USING INTERACTIVE VIGNETTES IN THE TEACHING OF THE MOLE CONCEPT IN SECONDARY CHEMISTRY

BY

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A thesis

Submitted to the Faculty of Graduate Studies

in Partial Fulfillment of the Requirements

for the Degree of

MASTER OF EDUCATION

Department of Curriculum, Teaching and Learning

University of Manitoba

2006

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES
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ACKNOWLEDGEMENTS

I wish to thank my advisor, Dr. Art Stinner, for the advice and encouragement he offered throughout the duration of my program. His stories, obtained from his years of experience, were always intriguing, and his enthusiasm towards work – both his and mine - was inspiring. I would also like to thank my advisory committee – Dr. Brian Lewthwaite, Dr. Don Metz, and Mr. John Murray - for the guidance they offered and the time they committed to developing this research study. However, my husband Steve was the ultimate source of guidance and support for the duration of my studies. Furthermore, I'm not sure how I would have managed some of the computer tasks without him. I owe him, and my two daughters, many hours of my time, as they so generously allowed me to work, undisturbed, on my thesis.

ABSTRACT

Students often rely upon the rote memorization of information in chemistry. This compromises conceptual understanding and makes chemistry uninteresting. Despite success solving stoichiometric problems, students often do not demonstrate an understanding of underlying concepts, particularly the fundamental concept of the mole. Research suggests that integrating history into teaching chemistry helps showcase it as an interesting and dynamic topic, and promotes student learning. This thesis investigated the impact of historically placed "interactive vignettes" on students' understanding of the mole concept, and their interest level in chemistry. Ten interactive vignettes, following the chronological history of the mole, were presented to a grade 11 Chemistry class. The application of a validated student attitude test ("TOSRA") showed an increase in interest towards chemistry leisure, chemistry careers, and openness to new ideas. However, students' academic scores showed no significant increase in their understanding of the mole. Going forward, the knowledge of the historical information presented in the vignettes may allow educators to approach the topic of the mole in a way that captures their students' interest and enables them to better understand the mole concept.

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CHAPTER 1

INTRODUCTION

1.1 The Mole: A Central Concept in Chemistry

All science subjects contain identifiable central concepts that should be emphasized when taught, as these provide the foundation for the construction of future knowledge. In elementary physics, the central concept in dynamics is force and in electricity it is the concept of charge. In the study of biology, one central concept is the cell as a basic unit of structure and function. Another main concept in biology is that the continuity of life is based on genetic information contained in DNA. In chemistry, one central and unifying concept is the mole. Each of these above-mentioned concepts is contained within a hierarchy of related concepts and skills. For example, in order to better comprehend the central concept of the mole, students need to have an understanding of atomic theory and Avogadro's number. They also need to be familiar with related concepts such as relative atomic mass, chemical formula, formula mass and amount of substance. In chemistry, students must also be able to work with, and interchange between three levels of representation; the macroscopic, symbolic and sub-microscopic. Students need to be able to correctly note observations, communicate them symbolically, and to think abstractly about atoms and molecules on the sub-microscopic level.

In chemistry, the mole concept is a principal foundation for such complex chemical topics as stoichiometry, gas laws, solution concentration, solubility product, equilibrium constant, and pH. The mole also serves as a main unit of measurement for an amount of substance, and is one of only seven internationally recognized units (Gower, D. M., Daniels, D. J., and Lloyd, G., 1977b; Staver and Lumpe, 1993). Staver and Lumpe (1993) claim that the concept of the mole is essential to "successful understanding of domain-specific knowledge in chemistry" and that its understanding and mastery is very important to chemistry students in their studies (p. 322). The mole concept is also fundamental to the "mathematics of chemistry", since a large majority of the quantitative work in high school chemistry involves the mole, either directly or as a bridge between a number of quantities (Gower et al., 1977b; Dorrin, H., Demmin, P., and Gabel, D., 1989). Therefore, students' understanding of the mole concept affects more than just one component of their studies in chemistry. Their success in chemistry, particularly in problem solving, will be limited if the proper foundation of the mole and related concepts is lacking.

Problems with the Mole Concept

Research on the mole concept has shown that it is one of the more difficult concepts for students to understand, even when they can successfully complete a variety of problems using the mole (Ben-Zvi, R. E. B. and Silberstein, J., 1986; Bodner, 1991; Driver, R., Leach, J., Mortimer, E., and Scott, P., 1994; Gabel and Sherwood, 1984; Gabel and Samuel, 1987; and Niaz and Lawson, 1985). Chemistry education research has shown that student difficulties with problem solving often fall into three areas. First, students lack the necessary conceptual knowledge required to solve the problem. Secondly, without this knowledge, students tend to rely on the memorization of rules and equations. Finally, students cannot transfer information between the macroscopic and sub-microscopic levels commonly utilized in chemistry (Staver and Lumpe, 1993). Unfortunately, these three difficulties have all been linked to students' problems with the mole concept.

Gower, Daniels, and Lloyd (1977a) developed a hierarchy of concepts that are fundamental to understanding and correctly using the mole concept (Figure 1 below).

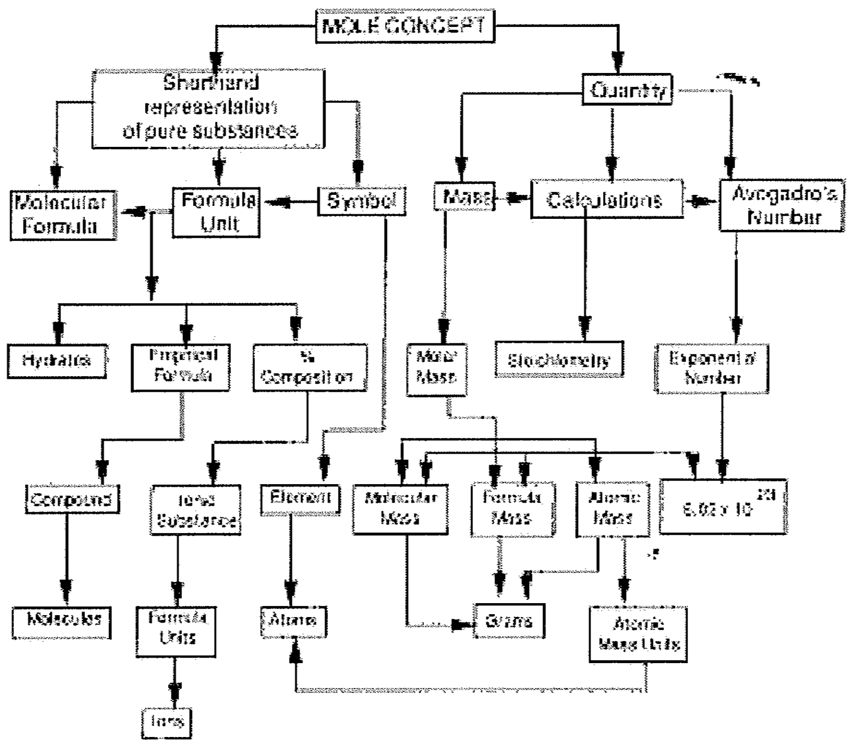


Figure 1. Mole concept map.

They first evaluated and charted the underlying concepts students required if they were to understand the mole concept (e.g. atom, mass, element, compound…). They then extended their flow chart to show the hierarchy of concepts necessary if students were to successfully problem-solve with the mole concept without relying on algorithmic memorization (e.g. gram to mole conversion, calculations involving Avogadro's number, and writing equations). Their evaluation of the hierarchy showed that some steps were common to solving all problems involving the mole concept and, since the mole concept was at the top of their hierarchy, it is considered one of the most difficult concepts to learn. According to Staver and Lumpe (1993), the mole concept originates from "abstract concepts of the atomic/molecular level". As well, the large value for Avogadro's number is too hard to understand concretely (p. 323). Therefore, student difficulties may not solely be with the mole concept, but might be attributed to a lack of knowledge on a lower level concept related to the mole, such as atom or molecule.

According to Garnett, P., Garnett, P., and Hackling, M. (1995), when conceptual understanding is incomplete, students are apt to downgrade the "theoretical knowledge and principles to a 'factual' level" and employ this knowledge in a rote manner. Since the emphasis of science education should not be the rote learning of facts and algorithms, scientific concepts need to be developed and taught in a fashion that will be better understood by students. Given its central role in chemistry, the mole is one of these concepts.

How can we better teach the mole concept in order to increase student understanding while avoiding simple rote memorization? The grade 11 Chemistry (30S) Transitional Curriculum for Manitoba (1998), used as a reference since this study was conducted in Winnipeg, Manitoba, recommends the use of activities that will increase conceptual development and present the nature of science as a dynamic process. This corresponds to the work of White and Gunstone (1989) who promote the use of metacognitive strategies to help students approach problems meaningfully. Over 2000 years ago, Aristotle said that, "to know a scientific fact we must not only know the fact but also know why it is considered a fact" (Manitoba Chemistry 30S Curriculum, 1998, unpublished). According to the Manitoba Transitional Chemistry 30S curriculum guide

(1998), "we must teach students not only what we know in science but also the reasons for knowing". Despite this suggestion, the curriculum suggests no method for teaching the mole in a manner that promotes student understanding. Perhaps one way of improving science teaching is by using the history of science to enhance students' conceptual and attitudinal development while, at the same time, emphasizing the central concept of the mole.

The final difficulty that students have with the mole concept and problem solving in chemistry is associated with the nature of chemistry and its representation on three different levels. Most observations about matter are made on the macroscopic and tangible level, but the explanations are usually given on the sub-microscopic level (e.g., atoms, molecules, ions) (Johnstone, 2000). For example, the observation that water disappears when boiled is explained by referring to the sub-microscopic molecules of water. The third level of representation in chemistry is the symbolic level. On this level, chemical formulae, symbols, chemical equations and mathematical algorithms are used to describe both macroscopic and microscopic observations and reactions. For example: $H_2O_{(l)} \rightarrow H_2O_{(g)}$ represents the change of water to steam of either a molecule of water or a mole of water. According to Johnstone (1991), these three ways of representing the same occurrence are part of what makes chemistry difficult to learn. Gabel (1999) also argues that the primary problem as to why chemistry is regarded by students as difficult to learn is that most instruction in chemistry occurs on the abstract, symbolic level. For example, Fe can refer to one atom of iron as well as a sheet of iron. Students often acquire a disjointed view of chemistry because educators often move from one level of representation to another while teaching. Gabel (1999) states that students' conceptual understanding can be improved by helping students work within all three levels of representation when learning about chemical phenomena.

Rationale for Using An Historical Approach to Teaching Science

According to Matthews (1989), the benefits of an historical approach to the teaching of school science have been well documented during the past two decades (Cushing, 1989; Brush, 1979, 1989; Kauffman, 1989; Stinner and Williams, 1993). Research focusing on the historical approach in science curricula, and on student attitudes and student performance has shown increased understanding and interest in science, enhanced critical thinking skills, and increase in females staying in science (Klopfer, 1969; Sherratt, 1982; Russell, 1981). The historical approach to education involves more than just providing students with conclusions, it shows how those conclusions were reached and what other plausible conclusions existed (Brush, 1989, Sherratt, 1982). A research study by Aikenhead (1974) found that students who are exposed to an historical approach in education gain “an appreciation of the roles of diverse approaches, imagination, confirmation, and instrumentation in the pursuit of scientific knowledge”. Arons (1989) claims that the best way to gain students’ interest is by way of a story line that outlines the historical settings of important discoveries and events.

Research Questions

Due to the fact that the mole is one of the most difficult chemistry concepts for students to comprehend, but is vital for mastery in chemistry, we need to ensure that students are equipped with information that will help them better understand the mole concept. This includes a good theoretical understanding of the development of the atomic theory, the sub-microscopic level of chemistry, and the symbolic representation used to identify elements, molecules and compounds. The benefits of an historical approach to teaching some topics in science have been suggested previously. However, specific research on an historical approach to the teaching of stoichiometry, with emphasis on the concept of the mole, has not been adequate to date. Many students can problem-solve using molar algorithms correctly even when lacking theoretical knowledge, which leads us to the first research question.

1. Does an historical presentation of the concept of the mole, in the form of interactive vignettes, increase students' conceptual understanding of this concept in chemistry?

Chemistry, in general, is a difficult subject to master due to the use of Johnstone's three levels of thought: the "macroscopic and tangible, the sub-microscopic atomic and molecular, and the representational use of symbols and mathematics" (Johnstone, 2000). In order to best understand chemistry, he believes one must work at the submicroscopic level, where "the behaviour of substances is interpreted in terms of the unseen and molecular and recorded in some representational language and notation". Johnstone further argues that instruction fails in this area, and suggests starting with new information that students will find interesting and possibly familiar, so that they can connect it to prior knowledge. This leads us to the second research question:

2. Will this conceptual understanding occur on all three levels of representation in chemistry; the macroscopic, symbolic and the sub-microscopic?

Finally, an historical approach will introduce students to various ideas that were presented over time. They will hear about some of the scientists' frustrations and triumphs along the way and will also see that scientific theories were continually questioned and changed according to new information and beliefs. The incorporation of this humanistic component of science into the student's chemistry class leads to the third research question.

