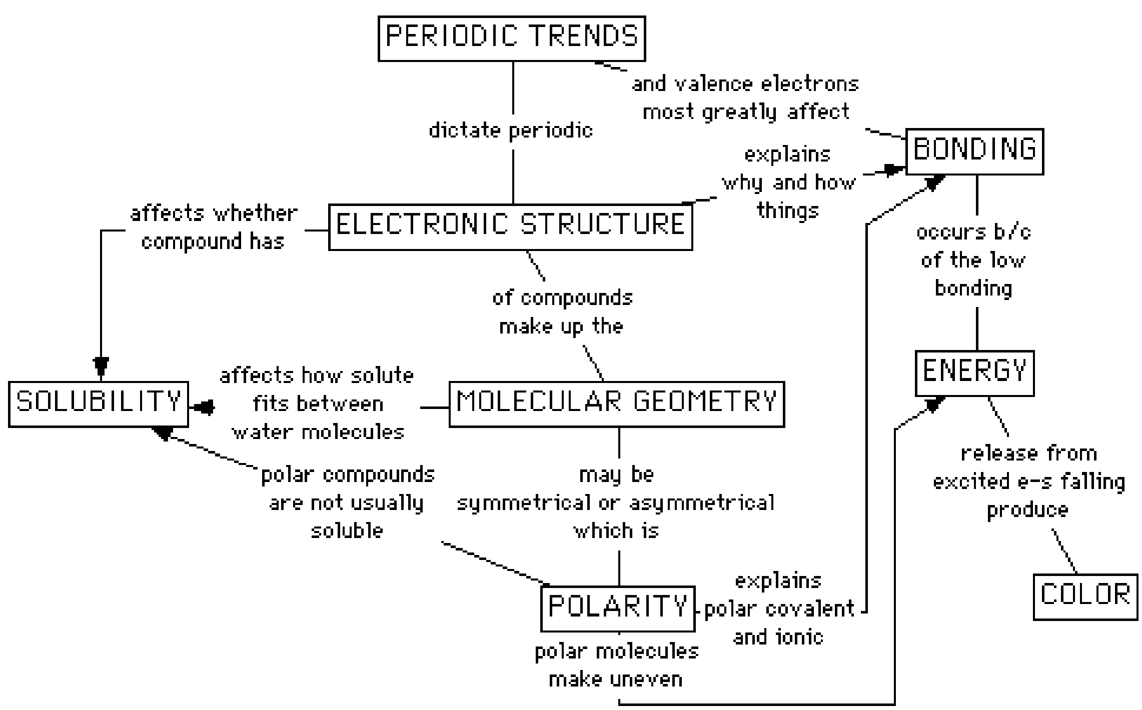
Net score = 20 points (8 for concepts, 10 for links, 2 for cross-links)

Experimental Class Concept Map: student #13b Prior to Study



Net score = 15 points (8 for concepts, 7 for links, 0 for cross-links)

Experimental Class Concept Map: student #13b After the Study



Net score = 27 points (8 for concepts, 15 for links, 4 for cross-links)

APPENDIX "B"

Quantum Science Across Disciplines Scoring Rubric for Concept Maps

The following rubric will be used for scoring the student' concept maps. Each concept map has three items that are scored positively:

1. Concepts that are connected in any way to the rest of the map are scored one point each.
2. Links that connect two concepts are scored two points each. If the link that connects the concepts is a minimal one (describes what the relationship between the concepts is, but not how or why the relationship exists) then it will be valued at one point only.
3. Cross-links that form a polygon in any way are scored "n" minus two points each, where "n" stands for the number of sides in the polygon, see figure 1.