3. Does the use of history, with emphasis on the central mole concept, improve students' attitudes toward and interest in chemistry?

Limitations of the Study

This study will be limited by a number of factors. First, since the history of the concept of the mole is not explicitly represented in the chemistry curriculum, students will not be assessed on the material presented in the interactive vignettes. Therefore, some students may choose not to pay attention to, or get involved in the interactive vignettes when presented in class. Another limiting factor is the seemingly inappropriate fit of the interactive vignettes, presented at the start of class, to the course material being taught for the remainder of the chemistry class. This is due to both the spiral nature of the curriculum (some material covered in the interactive vignettes has been taught in previous grades) and the style of the curricular content (more algorithmic and quantitative than biographical, historical, or qualitative).

There are some limitations associated with the test used for testing student attitudes (TOSRA). The test was modified to test for chemistry attitudes simply by replacing the word "science" with "chemistry", and was shortened to use only thirty-three items overall. The test was also used to assess changes in attitude that occur over a brief, ten-class period of time.

Only two groups of students participating in the study were chosen because they had been scheduled to have the same instructor for grade 11 chemistry (chemistry 30S) during the same semester. This non-random sampling of students, and small sample size, present more limitations to the study. Therefore, the outcomes of the research are only applicable to this setting and these students. However, they hold merit for consideration for other teachers and researchers.

Significance of the Study

In my own experience as a high school chemistry student, the mole was simply Avogadro's number of particles, just like a dozen is twelve. I do not remember any discussion of the history of either Avogadro's number or the mole, nor dialogue regarding the various determinations of Avogadro's number. What I do remember is studying day after day from a workbook that seemed to stress repetitive practice, especially in mathematical problem solving.

Later, as a teacher of chemistry, having obtained a Bachelor of Science degree with a major in chemistry, I admit that I was unfamiliar with the correct SI (International System for Units) definition of the mole until I read articles on difficulties with the mole concept. Perhaps the intended definition was part of my education, but I did not incorporate it into my understanding of the concept. The textbooks used in chemistry have oversimplified the concept of the mole in relation to memorizing Avogadro's number, and have emphasized the use of the mole as a tool for bridging various chemical quantities. This approach allows students to solve "type problems" correctly, but does little to improve conceptual understanding.

I know I am not alone in my misrepresentation of the mole to students. A review of the chemistry notes obtained from the teacher presenting the interactive vignettes also did not contain the SI definition of the mole, nor supplied any history to, or evidence for, Avogadro's number. I am convinced that this is a common occurrence, and one that could be corrected if the story of the mole was introduced in historically and pedagogically valid ways. Educators and students are usually not provided the opportunity to explore the lengthy and extensive process for determining Avogadro's number and its relationship to the SI unit of the mole. Customarily, they are taught a simplified and sometimes incorrect or incomplete version of the mole concept and Avogadro's number.

The significance of this research study will be revealed after analysis of the data, which may show that an historical approach using interactive vignettes will increase student interest in chemistry class and will help them better understand the core mole concept. The study was significant to me, as it revealed a dimension of chemistry that was unknown to me and gave me a new, interesting method to introduce the mole concept to my students. Just as important, this research study provides educators with a historical background to Avogadro's number and the mole concept. This information may enable them to approach the topic of the mole in a way that captures their students' interest and enables them to better understand the mole concept.

CHAPTER 2

HISTORY OF AVOGADRO'S NUMBER AND THE MOLE

2.1: Atomism: Fifth Century B. C.

In order to understand the historical development of Avogadro's number and the mole, one needs to start in the middle of the fifth century B.C., when Leucippus (~440 B.C.), a Greek philosopher, and his student Democritus (~420 B.C), introduced the important intuitive idea of atomism. They believed that the universe, and everything contained within, was comprised of small indivisible particles of matter, "atoms" that could neither be created nor destroyed because they were eternal (Gregory, 1999; Mason, 1962). These "atoms" were assumed to be very minute, indivisible particles composed of the same substance, but different in size, shape, mass and position. Different properties of various substances were due to the differences in the nature of their atoms. Water was thought to be a liquid because its atoms were smooth and round, whereas atoms that were rough and hard would produce a substance like iron (Jaffe, 1976).

However, there was no empirical evidence in support of the theory, so the idea of atoms was not taken seriously. Over the next two hundred years, two of the greatest scientific authorities, Plato (427-347 B.C.) and Aristotle (384 – 322 B.C.), rejected Democritus' theory. Instead of atoms, all objects in Plato's universe were composed of varying amounts of the four elements; earth, fire, air and water. Aristotle, influenced by Plato's long-standing philosophy of the universe, also believed in the element theory, but had a very different view of the mechanics of the universe. He believed that for an object to stay in motion, direct contact with a mover was required. Therefore, in order for an object to keep moving, Aristotle argued that the universe must be a "continuum of matter" (Mason, 1962, p. 43). This clashed with the atomists view that atoms were in constant motion with an empty space.

Although Aristotle's view was dominant, the theory of atomism was not altogether forgotten as both Epicurus (350-275 B.C.) and Lucretius (100 – 55 B.C.) described the theory of atoms in their work. However, without empirical evidence, the theory of atoms remained unworkable for nearly two thousand years during which the influence of Plato and Aristotle was paramount. It wasn't until the sixteenth and seventeenth centuries that the idea of "atomism" was revived (Mason, 1962; Stillman, 1924).

2.2: Mechanical Philosophers in the Seventeenth Century

During the 17^{th} century, there existed two main schools of thought of chemical theory, the iatrochemist's and the mechanical philosophers'. However, neither viewpoint was particularly useful in describing chemical reactions. The iatrochemists believed that "inorganic substances were alive, changing by virtue of inner vital forces" (Mason, 1962, p. 237). The mechanical philosophers, on the other hand, upheld the belief that "matter was dead and inert" and, only under the influence of "external mechanical forces" would change (Mason, 1962, p. 237). According to the mechanical philosophers, all types of matter underwent the same change, and according to the iatrochemists, particular vital forces caused certain types of reactions (Mason, 1962).

As the theory of atoms gained ground in the seventeenth century, it became assimilated with the mechanical philosophy that matter consists of "particles in motion", in part due to the writings mathematics professor Pierre Gassendi (Mason, 1962). In his work, Gassendi used the theoretical existence of atoms in motion to explain various observations on the behaviour of gases. Several scientists followed this with their own interpretations of the physical behaviour of gases.

Robert Boyle, a mechanical philosopher, had determined that the pressure applied to a gas varied inversely to the volume the gas occupied and explained his findings by considering the gas to be a collection of corpuscles in random motion. In chemistry, Boyle determined that some substances could be broken down into simpler substances. However, he observed that the four elements, earth, fire, water and air, could neither be extracted from any substance, nor be combined to produce any new substance. Boyle also observed that salt dissolved in water, but not in oil and explained these results by attributing "principles of variation" to the bodies involved. He claimed that, like the letters in the alphabet, the bodies could be joined together in many different combinations, each result having its own set of properties (Mason, 1962).

Although Boyle didn't follow through on this interpretation of chemical combination, he furthered chemistry by insisting on the use of quantitative experimentation with pure substances and gave the first definition for a chemical element in *The Sceptical Chymist* (1661). This led to the current definition of an element today; a substance that can combine with other elements to form compounds, but which cannot be broken down into simpler substances itself. Unfortunately, all this progress in chemistry was about to be sidelined by the iatrochemists and their phlogiston theory.

2.3: Phlogiston Theory: Late Seventeenth and Eighteenth Centuries

Chemists in the seventeenth century tried to explain the common processes of combustion and calcination (of metals) among substances. It had been observed that certain substances would release an unidentifiable product into the air when burned. Johann Becher (1625-1682) was first to suggest that every flammable substance contained "inflammable earth", later called phlogiston by Georg Stahl (1660-1734) (Loy, 1996). One of the main postulates of the phlogiston theory was that when a flammable substance underwent combustion or calcination it released heat and phlogiston, a colourless, odourless, and tasteless substance. The phlogiston theory provided a connection between the animal and plant kingdom and the mineral kingdom, classifications that previously had been considered quite distinct (Allchin, 1997).

The existence of phlogiston allowed for many observations to be explained. For example, it was also assumed that the air into which the phlogiston went had a limited ability to absorb it. Therefore, in a closed container, a flame will extinguish due to the presence of excess phlogiston (Loy, 1996).

Phlogiston adherents assumed that substances lost mass when they burned because they released phlogiston, but a problem arose when some metals were observed to gain mass during combustion. Some phlogiston theorists explained this phenomenon by assigning phlogiston a negative mass, but as experimentation increased, scientists were finding that not all substances lost mass during combustion. In order to fit with experimental findings, phlogiston could have a positive weight, negative weight, or no weight at all. Another problem that arose, was the finding that phlogiston had different solubility in water, depending on its source. This was the beginning of two types of phlogisticated air; "fixed air" dissolved in water, and "phlogisticated air" did not. Joseph Priestley, a main supporter of the theory, then discovered a new type of air that was a much better fuel for combustion (Loy, 1996).

The demise to the phlogiston theory occurred over many years as quantitative experiments improved and gained momentum. Experimental findings produced problems with the phlogiston theory that needed attention, resulting in the modification of the postulates of the theory. Eventually the theory could no longer explain observations adequately enough, so the majority of the supporters for the phlogiston theory left it behind (Loy, 1996). In the late 1700's, Antoine Lavoisier, repeated Boyle's experiment on heating tin in a flask, but first sealed the flask closed. He conclusively determined that the mass of the reactants and products was conserved during the reaction. Therefore, there could be no loss of phlogiston during the reaction. Instead he noticed the air rush into the sealed flask once it was open, and observed that the associated gain in mass was equal to the corresponding gain in mass when tin is calcinated. Finally, in 1783, Lavoisier stated that combustion and calcinations reactions involve the combination of the combustible substance with the gas he later called oxygen, and not phlogiston. Some phlogistians clung to their theory, claiming that Lavoisier's theory lacked adequate explanation of "heat, light and combustibility" (Allchin, 1997). Priestley was one of the long-standing supporters of the phlogiston theory, despite his experimental determination of oxygen, the substance which ultimately led to the demise of the theory (Mason, 1962).

2.4: Atomic Theory

i) Pre-Dalton

While the phlogiston theory was prevalent in chemistry labs, natural philosophers were still considering the existence of atoms. Robert Hooke, in 1658, described how particles of gas collide with the walls of their container. In 1738, Daniel Bernouilli described air as having fast, random moving particles that formed an elastic fluid. He explained that the gas pressure observed was due to these particles colliding with the sides of the container that held them, thus providing a modern explanation for Boyle's law.

Later, around 1780, Lavoisier's findings, with regards to oxygen, revived Boyle's earlier definition of an element, and took chemistry in a new direction. Quantitative approaches to chemistry were being stressed and resulted in the formulation of new empirical laws. In 1797 Joseph Louis Proust re-introduced and formalized the Law of Definite Proportions, an idea that some prior chemists had intuitions about. Proust, for over eight years, tried to persuade the scientific community that when elements combined to form compounds, they united in definite proportions by weight. Proust also identified the difference between a mixture and a compound. These findings were important because they allowed for the classification of new substances, and led to the revival of the idea of atoms in chemistry, which were last mentioned by Boyle in the seventeenth century (Mason, 1962).

In the early nineteenth century, chemists began to provide evidence for the existence of atoms, although not all scientists made the connection of their findings to the idea of atoms. For example, voltaic cells were becoming common in laboratories, and in

1802, two English scientists observed the electrolysis of water. After a few preliminary experiments with electricity, Sir Humphry Davy realized that electricity would be an excellent tool with which to attack chemistry problems. In 1806 he suggested to the scientific community that chemical and electrical attraction were caused by the same factor. He believed that electrical methods of investigation would lead to more knowledge about the true nature of substances, suggesting a fundamental connection between electricity and chemistry (Holmyard, 1929).

ii) John Dalton

In the early 1800's, John Dalton, a tutor of mathematics and natural philosophy at Manchester Academy, devoted all his free time to scientific research. Dalton was particularly interested in meteorology and was further investigating the constituents of the atmosphere. In 1801, Dalton found that gas pressure increased proportionally with the increase in temperature and concluded that caloric (heat) was the repulsive force that existed between gas particles. Dalton assumed that if there were repulsive forces between atoms of a gas, these substances should separate out. Since this did not occur he concluded that different substances had different atoms, not identical as previously believed. This was an important development in chemistry, for now all atoms were not considered identical, but instead each element had its own type of atoms with a distinctive set of properties, such as weight, size and density (Holmyard, 1929).

Dalton went on to argue that, since the mass of an atom of an element was constant, the composition of all compounds must be definite. In support of this claim, Dalton found that compounds formed from the same two elements always had the same ratio of weights. This became known as the law of definite proportions. Dalton then developed a small list of theoretical relative weights to hydrogen in order to support his claim that each atom had its own distinctive weight. Soon thereafter Dalton noticed that nitrogen and oxygen formed more than one type of compound, and, more specifically, for a fixed amount of nitrogen, the ratios comparing the weight of oxygen was 1:2:4. This led to Dalton's 1804 introduction of the Law of Multiple Proportions. This law stated when two elements form more than one compound the weight of one element in each compound forms a small whole number ratio when compared to a fixed weight of the other element. All of Dalton's ideas of atoms were compiled and presented in 1808 as Dalton's atomic theory which contained four major postulates that outlined the existence and behaviour of atoms (Holmyard, 1929).

After the 1808 publication of his atomic theory, John Dalton set forth to demonstrate that atomic weights could be determined experimentally, and that it was possible to determine the composition of the "ultimate particles" of compounds. If the number of atoms present in the ultimate particle (molecule) were known, one could find the relative weights by qualitative analysis. Since Dalton did not know the number of atoms in an ultimate particle of a compound, he assumed that when atoms combined to form compounds, they combined in small whole numbers to produce the ultimate particles of the compounds (Holmyard, 1929). After quantitative analysis of several compounds, Dalton was able to compose a table of relative atomic weights of atoms of elements, using hydrogen as his point of comparison. For example, water, the only known compound between hydrogen and oxygen, was regarded as a binary compound, HO. Quantitative analysis showed the ratio, by weight, was 8:1 oxygen to hydrogen, so the atomic weight of oxygen was taken to be 8, while hydrogen was said to be 1. The number of atoms in compounds proved to be quite elusive for another half-century.

Until new evidence arose, Dalton's Atomic Theory and simple laws of chemical combination (Conservation of Mass, Definite Proportions and Multiple Proportions) lent themselves to the test of experiment and gave some evidence for the existence of atoms. With the passage of time, Dalton's Atomic Theory managed to slowly gain acceptance within the scientific community.

2.5: Post-Daltonic Theory

In 1811, Jöns Jakob Berzelius, a firm believer in Dalton's Atomic Theory, introduced the modern system of chemical notation. This system represented an atom of an element using either the first one or two letters of the element's name (i.e. H = 1 atom of hydrogen, Zn = 1 atom of zinc). This eventually was applied to compounds as well: HO = water, NH = ammonia, CO = carbonic oxide and CO_2 = carbonic acid. The uncertainty that existed with Dalton's atomic weights soon also existed in Berzelius' method of nomenclature.

The first step in shedding the uncertainty surrounding the number of atoms in a compound began with Joseph Gay-Lussac, a French chemist. He published his observations about the behaviour of gases in chemical reactions in 1808, the same year Dalton published his atomic theory. Gay-Lussac observed that, when two gases react together, their volumes are related to one another, and to the volume of the product as well, if the product is also a gas (Jaffe, 1976; Mason, 1962). For example, two volumes of carbon monoxide will combine with one volume of oxygen to yield two volumes of carbon dioxide. This experimental data could be explained using the hypothesis that the ratio of the volumes of reacting gases must resemble the ratio of the numbers of atoms in those volumes of these gases. Since the volume ratio between the gases was 2:1:2, Gay Lussac assumed the ratio of atoms was also 2:1:2. This became known as Gay-Lussac's Law and it was in direct contradiction to Dalton's statement that equal volumes of gases could certainly not always contain equal numbers of atoms.

2.6: Avogadro's Hypothesis

Amadeo Avogadro, following Dalton's ideas, was one of the first scientists to make the important distinction between the ultimate chemical particle of an element, the "atom', and the ultimate physical particle of a substance, which he called a "molecule". Avogadro's hypothesis, published in 1811, simply stated that equal volumes of all gases at the same temperature and pressure contain equal numbers of molecules. Avogadro had no empirical evidence for his hypothesis, nor had he any way of determining how many molecules were present in a sample of gas, but he understood that the number must be quite large (Jaffe, 1976; Jones and Childers, 1993).

Avogadro's hypothesis amalgamated ideas from Gay-Lussac's Law of Combining Volumes and Dalton's Atomic Theory and provided a key to the structure of matter. According to Avogadro, the smallest, normally existing particle of hydrogen was not H, as Dalton assumed, but actually H_2, consisting of two atoms joined together. Avogadro's hypothesis allowed the chemical composition of Dalton's "ultimate particles" to be correctly established; water became H_2O, and ammonia, NH_3. The hypothesis also provided a way of determining the relative atomic weights of molecules gases, since equal volumes of the gases, at the same temperature and pressure, contained the same number of molecules. Unfortunately Avogadro's hypothesis was not embraced because it called for the acceptance of Dalton's Atomic Theory, which was still not appreciated by the scientists of this time.

2.7: Post-Avogadro Hypothesis

In 1819, French chemists Pierre Dulong and Alexis Petit made an important discovery that provided an independent method of choosing between various possible multiples of oxygen atoms found in compounds. They found that when the specific heat (the amount of heat required to raise the temperature of one gram of a substance by one degree Celsius) of a metallic element was multiplied by that element's atomic weight, a nearly constant value was obtained (Kieffer, 1962). This was true for over twelve elements. This enabled them to assign oxygen an atomic weight of sixteen. Not long after, chemists began to agree that this atomic weight for oxygen would be most convenient to choose as a basis of comparison between atomic weights.

The atomic theory was largely ignored between 1820 and 1860, resulting in confusion within the scientific community. Dalton's law of definite proportions and Gay-Lussac's Law of Combining Volumes were being used independently without a consideration of Avogadro's hypothesis, leading to different interpretations of quantitative results from chemical reactions (Jones and Childers, 1993). Most scientists were conducting experiments using a variety of atomic mass tables since there was the uncertainty surrounding the number of atoms combined in a compound.

Another problem in certain disciplines of chemistry was the belief in the electrical theory of chemical composition. Davy and Berzelius discovered two fundamentally different types of elements, electropositive and electronegative, during the electrical decomposition of inorganic substances. It was believed that compounds were formed when opposite charges were attracted to one another. In addition, if two atoms were from the same element, they would carry the same charge and repel one another. Therefore, the existence of Avogadro's molecules, two like atoms combined, was inadmissible to many. This chemistry theory became known as the dualistic theory, and was another reason why John Dalton, and many others in the scientific community, rejected Avogadro's hypothesis.

During the early 1800's, organic chemistry was developing in Germany. It was believed that organic substances were derived only from vital forces in living matter until 1828, when Fredrich Wöhler produced an organic compound, urea, from inorganic ammonium cyanate. The dualistic theory was extended to help explain findings in organic chemistry, but when Wöhler determined that certain organic substances could combine equally well with either electropositive or electronegative elements, with no changes to their properties, the dualistic theory faltered. In 1840, Jean-Baptiste-André Dumas suggested, instead of the dualistic theory, that it was the structure of organic substances that determined properties with structurally similar compounds having similar properties. When discussing his theory, Dumas referred to equivalents of a compound instead of atoms, although knowledge of the ratios of atoms was necessary if one was to learn of its structure (valency). The differing viewpoints on organic compounds, dualistic theory versus structural types, atoms versus equivalents, got more complex and confusing. Organic chemists needed more chemical theory that could explain these results, determine the structure of a chemical molecule, and determine valency (how many atoms of one element could combine with an atom of another). In order to address the state of confusion in chemistry, Kekule arranged an International Chemical Congress conference in Karlsruhe, Germany in 1860 (about four years after Avogadro's death).

A new break-through came when the Italian chemist, Stanislao Canizzaro, Avogadro's pupil, following Avogadro's assumption that gases existed diatomically in molecules, determined that the volume of a gas was associated with its gram-molecular mass. Avogadro's hypothesis, that equal volumes of all gases contain equal number of molecules or atoms, led Cannizzaro to conclude that the gram-molecular weight of a gas must be proportional to the density of the gas, with volume remaining constant. Using samples of hydrogen gas and oxygen gas, and the assumption that their relative molecular weights were 2.0 and 16.0 respectively, Cannizzaro determined the average volume of one gram-molecular mass of any gas to be approximately 22.4 L.

At the International Chemical Conference, Stanislao Cannizzaro tried to explain how Avogadro solved the problem earlier of valency and atomic weight determination, and made a recommendation that Avogadro's hypothesis be accepted and used, but most in attendance were still unconvinced. Eventually, Cannizzaro's work gained acceptance and Avogadro's hypothesis gained validity in the scientific world. Chemists, in the 1860s, were able to determine atomic weights and valencies for elements, and tried, once again, to place elements in related groups according to their properties. Both German chemist Lothar Meyer and Russian chemist Dmitri Mendeleev noticed periodic trends amongst the elements and each developed a periodic table in support of their findings. (Mendeleev's periodic table was published in 1869.) The fact that there was a periodic occurrence of similar physical and chemical properties, when arranged in order of increasing atomic mass, supported the recorded relative masses of the elements (Jones and Childers, 1993). These values soon became widely accepted by the scientific community.

2.8: Determination of Avogadro's Number

Years were spent looking for empirical evidence in support of Avogadro's hypothesis that would allow scientists to determine the actual quantity of molecules that exist in a gram-atom of a particular substance, where a gram-atom corresponds to a substance's atomic weight. This quantity in question became known as Avogadro's number, or "N", first used by Jean-Baptiste Perrin in his paper on Brownian Motion in 1908 (Perrin, 1923). Once an agreement of atomic weights was established, the pathway for determining the number of atoms in Avogadro's number became evident.

The methods used to calculate Avogadro's number have been extremely varied, yet have yielded quite similar results. Some of these methods have involved studies into the viscosity of gases, molecular distribution in emulsions, Brownian motion, the blueness of the sky, black body spectra, radioactivity and X-ray crystallography (Perrin, 1923). Overall, the use of such diverse approaches and the closeness in obtained values for Avogadro's number gives much support to the atomic theory and Avogadro's hypothesis.

A: Study of Crystals

It was the study of crystals and their structure that led to the next wave of support for atoms. As far back as 1665, Robert Hooke had illustrated the appearance of crystals under the microscope and had noted their symmetry, suggesting they were composed of a "regular arrangement of tiny particles" (Jones and Childers, 1993). However, it wasn't until 1791, when Rene Just Haüy accidentally found that crystals would cleave along specific edges into smaller and smaller pieces. He proposed that this would continue until the crystal was reduced to its smallest fundamental unit. By the early 19^{th} century, crystallographers were convinced that atoms were responsible for the shape and properties of crystals (Jones and Childers, 1993).

B: Brownian Motion

One of the first observations in support of atoms was based on the work of Robert Brown in 1828, a London doctor and botanist. Brown, investigating fertilization in a new plant species, was studying pollen grains through a microscope when he noticed their rapid motion. Although others had observed this random movement previously, Brown was the first to investigate it further. Brown observed that the motion was not limited to living material and found that very small particles of any solid suspended in water, seemed to be in a state of random motion when observed under the microscope. The cause of this seemingly perpetual random movement was doubtful for a long period of time, although some attributed it to thermal convection currents in the liquid medium.

C: Relationship to Electricity

The next major step in determining the elusive Avogadro's number came from Michael Faraday. In 1834, Faraday studied the effect of electric currents on water solutions of a variety of different substances. He showed that chemical compounds could be separated into their elemental components by passing an electric current from a battery through them, a process he called electrolysis. He suggested that the electric current caused some compounds to separate into electrically charged atoms that he called "ions".

Faraday completed many quantitative studies on chemical electrolysis, and from the analysis of the data he proposed that a definite amount of a substance was produced at an electrode by a fixed quantity of electricity. Furthermore, the amount of substance decomposed was proportional to the magnitude of the electric current used and to the elapsed time and determined that the quantity of electricity that produced 8 g of oxygen was also able to produce 35.5 g of chlorine. Faraday called these masses the "electrochemical equivalents" of the elements, and for many elements, these equivalents were the same as Dalton's reported atomic masses (Jones and Childers, 1993).

Through further experiment, Faraday was able to measure the total charge required to deposit the mass of a substance, in grams, equal to its atomic mass (gram atomic mass). This charge became known as the faraday (F), and since a gram atomic mass of a substance, according to Avogadro's hypothesis, would contain a definite number of molecules, Faraday had found a method of determining Avogadro's number

($F = N_a e$) (Jones and Childers, 1993). Faraday was aware of this relationship, and understood its significance, but was unable to find Avogadro's number (N_a) or the unit of charge (e) separately. Faraday was not able to prove that atoms actually existed, but his quantitative experimental data from electrolysis was clearly explained using the ideas of atomism and gave more credibility to the existence of atoms (Jones and Childers, 1993). In 1891, G. Johnstone Stoney coined the term "electrons" for the unit of charge found in Faraday's electrolysis experiments (Mason, 1962).

D: Kinetic Theory of Gases

Around 1857, Rudolph Clausius expanded the kinetic theory of gases. This theory was based on various experimental data that indicated gases behaved as they did because they were made of molecules, moving in random directions at great speeds, undergoing almost elastic collisions (Garber, Brush, & Everett, 1986). It was believed that the gaseous molecules were able to exert pressure on the walls of the container due to their random motion and kinetic energy, and more molecules created a greater pressure. Studies had shown that as temperature was increased, the kinetic energy of the molecules also increased, causing an increase in pressure. Around 1866, James Clerk-Maxwell showed that the pressure of a gas was proportional to the number of molecules in the sample. He argued that the most important consequence of the kinetic theory, having been improved by Ludwig Boltzman (~1877), was that a cubic centimeter of any gas, at standard pressure and temperature, would contain the same number of molecules (Knight, 1968). Maxwell believed that measuring the variables of temperature, pressure and volume of a sample of gas would indicate the number of molecules contained within (Kieffer, 1962).