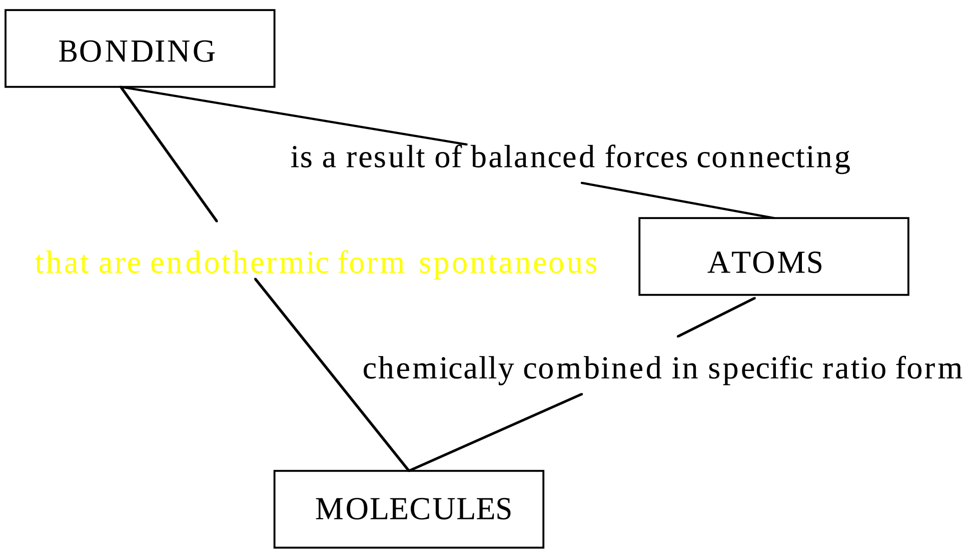


Fig. 1 Example of three propositions forming a polygon with three sides.

The following positive scores apply in figure 1 above since any connections between concepts start a potential proposition: the score would be +3 points for concepts, +6 points for links, and +1 point for a cross-link = +10 points. There are three items that might be scored negatively on each concept map. After the map is checked for accuracy, yellow highlighter is used to indicate links that are incorrect:

4. Concepts that are no longer connected to the rest of the map, deduct one point each. This occurs when invalid links leave a concept "dangling."

5a. Deduct two point each for links that that are incorrect and no longer connect a pair of concepts.

5b. Deduct one point each for links that are minimal if they point to the relationship without explaining how or why the relationship exists

6. Deduct the number of points originally scored for each of the cross-links that are no longer valid as a result of polygons that are incomplete

because links are broken (minimalist links will continue to count toward cross-links).

Example: Since the link between bonds and molecules, "that are endothermic form spontaneous," is incorrect the following negative scores apply to figure 1 above: negative score = -0 points for concepts, -2 points for links, and -1 point for cross-links; The total score for the example in figure 1 above would therefore be: +3-0 +6-2 +1-1 = 7

Concept Maps Scoring Comments for QSAD

When checking the student' concept maps we placed one of the following six markers next to each linking phrase on the concept map. To help interpret the use for markers I will include an incorrect example of each proposition. For simplification the concepts will be placed in square brackets.

√ = designates a link that explains the proposition. Not only what the relationship between the two concepts is but also how or why they are related that way.
Ex: [ENERGY] released with proper frequency produces [COLOR]

M = designates a link that has a minimalist statement that indicates there is a connection between the concepts but does not explain how or why they are connected. Certain words like affects, determines, or creates only state that there is a relationship but do not explain how or why the relation exists. If there is no explanation of the relationship on the map the link would be highlighted and scored one point only.
Ex: [ENERGY] affects [BONDING]

The following symbols are used to indicate incorrect linkages.

<-> = (a) designates a link that proposes a connection that would be appropriate for the reverse direction only.
(b) This symbol may also be used for a process that is incorrectly directed, as when endothermic is used in place of exothermic.
EX: (a) [POLARITY] is dependent on the molecules [SOLUBILITY]
(b) [ELECTRONIC STRUCTURE] e- excitation may release [COLOR]

W = designates a link that is worded in such a way as to not make sense.
Ex: [ELECTRONIC STRUCTURE] electrons repel each other increasing [PERIODIC TRENDS]

? = designates a link that is left blank, i.e. no phrase has been written on the linking line.
Ex: [SOLUBILITY] ??? [COLOR]

X = designates a link that is incorrect.
Ex: [POLARITY] electronegativity difference determines the [COLOR]

APPENDIX "C"

The Traditional E-block Class Totals
(four concept relationships show marked improvement)