E: Molecular Size

One of the first estimates of the size of a molecule was by the Austrian physicist, Johann Loschmidt in 1865. He based his method on the kinetic theory of gases, largely advanced by Clasius, Maxwell, and Meyer. He made use of their determination of the average velocity of molecules of gases in relationship to kinetic energy, and the mean free path of air molecules. In his calculations Loschmidt assumed that the volume of the substance, when reduced to the liquid form, would be not much greater than the total volume of all its molecules. He called this the coefficient of condensation, ε. This ratio was comparable to the ratio between the mean free path (l) (space between one collision and the next) of a molecule and one-eighth of the diameter of a molecule (s).

Loschmidt's equation: $\varepsilon = s / 8\, l$

Loschmidt's size of a molecule of hydrogen was such that two million arranged in a row would take up one millimeter of space. He found that one cubic centimeter, at normal temperature and pressure, would contain approximately 1.9×10^{18} molecules (Knight, 1968). These results were supported by the individual results obtained by Stoney in 1868, and by Kelvin in 1870, whose estimate was deduced using the thickness of soap bubbles and from the electric properties of metals.

It was known that, at a standard temperature and pressure, the volume any 22.4 litre sample of gas would contain the same number of molecules, and this number of molecules became known as Avogadro's number. Using Loschmidt's value for the number of molecules in 1 cm^3, Clerk-Maxwell mathematically estimated that there were 4.3×10^{23} molecules in 22.4 L of a gas (Knight, 1968).

By analyzing the scattering of light, Kelvin was able to obtain an estimate of Avogadro's number of molecules in a gas at $0^{o}C$ and 760 mm of mercury. His results gave a value of 5×10^{23}.

F: Discovery of Electrons

Late in the nineteenth century, scientists were researching the behaviour of electric discharges in Crookes tubes, and found that they filled with a green fluorescence near the positive electrode when high voltage was applied to the electrodes in the tube. It was thought that the fluorescence was due to rays originating from the negative electrode cathode, so these rays became known as "cathode rays". In 1895, Jean Perrin showed, later confirmed by J.J. Thomson, that these cathode rays carried a negative charge. Although previous research had shown that there was no effect, Thomson studied the effect of electric fields on cathode rays, and found they always deflected away from the negatively charged plate, supporting the idea that cathode rays were charged particles, not waves as some researchers had suspected. He also determined that the magnitude of deflection was proportional to the voltage applied across the plates (Jones and Childers, 1993).

In 1897, Thomson calculated the mass to charge ratio of these "cathode rays" by reasoning that a particle traveling between the plates would be deflected by the electric field at an angle, with an acceleration proportional to its mass, and once the particle had left the electric field, the angle of deflection could be calculated. Thomson was able to determine the mass to charge ratio, but the reciprocal of this value is used and is equal to 1.7588×10^{11} C/kg (Jones and Childers, 1993). Experimentation with different gases gave similar results supporting the belief that cathode rays were charged particles. Thomson concluded that these cathode ray particles were identical in mass and charge and were a part of all atoms, therefore, atoms must be divisible. He also concluded that if the charge, e, was the same size as the smallest unit of charge observed in electrochemistry, then the mass of the cathode ray particle was two-thousand times less than the mass of a hydrogen atom (the smallest mass known at that time). Thomson called these cathode ray particles "corpuscles", but they soon became known as "electrons".

G: Return of Brownian Motion

Previously the rate of Brownian motion had been found to vary proportionally with changes in temperature. According to the kinetic theory of motion, an increase in temperature would cause the kinetic energy with which the molecules of the substance are moving to increase as well. Therefore, in 1877, it was suggested that Brownian motion of particles might be related to the molecular motion of the liquid portion of the suspension. This was an important link, offering the first observable phenomenon to corroborate the kinetic theory of gases.

In 1905, Albert Einstein published three papers in physics and chemistry that were significant for modern physics, as well as chemistry. In one of these papers Einstein made some very important statements regarding the existence of atoms, although atoms and molecules were still open to objection in the scientific world. In his paper, Einstein described how the random motions of larger particles in a suspension, as viewed under a microscope, were the result of collisions with the random movement of smaller molecules in a liquid, which moved according to the kinetic theory of gases. The random bombardment of a particle would cause it to move in the same way Robert Brown had described it years ago and, due to the large size of the particle, measurements could be made more easily than on the water molecules themselves. Einstein determined that the displacement of a Brownian particle would not increase linearly with time but with the square root of time, since the particular motion resembles that of a "random walk" (Bent, 1980; Haw, 2005).

Random walks hold the same sort of predictability as obtaining a certain number from a roll of dice. It is quite unlikely, although possible, for a walker to head off in one direction and continue in a straight line. More often, a walker's path will loop back upon itself and, in the end, the walker does not venture too far off from his starting point. It has been proven that after N random steps, such a walker will *on average* end up at a distance of $\sqrt{N}$ from its starting place. For example, a person taking 100 random steps, each one foot in size, will end up only 10 feet ($\sqrt{100}$) *on average* from their starting position.

In his paper, Einstein provided an equation by which Avogadro's number could be determined simply by studying Brownian motion. This equation replaced the number of steps in a random walk with the number of collisions of a particle. The equation also took particle size, temperature and liquid viscosity into consideration:

$$\text{Einstein's Equation: } N = \frac{RTt}{3\pi k a \lambda^2_x}$$

N = Avogdaro's number, R = universal gas constant, T = temperature in Kelvin, *k* = viscosity of water, *a* = particle diameter, λ_x = displacement (random walk)

According to Einstein, Avogadro's number was proportional to the product of the universal gas constant, temperature in degrees Kelvin and the time period for the particle's displacement. Avogadro's number was inversely proportional to 3π times the solution's viscosity, particle diameter and the particle's random walk observed during the time interval used.

Einstein suggested that Avogadro's number could be determined by measuring the average position of a microscopic particle over time. His paper gave chemists an experimental way by which they could use an everyday microscope to count atoms (Bent, 1980). Einstein was the first to provide persuasive evidence for the physical existence of atoms. This almost 100 years after Avogadro made his hypothesis.

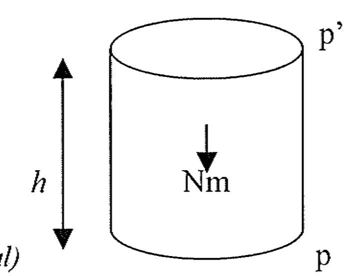
H: Application of Einstein's theory: Perrin

Early in the twentieth century, Jean-Baptiste Perrin proceeded to use various emulsions to determine Avogadro's number (Perrin, 1923). The methods Perrin used included measurements of the vertical distribution of particles in a column, and properties of Brownian motion that included displacements and diffusion. Working with his emulsions, which included variations in both the size and mass of grains, Perrin was able to determine values for Avogadro's number, with, according to Perrin, the most accurate measurements being 64×10^{22} (Perrin, 1923).

As early as 1810, while working on the relationship between altitude and barometric pressure, Pierre-Simon Laplace determined that any vertical column of gas will be compressed under its own weight. He derived an equation that connected the pressure of a gas at two different heights in a vertical column and found that the ratio of the two pressures remained constant if the height was unchanged (Perrin, 1923). In 1908, Perrin noticed that particles suspended in a liquid resemble the particles of a gas in terms of their distribution. More specifically, the way the density of gas particles in the atmosphere decrease with distance from the earth, the density of the suspended particles drops with an increase in height, independent of their initial distribution. Perrin, using Laplace's earlier work, derived an "equation of distribution" for an emulsion that clearly showed that the concentration of granules in an emulsion decreased exponentially manner as a function of height.

Perrin's equation:

$$n'/n = 1 - (N/RT)\, m\, (1 - d/D)\, gh$$



(d = density of the liquid and D = density of the particle's material)
p' and p are the two pressures found at different heights
h is the height of the column, N_M is molecular weight of the particles

Once the emulsion of gamboge (dried vegetable latex) and mastic (a resin) was prepared, by repeated use of a centrifuge, Perrin determined the density and volume of the grains by different methods. Then Perrin placed a drop of the emulsion in a 0.1 mm hollow section of a glass slide and observed the emulsion either vertically, where the complete distribution of the emulsion was observed at once, or horizontally, where the emulsion was observed on one layer of particles at a time as the microscope was raised or lowered. He then counted the grains contained within, since the ratio of particles at the two different heights, n' to n, still needed to be determined (Perrin, 1923).

Every hour Perrin determined the ratio of the grains at the two fixed heights and found that after one hour the ratios did not change, and they remained the same up to 15 days later. Perrin repeated his findings with emulsions containing particles in varying sizes, a different nature of grain, different intergranular liquids and varying grain densities. He also supervised the study of the influence of temperature on the emulsion, where samples were tested at –9°C and at 60°C. Despite all the changes, Perrin found that the value for Avogadro's number remained relatively constant between 65 x 10^{22} and 72 x 10^{22}.

Perrin also determined Avogadro's number by separately focusing on particles' Brownian motion. With the aid of a microscope of known magnification, he recorded random displacement of a grain over consecutive periods of time. After repeated trials with large variations in grain size, Perrin was able to determine values for Avogadro's number, using translational motion, that were approximately 70 x 10^{22} (Perrin, 1923). For rotational motion, using over 200 measurements, Perrin was able to calculate a value for Avogadro's number of 65 x 10^{22}.

The last experimental study Perrin completed to confirm Einstein's laws was to look at the diffusion of emulsions and see if the value obtained for Avogadro's number agreed with those already found. To do this Perrin studied the diffusion of sugar in water. The value for Avogadro's number obtained was 65 x 10^{22}. M. Brillouin, one of Perrin's associates, then studied the diffusion of visible gamboge grains by photographing an absorbing partition twice a day and counting the grains that were attached. He obtained a value of 69×10^{22}. The similarity in all of Perrin's results gave Einstein's formula considerable support as well as lends confirmation to the molecular theory. In 1926 Perrin received a Nobel prize for his work on atoms in 1926.

I: Radioactive Decay

In 1911, Ernest Rutherford and Bertrum Boltwood counted the number of radioactive disintegrations occurring in standard sample of naturally radioactive materials like radium. They had learned that alpha particles emitted by the radium sample would pick up electrons and become helium gas molecules. Since one disintegration would produce one helium gas molecule, counting the disintegrations and measuring the number of moles of helium gas produced would provide a good estimate of Avogadro's number. On one day 2.25×10^{15} disintegrations occurred in a 192 mg sample, so 2.25×10^{15} molecules of helium were produced. Calculations using the Ideal Gas Law produced a value for Avogadro's number of 6.14×10^{23} molecules.

Rutherford and Hans Geiger also counted the number of projectiles being emitting from a radioactive source by constructing a device that caused the emitted α particles to produce a trail of ions as it ionized the molecules with which it collided. The discharges produced were large enough to deflect an electrometer and noticeable enough to be accurately counted. Rutherford and Geiger then permitted the α particles to fall within a Faraday cylinder, and determined the charge of a single projectile. Once the charge of the projectile was calculated, Avogadro's number could be determined, and was found to be 62×10^{22} (Perrin, 1923).

J: X-Rays

The effect of X-rays on crystals also became known in 1912. Max Von Laue, German physicist, had found that X-rays, when aimed at pure crystals, separated like a diffraction grating producing an X-ray spectrum. Using this knowledge, William Bragg and his son developed a method that would allow them to see the inner structure of salts. They sent X-rays through very thin crystals and photographed what they saw. They were able to see regularly spaced rows of atoms that were approximately one twenty-millionth of an inch apart (Jaffe, 1976). In 1912, Poincare made the statement, "atoms are no longer a useful fiction, things seems to us in favour that we see them since we know how to count them...The atom of a chemist is now a reality" (Haw, 2005).

K: Discovery of the Charge on the Electron

Recall that in 1897, J. J. Thomson determined the mass to charge ratio for a corpuscle, later termed an electron. Being unable to determine either the mass or charge separately, he could not calculate Avogadro's number. From 1913 to 1917, the American scientist Robert Millikan, studied the movement of charged drops of oil in opposing electrostatic and gravitational fields and was able to determine both the mass and charge of an electron. He was able to repeat this experiment with other substances, such as mercury and glycerin. The mass of the electron was determined by Millikan to be 9.1×10^{-31} kg, and the charge of the electron was determined to be 1.6022×10^{-19} Coulombs (Mason, 1962). When applied to Michael Faraday's assumption that Avogadro's number equals the faraday divided by the unit of charge, a value of 6.0217×10^{23} is obtained.

Modern methods of determining Avogadro's number rely on the use of X-ray crystallography to get the precise dimensions of the atoms in crystals. Calculations, using Bragg relationships, have provided estimates for Avogadro's number at 6.0215×10^{23}. The values obtained by this method are said to have an error of less than 1.0×10^{-8} (Dice, 1996).

Through the years, many different phenomena have been involved in the determination of Avogadro's number. Whether it was the kinetic theory and gases, charged particles in solution, or radioactive substances, the results for Avogadro's number are quite similar to one another. Table 1 below summarizes the range of some studies done, and shows the closeness between the results for N. This gives much support to the atomic theory and Avogadro's hypothesis.

Table 1: Summary of Various Methods that have given values for N
(Perrin, 1923)

Phenomena Observed		$N/10^{22}$
Viscosity of Gases		62 (?)
Vertical Distribution in dilute emulsions		68
Vertical Distribution in concentrated emulsions		60
Brownian Movement	Displacements	64
	rotations	65
	Diffusion	69
Density fluctuation in concentration emulsions		60
Critical Opalescence		75
Blueness of the Sky		65
Diffusion of light in Argon		69
Black Body Spectrum		61
Charge as microscopic particles		61 (?)
Radioactivity	Projected charges	62
	helium produced	66
	Radium lost	64
	Energy radiated	60

2.9: The Idea of the Mole

Surprisingly, the term "mole" did not originate with Avogadro, but was introduced around 1900 by Wilhelm Ostwald, a famous German chemist, in reference to work done on ideal gases. One mole, as defined by him, was "the molecular weight of a substance in mass grams" (Gorin, 1994). The term mole became a convenient way to count very large numbers of atoms or particles. Prior to 1959, in chemistry, units used to specify amounts of a substance were based on relative masses, with the agreed upon atomic weight of oxygen (16) being used. However, in physics "16" represented one single oxygen isotope, and in chemistry is referred to the average of three isotopes. Therefore, in 1960 the International Union of Pure and Applied Physics (IUPAP) and the International Union of Pure and Applied Chemistry (IUPAC) assigned the exact value of 12 to the relative atomic mass of the isotope of carbon with mass number 12 (carbon 12, ^{12}C). The mass of carbon-12 was set at 0.012 kg, and 'the unit of the quantity "amount of substance" was given the name mole (symbol mol)' (National Institute of Standards and Technology).

In 1967, the International Committee for Weights and Measures adopted the above definition, and in 1971, the mole was adopted as the official System International unit for an amount of substance. It is defined as "the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12" (NIST). In 1980 this definition was expanded, by the International Committee for Weights and Measures, to clarify that the carbon-12 atoms are unbound and in their ground state.

The definition for a mole doesn't mention the actual number of entities that are found in 0.012 kilograms of carbon, so the connection to Avogadro's number is unclear. However, one mole of carbon is the same as Avogadro's number of atoms of carbon, or one mole of any substance is equivalent to Avogadro's number of atoms/particles of that same substance. This link between Avogadro's number and a mole is used regularly in chemical stoichiometry and is a cornerstone to many calculations in the chemistry classroom.

2.10: Summary

The path by which a new scientific theory is first conceived, developed, unveiled, and then accepted by the scientific community is usually lengthy, and fraught with many unexpected problems along the way. Usually the development of the theory remains unknown to the general population and science students, and, instead, the final product is showcased and eventually utilized as mainstream fact. People often are unaware of some of the barriers scientists face in pursuit of their beliefs. These barriers usually are technological in nature, but sometimes are related to outside influences such as religion and politics. This is definitely true for the development of Avogadro's hypothesis and the eventual determination of Avogadro's number, which extended through many disciplines and covered approximately two hundred years of scientific thought and experimentation.

CHAPTER 3

LITERATURE REVIEW

The review of the literature will be divided into two sections. The first section will outline the prescribed use of an historic approach in education. This will be followed by results of some research into the use of an historical approach as it related specifically to science courses. The second section of the literature review will emphasize the role of science textbooks in education. In particular, their use in the classroom and their presentation of the concept of the mole.

3.1: Research into History in Science Education

Driver, in her article "*Students' Conceptions and the Learning of Science*" (1989), discusses the research on students' conceptions of natural phenomena and the belief that "meaningful learning involved the structured organization of a knowledge system in which concepts take their meaning from the theories in which they are embedded" (p. 481). She mentions the literature which indicates that students' prior conceptions can influence their learning of new concepts, especially if they differ from the ideas being taught. Driver further describes the constructivist perspective of learning, where students are believed to build their own mental representations of the world around them and then use these to interpret new information, revising and adapting their mental representations as needed. Unlike Piaget's idea of personal construction of knowledge, Driver states that "learning science…is seen to involve more than the individual making sense of his or her personal experiences but also being initiated into the ways of seeing which have been established and found to be fruitful by the scientific community" (p.482).

In discussing conceptual change in students, Driver brings forth the research perspective that draws a connection between the pattern of conceptual change in students and the way scientific theory has been seen to change and proceed over time. It was found that there was a similarity between the historic development of science and the growth of individual understanding (Driver, 1989; Piaget, 1970; Sherratt, 1982). Research has been directed towards substantiating this hypothesis that intuitive beliefs mirror stages in the history and development of science (Matthews, 1989; Rowell, 1989; Niaz, 1991).

As early as the nineteenth century, Georg W. F. Hegel, Herbert Spencer, and Ernst Mach believed that historical presentation had a psychological role to play in the development of understanding. Pierre Duhem believed that the best and only way to give students a "correct and clear view of the very complex and living organization" of science was by way of an historical approach that involves the retracing of stages by which empirical data was obtained and theories were first conceived (p.268). Piaget (1970) was the major advocate of this idea in the twentieth century (Matthews, 1989).

Piaget's hypothesis, of the same title as his influential book *Genetic Epistemology* (1970), claims that there "is a parallel between the progress made in the logical and rational organization of knowledge and the corresponding formative psychological processes" (p. 13). "Genetic Epistemology" attempts to explain scientific knowledge on the basis of its history, and especially the psychological origins of the notions and operations upon which it is based. Piaget further stated that scientific knowledge is a process of continual construction and reorganization. Therefore, historical and psychological factors in these changes are of interest when attempting to understand the nature of scientific knowledge. In science education, it is generally believed that the historical progression of science is similar to one's individual psychological development. For example, students begin with concrete thinking, with their concepts tied to different sensations and, under the influence of education, slowly develop more refined or abstract concepts. Although a complete historical recapitulation is not possible, historic progression is still important to science educators. Genetic Epistemology suggests that knowledge of the obstacles to the historical development of science can indicate where problems might arise in student understanding, and can clarify the presence of science learning (Driver and Easley, 1978; Matthews, 1989). If this is the case, an historical approach that highlights the main obstacles in the development of the mole concept may help students work though their own stages of understanding of this concept.

An historical approach, as defined by Stephen Brush, in his article "*History of Science and Science Education*" (1989), does more than just "assert the conclusions", but describes the plausible alternatives and then shows how the conclusions were reached (p. 61). He claims that experiments and thinking are integral parts to the historical approach. The Interactive Vignettes that are used in my research attempt to involve students in either a thought experiment or a hands-on activity in order to demonstrate certain historical concepts that helped develop Avogadro's number and the concept of the mole.

In his book *Science Teaching – The Role of History and Philosophy of Science*, Michael Matthews claims that an increased role of the history and philosophy of science should increase students' awareness of the cultural, social and philosophical dimensions of science and should increase their understanding of the science subject matter being taught (1994). Matthews states that the use of the history of science in earlier curriculum reforms was often ineffectual because it "was taught as a rhetoric of conclusions" and "the fluid nature of scientific inquiry and conclusions was seldom apparent" (p. 19). He believes that curriculum should be guided by the history of science, as it provides "a wonderful opportunity to learn about science at the same time that one is learning the subject matter of science" (p. 135). In describing the use of the pendulum for the study of motion, Matthews states:

> "The history of human efforts to understand pendulum motion is far from boring: it is peopled by great minds, their debates are engaging, and the history provides a story line on which to hang the complex theoretical development of science. As well as improved understanding of science, students taught in a contextual way can better understand the nature of science, and have something to remember long after the equation for the period of a pendulum is forgotten." (p. 135).

The history of Avogadro's number and the mole could be described in the same fashion. Instead of just memorizing the definition and value for Avogadro's number, students, when using an historical approach, learn about the conflicting beliefs between Dalton and Gay-Lussac, and then Cannizzaro and the scientific community. They hear how many great minds, over many years, contributed to the development of Avogadro's number and have some hands-on activities to draw them into the stories presented. This makes the information much more intriguing and memorable than being given a seemingly meaningless value to memorize and use in rote calculations.

Many research studies have looked at the use of history of science in science education only to find conflicting results on its effectiveness. An historical approach has been used to assess students' views of the nature of science (Abd-El-Khalick and Lederman, 2000; Bentley, 2000; Boujaoude, 1995; Dennison, 1993; Duschl, 1990; Irwin, 1997, 2000; Matthews, 2000), student learning of science (Klopfer and Cooley, 1961; Seroglou et al, 1998; Stinner and Williams, 1993; Wandersee, 1985), and student interest in science (Becker, 2000; Solomon et al. 1992; and Warrick, 2000). Abd-El-Khalick and Lederman (2000) studied the use of history of science to change student's views on the nature of science and found no discernable effect. However, Irwin (1997, 2000) and Solomon et al. (1992) found that students' views of the nature of science are altered with an historic approach, but there is no change in their understanding of scientific concepts. Alternatively, studies by Seroglou et al. (1998), Stinner and Williams (1993), and Wandersee (1985), have shown an increase in student learning through the use of the history of science.

Stinner and Williams, in "Conceptual Change, History, and Science Stories" (1993), discuss the use of historically based science stories (large context problems) for science classrooms. They claim that an historical setting would provide a meaningful learning context and would serve as an appropriate vehicle for students' conceptual change. It seems that students would benefit cognitively if certain difficult concepts were historically introduced and then progressively developed towards the common scientific view held today. In 1858, Stanislao Cannizzaro, advocate for Avogadro's hypothesis which changed the face of chemistry, said: "in order to lead my students to the conviction which I have reached myself, I wish to place them on the same path as that by which I arrived at it – the path that is of the historical examination of chemical theories" (personal letter to Professor De Luca).

Seker and Welsh (2003), in "The Differentiation of Contexts Provided by History of Science", argue that the variation in results is attributable to the context in which the history of science is presented. Their own study on the effectiveness of different class contexts provided by using the history of science, showed that the varied methods (historical stories of scientists' lives, scientific concepts, and nature of science) had different effects on student learning of science, their understanding of the nature of science, and their interest in science class. They were able to conclude that student interest increased with the use of stories of scientist's lives and that the students who learned the historical background to concepts had more valid propositions.

This research is relevant to my research because the interactive vignettes serve to introduce some biographical information about each scientist with their historical contribution to the concept of Avogadro's number and the mole, with the hope of increasing both student interest and understanding of the mole concept.

In Sherratt's article (1982), "History of Science in the Science Curriculum: an historical perspective; Part 1: Early interest and roles advocated", he discusses many reasons why history has been used in the science classroom. He states that one of the most frequently mentioned arguments for the use of the history of science is that it can demonstrate the cultural and humanistic aspects of science. This is important since many of the concepts taught in the classroom are introduced and treated as if they were unproblematic from their inception. Students do not learn to appreciate that science is a creative human endeavor, fraught with moral and aesthetic dilemmas. The historical approach goes beyond simple biographies of the scientists, and instead, it is a way of showing high school students the complex interactions that lie behind the "facts" presented in science courses (Lühl, 1992; Sherratt, 1982; Holmyard, 1923). According to Sherratt, advocates of the history of science urged educators to place historical "facts" into a wider context, including social and intellectual components, and then evaluate them from within.

Sherratt includes the following quote from Humby and James as early as1942:

> "...science is taught as a collection of laws and facts rather than as a constantly growing body of knowledge with social implications of vital importance...pupils too rarely realize...that the pursuit of scientific knowledge is a social activity, that science has the power to affect society and society the power to direct science. The relation between science and history is taught, if at all, in the most uninteresting and irrelevant way. The social repercussions of science are relegated to a few isolated industrial applications"

Often, chemical stoichiometry is taught as a means to an end. Students learn how to write formulas for compounds, balance equations and then solve algorithmic problems, and the experiments simply involve applying their mathematical solutions to a real chemical reaction. Rarely are students introduced to the humanistic side of chemistry and informed about how society has transformed science over the years, simply due to the belief system at the time. The use of the Interactive Vignettes will show how society was slow to accept new scientific ideas and stalled the progress of chemistry at certain times.

Lühl (1992) studied the use of an historical approach to teaching the atomic theory and found that students became familiar with varying approaches to scientific enquiry. Students also learned to appreciate the philosophies behind each approach and identified the role society played in some of them. A study by Allchin, titled "Rekindling Phlogiston: From Classroom Case Study to Interdisciplinary Relationships" (1997), introduced the concepts of metals and oxidation through a hands-on historical account of the phlogiston theory. Allchin found that this approach made the students more accepting of previous ideas and less likely to view "current ideas as self-evident" (p. 486). He argues that history should not be the only consideration when developing a conceptual sequence for instruction, as the students in his study were able to reach the same place as the late phlogiston theorists even with knowledge of the existence of elements. A healthy injection of history can provide students with a sense of the movement, progress and continuous change inherent in science. Without exposure to this dynamic feeling of science, students are apt to regard the science they learn as a finished, unchanging product. Inclusion of history in the classroom places the nature of scientific discoveries in perspective, instead of presenting them as isolated, independent events involving great scientists (Kauffman, 1989; Sherratt, 1982; Brush, 1979).