17EPRE.TOTAL	BONDING	COLOR	ELECTRONIC STRUCTURE	POLARITY
BONDING	X			
COLOR	mxx	X		
ELECTRONIC STRU	√√√√mmmxxx	xxx	X	
ENERGY	mmmmmmmxxx	√√mmxx	mmmmxxx	
MOLECULAR GEOM	mxxxxxx		mmmmxxxx	
PERIODIC TRENDS	√xxx	xxxxx	√√mmmmmxxxx	
POLARITY	mmxxxxxxx	xxx	mmx	X
SOLUBILITY	mmmx	xxx	x	√√mmmmmmxxxxx

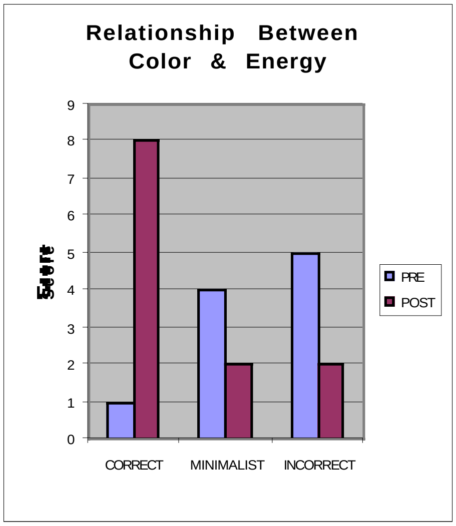
17EPOST.TOTAL	BONDING	COLOR	ELECTRONIC STRUCTURE	POLARITY
BONDING	X			
COLOR	mx	X		
ELECTRONIC STRU	√√√√√√√√√√√√mmmmx	√√mmmmmx	X	
ENERGY	√√√√mmmmmmmx	√√√√√√mmmmmxxxx	√√√mmmmxxxxx	
MOLECULAR GEOM	mmmmmmmmmxxxx		√√mmmmmmmmmmxxx	
PERIODIC TRENDS	√mmxxxxxx	xx	√√√√√√√mmx	
POLARITY	√√√mmxxxxxxxx		√mmmmx	X
SOLUBILITY	√mmxx	x	mmxx	√√√√√√√√√√√√mmmx

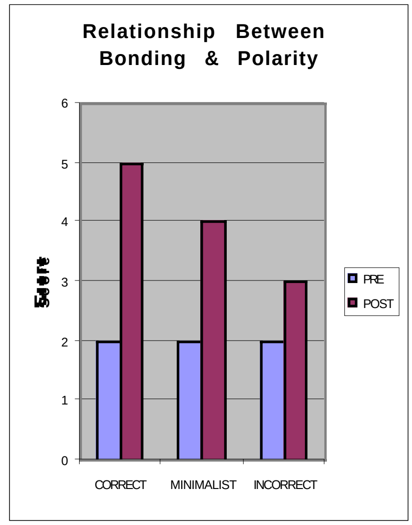
The Experimental A-block Class Totals
(eight concepts show marked improvement)

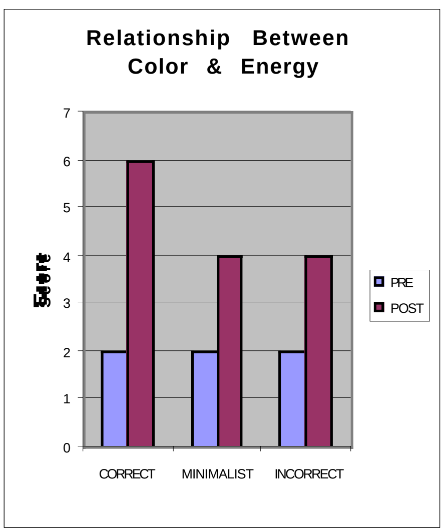
APRE.TOT	BONDING	COLOR	ELECTRONIC STRUCTURE	POLARITY
BONDING	X			
COLOR	√m	X		
ELECTRONIC STR	√√√√√√√√mxxxxxx	√√m	X	
ENERGY	√√mmmmmmmmm	√mmmmxxxxx	√x	
MOLECULAR GEO	√mmmmmmmmmmmxx	xxxxx	√mmmmmxx	
PERIODIC TREND	√√mx	xxxxx	√√mmmmmxxxx	
POLARITY	√√mmxxx	xx	√√√mmmmmmmmxx	X
SOLUBILITY	mx	x	xxxxx	mmmmxxxxx