3.2: Textbook Use in Science Education

Due to students' difficulties with the mole concept, much research has looked at various aspects involved in students' understanding of this concept. Research into the mole concept has focused on; textbook presentation of the concept, students' ability to solve problems, characteristics of successful problem solvers; student preconceptions, pedagogical style and instructional method, and educator's own conceptions (Cervellati, Montuschi, and Perugini, 1982; Furio, Azcona, and Guisasola, 2002; Gower et al., 1977; Lazonby, Morris and Waddington, 1985; Nelson, 1991; Stromdahl, Tulberg, and Lybeck, 1994; Tullberg, Stromdahl, and Lybeck, 1994; Staver & Lumpe, 1993, 1995). The following section will look at some results obtained through the analysis of various chemistry textbooks, and textbooks in general, and their impact on student's overall understanding of the mole concept.

In the classroom the textbook is a main source of information for both teacher and student, especially in the area of science. According to a 2001 survey, textbooks are used in 96% of science classes from grades 9 – 12, and 60% of teachers said the textbook had a "major influence" on their teaching (National Science Teachers Association). It was found that a majority of science teachers (90%) use a textbook in their classes 90% of the time, making it the prime source of information for both teacher and student (Baker, 1991; Staver and Lumpe, 1993; Yager, 1983). This is not surprising since most science teachers are the "product of textbook-centered teaching" themselves (Stinner, 1996; Yager, 1983). In 2001, a series of research studies into the effectiveness and quality of high school science textbooks concluded that most textbooks fail to provide students with what they need to learn science (American Association for the Advancement of Science). It was found, for example, that textbooks often contained too many poorly developed topics, and recommend that educators reduce the number of topics covered in order to ensure more meaningful and long-lasting learning of the important ideas.

Unfortunately, science teachers often determine what is taught, and the methodology by which to teach it, by the textbooks used in their class (Shymansky & Kyle, 1992; Wheatley, 1991; Yager, 1983, 1992; Yore, 1991). The textbook may guide the teacher as to the specific order in which a unit of study is taught, and may determine which areas an educator emphasizes or omits during instruction, due to the way they are presented in the text. A textbook may focus on algorithmic problem solving and might contain certain types of challenge and review questions that focus on specific areas of problem solving, neglecting a more thorough understanding of the concepts. A textbook may even establish the types of activities and interactions performed in the classroom. When a textbook has been assigned for a course, teachers are more apt to use it as a central source of information, especially when the teacher has inadequate time to prepare a course, or has a limited background in the subject matter.

Despite research into students' conceptual understanding in science education that has shown the need for further developing students' understanding of fundamental concepts, science textbooks have been found to overemphasize the effectiveness of mathematical formulation and the memorization of scientific fact, giving students a false sense of subject mastery (Yager,1983; Hewitt, 1990; von Bayer, 1990; Stinner, 1992). Several studies have indicated that there is an alarming proportion of students who can successfully solve algorithmic problems of the textbook type, but when asked to explain certain aspects of the science concept their misunderstandings become evident (Gabel and Sherwood, 1984; Nurrenbern and Pickering, 1987; Pickering, 1990; Sawrey, 1990; Nakhleh, 1993; Zoller, Lubezky, Nakleh, and Tessier, 1995; Niaz, 2005).

Niaz (1998) claims that most textbooks resort to the testing of predictions through observation and controlled experiment, meanwhile ignoring the "mathematical, philosophical, and metaphysical issues that could make chemistry more interesting". The majority of science textbooks place emphasis on the objective facts of a current theory, but fail to mention how this scientific theory arose, and, especially the context surrounding it. In his book, *The Teaching of Science*, J. J. Schwab (1962), claimed that chemistry is usually taught as a "rhetoric of conclusions in which the current and temporary construction of scientific knowledge are conveyed as empirical, literal, and irrevocable truths" (p. 24). Even decades later, textbooks tend to accentuate experiments and their conclusions, ignoring the theoretical ideas that led scientists to experiment in the first place (Niaz, 2005). Students are not made aware of the dynamic progress of science and the many competing and conflicting frameworks of understanding that existed before evidence arose and a way of thinking was adopted (Niaz, 1998). According to Chaippetta, Sethna and Fillman (1991), chemistry textbooks "deemphasize science as a way of thinking" (p. 949). They argue that textbook authors neglect to mention the historical development of certain concepts, the importance of where scientists' ideas and experiments originated, "cause and effect, evidence and proof, and self-examination of one's thinking in the pursuit of knowledge" (Chaippetta, Sethna & Fillman, 1991). Most textbooks and/or teachers do not make it clear to students that science is a human enterprise. This is especially true for instruction on the mole concept and students are often left with many questions about its origin (Kieffer, 1962).

3.3: Definition of the Mole

Before looking at the results of research into chemistry textbooks' presentation of the mole concept, it is important to understand the origin and the accepted definition of the unit called the mole. This will allow us to later compare the various definitions and meanings of the mole found in different sources available to the educator and the student.

In Paris in 1960, the name "Systeme Internationale (SI)" was established at the General Conference on Weights and Measures to ensure worldwide uniformity of measurements as recognized by the scientific community. Currently there are seven base units of measurement that are used internationally for scientific purposes. In chemistry the units of "gram-atom" and "gram-molecule" were used to specify amounts of particular elements and compounds. Following recommendations from the International Union of Pure and Applied Physics (IUPAP), the International Union of Pure and Applied Chemistry (IUPAC), and the International Organization for Standardization (ISO), the International Committee for Weights and Measures (CIPM) developed a formal definition for a unit of amount of substance, the mole, which was officially adopted in 1971. The definition is:

1. The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12; symbol is "mol".
2. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified such particles.

Carbon-12 is used as the reference standard for the relative masses of elements on the modern periodic table. Incorporating the SI definition for a mole, one mole of carbon is exactly 12 g of carbon (its molar mass), setting up a relationship between one atom (12 amu) and one mole of carbon (12 g) (Staver and Lumpe, 1995). According to Staver and Lumpe (1995), the key to understanding the mole concept comes with the realization that "a mole of any substance always contains the same number of entities, and that the amount of substance is proportional to the number of entities of that substance." The amount of entities can be determined experimentally and has been found to be equal to Avogadro's number, $\sim 6.022 \times 10^{23}$. It is important to note that Avogadro's number does not define the mole, but is its experimentally determined value (Staver and Lumpe, 1995). The mole enables scientists to macroscopically study chemical reactions that are taking place at an atomic level (microscopic). In other words, chemists can observe and measure amounts (masses and/or volumes) of reactants and products in a chemical reaction and, using Avogadro's number and the mole, can then calculate how many atoms or molecules were actually involved in the reaction.

3.4: Textbooks and the Mole Concept

The mole concept in chemistry acts as a unifying concept among several chemical quantities (mass, volume, number of particles) in stoichiometry. It also serves as a tool for allowing students to work between the microscopic representation (atoms and molecules) and the macroscopic representation of reactions (mass and volume). Since the mole concept can be presented in various ways, it is important to understand how chemistry textbooks approach its introduction. In addition, with research indicating that a majority of students and educators do not associate the mole as the SI unit for an "amount of substance", as it is intended, it would help to ascertain how textbooks define the mole.

Analysis of over one hundred chemistry textbooks, written between 1891 and 1970, found a positive correlation between the use of Avogadro's number and the concept of the mole (Hawthorne, 1973). In another study, Staver and Lumpe (1993) analyzed twenty-nine chemistry textbooks, at both the high school and introductory college level, to determine how the concept of the mole was introduced and defined. They were specifically looking at: what concepts regarding the atom were presented beforehand; what definition of the mole was given; the context in which it was presented; and, if Avogadro's number was presented as an experimentally determined value. Among their conclusions they found two prevalent ways in which the mole was defined; first, as Avogadro's number of entities, and, second, in terms of carbon-12 (the SI definition). Since students must be able to ascertain the relationship between Avogadro's number and the mole in the first definition, and compare a mass to the carbon-12 isotope in the second, both ways of defining a mole require a high level of thought (Furio et al., 2002).

Another study by Cervellati et al, analyzing thirteen chemistry textbooks, found that only three of them defined the mole correctly, according to the current SI definition, although all thirteen textbooks made reference to Avogadro's number (Staver and Lumpe, 1993; Azcona, 1997; and Furio et al., 1999) researched the instruction of the "amount of substance" and the "mole" and found that most chemistry textbooks provide incorrect meanings of these concepts when introducing them, again relating them instead to chemical mass and/or number of elementary entities. They also found these incorrect interpretations within scientific and educational journals, as did Stromdahl (1994). Therefore, Azcona (1997), Furio et al (1999), and Stromdahl (1994) believe educators may develop incorrect ideas of the concept of the mole and transmit them to their students.

The majority of the textbooks studied used analogies to known quantities like a dozen (12 entities) and a dollar (100 cents) when describing a mole, and simply referred to the mole as a way to count extremely small particles (Hawthorne, 1973; Staver and Lumpe, 1993). The use of analogies to help illustrate a new concept, such as the mole, has been found to be useful, and many different analogies specific to concepts related to, and including the mole concept, have been documented (Alexander, M. D., Ewing, G. J., and Abbot, F. T., 1984; Fulkrod, 1981; Felty, 1985; Fortman, 1994; Henson & Stumbles, 1979; Myers, 1989; De Berg, 1986). As mentioned previously, textbooks often take advantage of analogies when explain the mole concept and Avogadro's number. Poskozim, Wazorick, Tiempetpalsal, and Poszokim (1986) reviewed textbook analogies on this topic and found that most deal with calculating either the time involved in counting Avogadro's number of items, or determining what volume or surface would be occupied by such an amount. According to Friedel, Gabel, and Samuel (1990), the use and choice of certain analogies must follow certain guidelines if they are to be a successful learning tool. They suggest that the chosen analogy must: be easily understood; have a clear relationship to the chemical concept it is being compared to; have transferable solutions to the chemistry problem; and, be used over an extended period of time.

Another study of content analysis of chemistry textbooks indicated that the mole concept is poorly presented from its introduction and that textbooks take a variety of approaches to reach the main mole concept (De Berg, 1986). Typically, though, the mole is utilized simply as a tool for stoichiometric calculations, serving as a bridge between the quantities of mass, volume and number of particles.

Aside from defining the mole as an "amount of substance", students should be made aware of how a mole was determined to be equal to Avogadro's number. In the analysis by Staver and Lumpe (1993), it was found that most textbooks referred to the fact that Avogadro's number was experimentally determined, in the majority of textbooks that included Avogadro's number, but the specific experiments are seldom, if ever, mentioned. The same is true for the study by Cervellati et al., (Staver & Lumpe, 1993). There was no mention of the experimental aspect of Avogadro's number or any discussion of the history of the mole in any of the textbooks analyzed. Instead, students are left to accept Avogadro's number as presented and to memorize Avogadro's number for use as a tool in stoichiometric calculations. Any questions about the origin of Avogadro's number are left for the educator to answer and explain.

3.5: Educators' Understanding of the Mole Concept

Stromdahl et al. (1994), in a study on educators' concept of mole, found that the majority (61%) of educators defined a mole as Avogadro's number. A smaller percentage (25%) of educators linked the mole to mass, and only 11% stated that the mole was a unit for an "amount of substance" as is stated in the SI definition. The teachers either obtained their incorrect and incomplete knowledge on the mole concept from classroom textbooks, or from prior experience with the concept. Therefore, students' misunderstandings with the mole concept are most likely due to their educator's own difficulties with it, which differ from the scientific community's SI definition of the concept (Stromdahl et al, 1994). According to Tullberg et al. (1994), teachers need to be made aware of their own understandings of the mole concept, especially how they relate to the current SI definition, if they want to ensure student understanding of this concept.

Azcona (1997), and Furio et al. (1999), in their research into instruction of the mole concept, found that "the usual presentation of the mole concept is arbitrary, since it does not specify which is the problem that the introduction of the mole concept attempts to solve" (Furio et al., 2002). Teachers do not follow the evolution of the mole concept from its inception in the "equivalent weight framework" to the atomic framework where it exists today. Not surprisingly, Azcona (1997) and Furio et al. (1999), have found that teachers are unknowledgeable about the history of the mole concept, as it relates to Wilhelm Ostwald, or how it came to be used as a unit for an "amount of substance" (Furio et al., 2002). The latter half of this problem could be related to the late timing of the use of the mole as an official SI unit (1971). However, the fact that textbooks spanning several decades contain irregularities in information and the definition of the mole indicates that educators have been misguided for years and hold different views of the mole concept than what was intended by the scientific community (Furio et al., 2002). In order to develop educators' and teachers' conceptions of the mole, making them more in tune to the intended SI definition, chemistry curricula and support documents (including textbooks) would need to be altered. This would provide an opportunity to introduce sound history of science.

CHAPTER 4

METHODOLOGY

4.1: Overview of Method

The historical approach used in this study was more than anecdotal renditions of a story (vignettes). A vignette serves as a way to develop student interest, but by itself is not sufficient to increase student understanding. Therefore, my advisor and I developed a tentative working definition for what we now refer to as an **interactive vignette (IV)**. An historical approach using interactive vignettes (IVs) provides an opportunity for conceptual development and practical application. Depending on the topic, the interactive vignettes might sometimes be just an informative story, but in most cases venture beyond story telling to include qualitative and quantitative aspects of a topic, fostering both physical and cognitive engagement. These interactive vignettes include an historical story as well as a demonstration and/or activity that provide relevant and detailed information related to stoichiometry and the mole concept. In short, the interactive vignette required student interaction and participation.

These interactive vignettes; introduced students to opposing theories and experimental findings that led to Avogadro's hypothesis; exposed them to evidence for the existence of atoms, and, outlined many ways Avogadro's number was determined experimentally. Students saw how the mole developed over time into a standard unit of measurement. The discussion, interpretation, and analysis of various theories that existed historically had students working on more complex levels within Bloom's Taxonomy, which classifies types of questions found on tests into six categories of knowledge, based on the level of abstraction involved. Within this taxonomy the simple recall of information is found on the lowest level, whereas comparing and discriminating between ideas is found on the highest level. The ten interactive vignettes span over one hundred years of science, starting in 1808 with Dalton's atomic theory and ending in 1926 with Jean Perrin's Nobel Prize for his work on atoms. Students were not assessed on the specific history injected into their lessons, since the history was not an outcome in the curriculum, but hopefully gained an appreciation of the dynamic nature of science and the lengthy development of the mole concept.

Once permission to carry out the study was granted (appendix A.), a comparative study between two chemistry 30S (grade 11) classes was undertaken. The teacher instructing both the control and intervention classes had four years of experience teaching chemistry, and was teaching both classes in the same semester. I had no reservations about this teacher conducting the study, as he is very dedicated to providing his students an innovative and enriched learning environment. He typically has several conceptually appropriate demonstrations for his students each week, and has students completing hands-on activities and laboratories on a regular basis. Prior to the unit on stoichiometry and the mole, both grade 11 Chemistry classes were exposed to a unit on physical properties and changes. This unit had the students completing at least five experiments (i.e. physical vs. chemical properties, physical vs. chemical changes, melting point vs. freezing point, boiling point vs. molecular mass, and vapor pressure) within their first four weeks of classes, not to mention several smaller-scale activities and demonstrations. This unit was followed by several laboratories on chemical reactions, including "indicators of chemical reactions" and "types of chemical reactions" before the concept of the mole was introduced. The teacher involved in the study also utilizes the three levels of representation where possible. He often represents substances symbolically and microscopically when providing students information and will get them to draw their own representations as well, when solving problems.

Students were introduced and recruited to the study by another teacher in the school and their involvement was entirely voluntary and anonymous. Interested students and their parents/guardians signed assent/consent forms (Appendix B & C), allowing me to keep copies of the chemistry tests for the unit involved and also their results on the chemistry attitude tests.

Participants' attitude towards chemistry was measured before and after the historical intervention using a modified Test of Science Related Attitudes (TOSRA). This test is described in more detail in section 4.3: Measuring Instruments. After all students completed the test of chemistry related attitudes (TOCRA) pre-test, both classes followed the prescribed grade 11 Chemistry transitional curriculum (1998) for the unit on the mole and stoichiometry, but the method of instruction was varied in one class. In the experimental class, the interactive vignettes were presented daily for a period of ten consecutive classes. These interactive vignettes were short, ten to fifteen minutes each, and did not involve a discernable difference in time between the two classes.

The teacher conducting the class has no formal background in the history of science, but is enthusiastic about the topic and has sought to further his knowledge in this area. He received all the interactive vignettes from me. I advised him as to where the stories should be placed within the curriculum, helped him with his understanding of the history presented, and demonstrated all activities that were to be completed as well. All other classroom information delivered between the two classes was as similar as possible. The teacher and I met on an ongoing basis throughout the study to discuss any problems that arose. One possible issue might have been that of cross-contamination between the two classes involved in the study. To avoid this, we asked students in the intervention class not to discuss the historical story or activity performed with students from other classes, but we could not ensure that this was done.

After the unit on chemical equations, stoichiometry and the mole was completed, students took the TOCRA again. The class exposed to the interactive vignettes also answered an open-ended question assessing their opinion of the effectiveness of the interactive vignettes in increasing their interest in chemistry, and their understanding of the mole concept. Students' understanding was also tested in both classes using a chapter test that tested for conceptual understanding in the unit of chemical stoichiometry, as would have been done without the intervention. This test included several multiple-choice questions as well as a series of different long answer (open-ended) questions. Multiple-choice questions ranged from simple recall of information to analysis of information. The long answer questions had students solving algorithmic problems, interpreting visual diagrams of chemical reactions at the molecular level, and offering explanations for certain chemical phenomena. The test is described more in depth in section 4.3. After students completed the tests, all results were given to me anonymously for analysis.

Once data was collected I completed paired statistical t-tests on both the chapter and attitude tests. The methods for comparison and analysis are explained in more detail in Chapter 6. Analysis of their unit tests allowed me to identify which class had a better overall understanding of the mole concept and of stoichiometry in general. In particular, I focused on those questions that were related to the interactive vignettes. I also tried to identify differences between the two classes in terms of the types of problems with which they struggled. Increased conceptual understanding was evident if students answered some of the questions using higher levels of cognition, such as evidential arguments over simple recitation of information.

On the attitudes tests, I compared the pre- and post- tests for both classes and determined if the interactive vignettes had any effect on their interest in the class, as compared to the class taught without exposure to them. I expected the class exposed to history of science to have a richer understanding of the mole concept and, as well, have a better attitude towards chemistry.

4.2: Methodology of The Interactive Vignettes and Related Background Information

The specific interactive vignettes that were presented introduced some of the key ideas in the development of the mole concept. There were ten in total, and they started at an appropriate place in the curriculum, and continued for ten consecutive classes. The interactive vignettes, as presented to the teacher, can be found in appendix D. Some of the information within the interactive vignettes was placed on overheads, and each interactive vignette was introduced with a picture of the scientist(s) being discussed that day. A brief overview of the ten interactive vignettes are:

1. John Dalton's Atomic Theory (1808):

Students were re-introduced to John Dalton's atomic theory and the background that led to the four postulates of his atomic theory. In this story, students heard and saw how Dalton viewed atoms and determined his relative atomic weights and chemical formulae despite having poor experimental results. Students performed a quick activity that demonstrated Dalton's law of definite proportions.

2. The Clash Between Dalton and Gay-Lussac Resulting in Avogadro's Hypothesis (~1811):

The second interactive vignette presented the conflicting theories of John Dalton and Joseph Louis Gay-Lussac, and introduced the students to Amadeo Avogadro. Students were presented with a thought experiment involving observed volumes of gases found in a reaction between two gases. During discussion of their hypotheses, the two conflicting ideas of Dalton and Gay-Lussac that were in existence at the time were presented.

Finally the students were shown how Avogadro reconciled the two ideas (atoms and law of combining volumes) by making the distinction between the ultimate chemical particle of an element, the "atom", and the ultimate physical particle of a substance, which Avogadro called the "molecule". At this point, students heard Avogadro's Hypothesis, which states that equal volumes of gases at equal temperatures and pressures contain equal number of particles.

3. Berzelius' Scientific Notation (~1813):

The third interactive vignette was a brief account of how Jacob Berzelius, a firm believer in Dalton's Atomic Theory, introduced the modern system of chemical notation and helped establish some consistency in the world of chemistry. First, students were shown drawings of Dalton's circular symbols for atoms so that they could compare them to the way Berzelius represented them, using the initial or first two letters of the element's name (i.e. H = 1 atom of hydrogen, Zn = 1 atom of zinc). Students also saw how this was eventually applied to compounds as well: HO = water, NH = ammonia, CO = carbonic oxide and CO_2 = carbonic acid (Jaffe, 1976). By this point students picked up on the incorrectness of these formulae and questioned the ideas being presented.

4. Brownian Motion (~1828):

The fourth interactive vignette described one of the first observations in support of atoms by Robert Brown, a London doctor and botanist. Students heard how, in 1828, Brown observed that plant pollen particles, suspended in water, seem to be in a constant state of motion when observed under the microscope, and that the cause of this movement was doubtful for a long period of time (Jaffe, 1976). Students then observed Brownian motion on video, through a microscope, or through a computer simulation. Several historical theories that explained this motion were then presented to the class, one such explanation being motion due to thermal convection currents.

5. Faraday's Laws of Electrolysis (~ 1834):

The fifth interactive vignette outlined Michael Faraday's findings, one of the next major steps in determining the elusive Avogadro's number. To allow students to gain a better understanding of Faraday's work on electrolysis, some electrolytic cells were set up for students to observe the production of an element at one of the electrodes. Faraday's work on electrolysis was explained and his determination that chemical compounds could be separated into their elemental components by passing an electric current through them was discussed. Students heard how Faraday was able to measure the total charge required to deposit the mass of an element, in grams, equal to its atomic mass, which gave him a way to determine Avogadro's number of atoms, but was unsuccessful at this task. However, he gave still more credibility to the existence of atoms.

6. Cannizzaro's Quest (~1860):

The sixth important interactive vignette told was that of young scientist Stanislao Cannizzaro who, after Avogadro's death, tried to convince the scientific world of the importance and truth of Avogadro's hypothesis. Students heard information from Cannizzaro's "Sketch of a Course of Chemical Philosophy" that displayed his strong belief in the existence of atoms and Avogadro's hypothesis. Through this story, science was presented as a human endeavor, and students heard how one man's viewpoint and persistence changed the face of science.

7. Loschmidt's Number (1865):

This interactive vignette was introduced using a soap bubble demonstration that showed students how the approximate size of a molecule could be determined. Students were given an explanation of how a soap bubble, made by placing a wire loop in a container of dish soap, shows many colours due to the interference of light when placed in front of a light bulb. Due to the action of gravity on the bubble, producing a wedge, there is a place where the film is the thinnest, much shorter than the wavelength of visible light ($<10^{-7}$m). At this spot, there will be no visible reflection and the bubble will look black. The bubble is only about $10^{-7} - 10^{-8}$ m thick at this spot and will soon pop. Knowing the thickness of the film, students estimated how many molecules could exist in that distance and calculate a rough estimate of the size of one molecule.

After this demonstration, students were provided with an interactive vignette that described of one of the first estimates of Avogadro's number as done by Josef Loschmidt in 1865. They heard how Loschmidt was able to achieve a good value for the diameter of a molecule by using the kinetic theory of gases, which students had been exposed to previously, and were surprised that two million hydrogen atoms arranged in a row would take up one millimeter of space.

8. Einstein the Chemist (1905):

Most students do not know that Einstein enjoyed chemistry and made some very important statements regarding the existence of atoms. Therefore, the eighth interactive vignette tells a story that celebrates Albert Einstein, the chemist. Students heard how, in 1905, Einstein described a method by which Avogadro's number could be determined by studying Brownian motion. Students were exposed to Einstein's idea of "random walk" by the use of a computer simulation (Fowler, M. "Einstein and Brownian motion: simulation of random walk).

The final two interactive vignettes introduced the physicist Jean Perrin and his two methods for experimentally determining the value of Avogadro's number, which earned him the Nobel Prize in 1926.

9. Jean Perrin and Brownian Motion:

This interactive vignette showed students the method by which Perrin, guided by Einstein's work, studied Brownian motion and came to a value for Avogadro's number. For this segment, students used a video on Brownian motion, prepared by students at the University of Winnipeg, to make similar calculations to Perrin's, and actually determine Avogadro's number. To complete this vignette, students heard how Perrin was awarded the Nobel Prize in Physics for his work and how he finally ended any skepticism surrounding the existence of atoms.

10. Jean Perrin and the Vertical Distribution of Particles in Emulsions:

The final interactive vignette explained Perrin's examination of gamboge emulsions that led him to values for Avogadro's number. The teacher took advantage of the fact that students had already learned that air pressure is greatest at sea level, and that it decreases as altitude increases. Relating this idea to an emulsion, the teacher explained how, once the opposing effects of Brownian motion and gravity reach equilibrium, equal height differences in the liquid corresponds to equal differences in the numbers of particles. This led nicely into a story describing Perrin's experiment. The interactive vignette described how Perrin prepared many emulsions (varying the types of particles, particle size, solution viscosity, and solution temperature) and counted the grains at various heights in order to determine the ratios of grains at two fixed heights, yet found that the value for Avogadro's number remained relatively constant between 65×10^{22} and 72×10^{22}.

In summary, the teacher conducting the classes mentioned some of the major independent methods by which Avogadro's number was determined, and explained that extremely precise values can now be obtained using x-ray crystallography. Students became aware of how many different domains in science are affected by Avogadro's number and the mole. At this stage in the study students were also asked to re-examine Dalton's atomic theory to see how well it stood the test of time.