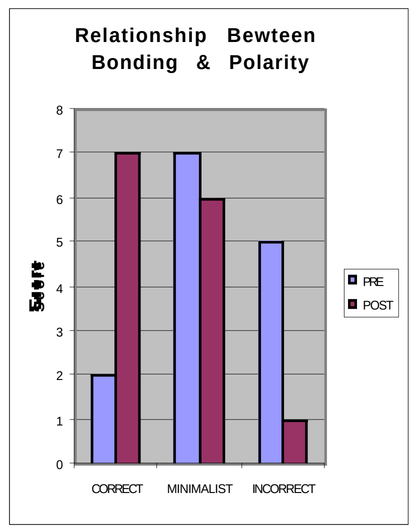
NSAPOST.TOT	BONDING	COLOR	ELECTRONIC STRUCTURE	POLARITY
BONDING	X			
COLOR		X		
ELECTRONIC STR	√√√√√√√√mmmxxxx	√√√√√√√√√m	X	
ENERGY	√√√√√√√√√√√√√mmxx	√√√√√√√√mmxxx	√√√√m	
MOLECULAR GEO	√√√√√√mmmxxx	xxx	√√mmmmmmmmmxx	
PERIODIC TREND	√√√√√√√mx	√√mmxx	√√√√√√√√√√√√mmxxx	
POLARITY	√√√√√mmmmxxx		√√√√√√√√√√√√mxxx	X
SOLUBILITY	√√√√mmxx	x	√xx	√√√√√√√√√√mmmmm

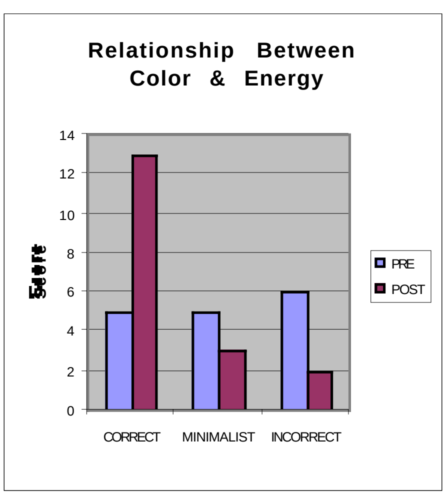
APPENDIX "D"

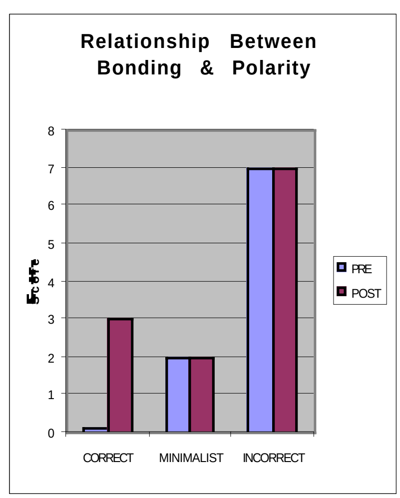

Relationship Between
Color & Energy
0
1
2
3
4
5
6
7
8
9
CORRECT
MINIMALIST
INCORRECT
PRE
POST


Relationship Between
Bonding & Polarity
0
1
2
3
4
5
6
CORRECT
MINIMALIST
INCORRECT
PRE
POST


Relationship Between
Color & Energy
0
1
2
3
4
5
6
7
CORRECT
MINIMALIST
INCORRECT
PRE
POST


Relationship Bewteen
Bonding & Polarity
0
1
2
3
4
5
6
7
8
CORRECT
MINIMALIST
INCORRECT
PRE
POST


Relationship Between
Color & Energy
0
2
4
6
8
10
12
14
CORRECT
MINIMALIST
INCORRECT
PRE
POST


Relationship Between
Bonding & Polarity
0
1
2
3
4
5
6
7
8
CORRECT
MINIMALIST
INCORRECT
PRE
POST