4.3: Measuring Instruments

This research study involved collecting data of two types. First, students' attitudes towards chemistry was collected using a Likert-type questionnaire at the beginning and end of the unit on stoichiometry. Students' understanding of the concept of the mole, as related to the interactive vignettes, was determined using appropriate portions of a chapter test that was administered at the completion of the unit. This unit test included information taught outside of the ten-day period during which the interactive vignettes were presented to the experimental class. What follows is a more detailed discussion of each of the instruments used.

i) Test of Chemistry Related Attitudes:

A modified Test of Science Related Attitudes (TOSRA), originally developed by Dr. Barry Fraser (1978), director of the Science and Mathematics Education Center in Perth, Australia, was used to measure student attitudes towards various aspects of chemistry. This instrument is a Likert-type questionnaire, consisting of statements to which the subjects respond on a scale from strongly disagree to strongly agree, usually identified with the numbers one through five. This test was administered to both the control class and the experimental (IV) class at the beginning and end of the unit on stoichiometry and the mole. Smist, Archambault, & Owen (1994), subjected the TOSRA to a validation study and modified the original TOSRA to include only six subscales that measure science related attitudes. These scales include attitudes towards; the social importance of science, preference for experimentation, openness to new ideas, science classes, science leisure, and science careers. The attitudes test used for my research was shortened, and consisted of 33 questions from the TOSRA (see appendix E). To make the test more specific to student's chemistry class, the word "science" was replaced with "chemistry" throughout the document, making it a Test of Chemistry Related Attitudes (TOCRA). Although the TOSRA was not specifically developed for use in chemistry classes, it is likely to have good transferability due to the general type of questions asked and the similarity in the subject areas of science and chemistry. Despite the fact that my research was only interested in the effect of the use of interactive vignettes on attitude 3 (student's openness to new ideas), and attitude 4 (student's attitude towards chemistry class), the other attitudes were included as well. Appendix F outlines which questions match each attitude.

In order to determine any difference inherent in the pretest results between the control class and the experimental class, a statistical t-test was performed. The t-test assesses whether the means of two groups are statistically different from each other, taking into consideration the variability of the data. The t-test compared the mean for the pretest scores of the control group for one attitude to the mean of the pretest scores for the experimental group on the same attitude. This was repeated for each of the six attitudes.

The class exposed to the interactive vignettes was also asked an open-ended question at the end of their final attitudes test (see appendix G) and responses were categorized for analysis. This purpose of this question was to gain a more complete picture of the usefulness of the interactive vignettes in both increasing interest and understanding of the mole concept.

ii) Chapter Test

The chapter test that was used to assess students on their unit of stoichiometry and the mole consisted of 24 multiple-choice questions and 11 long-answer questions. There were two versions of the test (A and B), but the only difference between them was the order of the questions. For the analysis of the effectiveness of the interactive vignettes, only those questions that related to the material discussed in interactive vignettes were tabulated and used. Some of the test questions were obtained from Krishnan and Howe's article (1994), "The Mole Concept: Developing an Instrument to Assess Conceptual Understanding".

This article describes how research into students' alternative frameworks in science has found that students' prior knowledge provides the scaffolding for the acquisition of new concepts. When students' conceptions are different than the agreed upon definition by the scientific community, they are referred to as "alternative frameworks" or "misconceptions". It has been shown that if students' prior knowledge contains misconceptions, they have more difficulty acquiring new knowledge, because meaningful connections to previous material are not easily formed. Educational research has also indicated that many educators are unaware of students' misconceptions, and, as a result, do not provide information that will enable student learning. The determination of students' misconceptions is usually a lengthy process involving student interviews, but a few pen and pencil diagnostic tests have been developed in specific learning areas. Krishnan and Howe (1994) developed such a test to assess students' conceptions on the mole concept in chemistry. To develop their test, the mole concept was defined in statements and then validated for scientific accuracy. Next the statements were redefined as learning objectives for the mole concept. Then, experimentally determined misconceptions on the mole concept were compiled for use on the test. Finally, test items were developed using the identified list of misconceptions as distracters for certain questions. Four types of questions were used to best cover all the learning outcomes; simple multiple-choice questions, two tier true-false questions, two-tier multiple-choice questions and open-ended mathematical problems.

Of the 24 multiple choice questions on the chapter test, seven relate to the interactive vignettes and were used for analysis of the test data. Multiple-choice responses were evaluated and results for the control group and experimental group were compared using paired statistical t-tests. Further analysis involved a comparison of the alternative responses chosen by each class, if they answered incorrectly.

The long answer portion of the test consisted of eleven questions. These questions required students to; write and balance chemical equations, complete one-step calculations of mass, moles, number of particles, or volume, complete multiple-step stoichiometric problems for chemical reactions, convert from either mass or volume of a reactant to mass or volume of product (considering limiting factors), and to a interpret pictorial representation of the products of a chemical reaction. Since stoichiometric calculations were not a part of the interactive vignettes, only those questions that required students to use their knowledge of Avogadro's number, relative atomic mass, and the mole were used for analysis, as were the molecular level representation of the products of a chemical reaction. See appendix H for a copy of one version of the test used.

Students' total marks on the long answer portion of the unit test were determined and a comparison was made between the control group and the experimental group using paired t-tests. Long answer responses were also looked at individually, comparing students' methods of calculations rather than just their final answers. Therefore, any individual steps or processes that may have caused difficulty in answering the question could be ascertained.

CHAPTER 5

ANALYSIS OF RESULTS

The analysis of the results will be divided into several sections. First, the two groups involved in the study will be compared in terms of gender make-up and performance in chemistry. This will be followed by a discussion of the purpose of each interactive vignette and its relationship to the grade 11 Chemistry curriculum. Then the results of the pre and post attitudes tests for both groups (control and experimental) will be presented and discussed. Student responses to the open-ended question found on the final attitude test of the experimental group, will follow. In order to assess if there was any change to students' understanding of the mole concept, the analysis of the chapter tests written at the end of the unit will then be presented, separated into multiple choice and long answer. Finally, a summary of all results of the research study will conclude this chapter.

5.1: Overview of the Research Groups

The two classes chosen for the research study were very similar in composition, both in gender and ability. Each class had 26 students, and all but one from the control class agreed to participate in the study. The control class consisted of 14 boys and 12 girls, whereas the experimental class was comprised of 11 boys and 15 girls. The control class was scheduled for chemistry at 8:30 in the morning, whereas the experimental group met for their chemistry class at 2:20 p.m. Both classes were seventy minutes in duration, on a daily basis. Prior to the unit of study on the mole and stoichiometry, the control and experimental groups had very similar chemistry averages, 78.5% and 77.9% respectively. Due to student absences on test days, 25 out of 26 students in the control group wrote both the TOCRA and the unit test. In the experimental group (those exposed to the interactive vignettes) 24 out of 26 students wrote the attitudes tests, and all but one student wrote the unit test. Therefore, both classes had 25 students who wrote the final summative unit test on the mole and stoichiometry.

5.2: Overview of Curriculum and Interactive Vignettes

The prescribed outcomes in the grade 11 Chemistry curriculum for this unit emphasize calculations and problem solving. Only one outcome requires that students to be able to describe the concept of the mole and its importance to measurement in chemistry. After this, students are expected to be able to calculate the volume and molar volume of gases based on their densities, and solve a variety of problems using the inter-conversion between mass, volume, number of particles and moles. Ten out of thirteen outcomes in this section specifically state that students either calculate or solve certain types of problems, leading to a very algorithmic approach to Avogadro's number and the mole concept.

The interactive vignettes tended to focus on the main theories and activities that led to the determination of Avogadro's number and, since the high school chemistry curriculum does not cover the history of the concept of the mole, students were not tested on the specifics of history on their final unit test. However, several of the interactive vignettes involved two underlying concepts that are a vital part of Avogadro's number and the mole; atoms and molecules. Several of the interactive vignettes also presented information using the different levels of representation in chemistry, in order to facilitate student understanding of the concepts presented. Other interactive vignettes served to show how human nature and society affect scientific development. Students heard how scientific theories often progress slowly, amidst conflict and setbacks, and involve communication and cooperation between scientists.

The first interactive vignette introduced John Dalton and served to present Dalton's intuitive belief in atoms that led to his Atomic Theory, Law of Definite Proportions, and table of atomic weights. The purpose of the vignette activity was to give students items analogous to atoms (rings and fasteners), where they could see how atoms of one element are the same (all rings looked the same), but atoms of a different element would be different (rings versus fasteners). The rings and fasteners served to represent the submicroscopic level of chemistry, and were represented symbolically by Fs and R. By comparing the two different substances, students were also able to see how relative atomic masses were determined. Using this analogy of fasteners and rings for atoms, students were able to see the difference between an atom and molecule, since they combined individual atoms to form molecules of a new compound. Students could also see how compounds always combine in set ratios, which results in molecules of the same compound having the same mass. Also important in this first vignette was Dalton's simplistic approach to determining relative atomic masses of elements, and the composition of simple compounds. Although Dalton's Atomic theory contained many incorrect postulates, and some of his elements and compounds were given incorrect relative atomic masses, his ideas still advanced the progress of science and studies of chemical composition.

The second interactive vignette served to demonstrate how observations could be explained using different theories. Students were introduced to Avogadro's hypothesis, and saw a pictorial submicroscopic representation of individual atoms, diatomic molecules, and compounds. Students were introduced to the idea of a common quantity of particles, known as Avogadro's number, and were shown how a chemical equation relates the amounts of gas, either in terms of volume or number or particles. The thought experiment brought together macroscopic observations and submicroscopic representations of substances. These first two interactive vignettes also showed the students how scientists sometimes depended on their own beliefs to guide them when evidence is lacking, and how the scientific community is not always in support of new ideas.

The next several interactive vignettes which dealt with Berzelius and chemical notation, Brown and Brownian Motion, Faraday and electrolysis, and Cannizzaro's personal quest, showed some important developments in the determination of Avogadro's number. By involving students in these stories, students became aware of the sometimes, tentative nature of scientific discoveries and the lengthy time frame involved in gathering evidence, collaborating, communicating findings, and convincing the scientific community of their importance. Some of these interactive vignettes also demonstrated various aspects of the three levels of representation. For example, the vignette on Berzelius reintroduced students to chemical symbols and the notion of subscripts to identify the number of atoms of an element. These were compared to Dalton's atomic symbols, which consisted of patterned circles that portrayed the type and quantity of atoms he believed existed. The interactive vignettes describing Brownian motion and Faraday's electrolysis focused on the macroscopic observations that were available, but did not represent the observations on a submicroscopic level.

The final series of interactive vignettes were used to convey how molecule size and Avogadro's number were actually determined, despite the still tentative nature of atoms. The final two interactive vignettes gave Avogadro's number a value and students saw how it was determined experimentally, and how even they could determine its value. These IVs focused on macroscopic observations and the symbolic representation of the information, such as the colours on the bubble film relating to particle diameter, the random walk of particles or the position of suspensions in a particle both relating to Avogadro's number. Although these interactive vignettes do not help students with the stoichiometric problem-solving they will face in chemistry, they were important, as they provided students with the necessary background on which to develop the concept of the mole, instead of simply having Avogadro's number as a value to memorize and use.

5.3: Test of Chemistry Related Attitudes Results

In order to analyze the attitudes test, the attitude statements were first grouped according to which attitude they represented. The mean score and standard deviation were then calculated for both the pre- and post-test questionnaires, for both the control and experimental group. It should be noted that the results for students who did not complete the test correctly (e.g. placing more than one answer per statement) were not used in the calculations. It is also important to note that, for the purpose of uniformity, scores were reversed, due to the wording of the underlying question. In the tally, a higher score was always attributed to a more positive attitude towards chemistry.

Statistical t-tests were used to determine any difference inherent in the pretest results between the control class and the experimental class. The t-tests compared the mean for the pretest scores of the control group for one attitude to the mean of the pretest scores for the experimental group on the same attitude. This was repeated for each of the six attitudes and a summary of the results is available in appendix I. An indication that the results obtained are significant, and would not likely occur through chance, is evident when the p-value for the t-test is <0.05. The t-test results obtained all had $p>0.05$, showing no significant differences in the means for any of the six individual attitudes or for all attitudes combined, indicating that the two classes were quite similar at the start of the research study.

The t-tests comparing the total post-attitudes of the two groups showed no overall difference (see appendix I). However, analysis of individual attitudes showed two statistically significant increases for the experimental group. The t-test result for attitude 5 (students' attitude towards science leisure) showed a p value of 0.005 at a 99% confidence level. This attitude looks at the student's interest in joining a chemistry club, watching a chemistry-based TV show, or reading a chemistry book for leisure. Students in both classes had been exposed to a lot of practical work in chemistry prior to the research study, so this increase in student attitude is most likely not due simply to the presence of an activity, but a combination of the history of science with the related activity. Also, not all of the activities were typical chemistry activities, where students mass and mix substances and observe results. In these interactive vignettes students made large bubbles in order to see the light interference and used microscopes to see Brownian motion in a sample of carbon in water. These different types of activities introduced students to some alternative activities of chemists, and demonstrate that chemistry doesn't always consist of theory, algorithmic manipulation and confirmation experiments.

The result for attitude 6 (attitude toward chemistry careers) showed a smaller increase, $p = 0.05$ at a confidence level of 90%. Items in this subscale assessed whether or not students considered a future career in chemistry, if they thought such a career would be dull and boring, or if they would like to make chemical discoveries. The interactive vignettes described many different chemists' work, showing quite a variation in possible areas of study, and actively involved the students in some of the chemists work. Once again, students find that chemistry is not necessarily what they see occurring in their chemistry classroom.

These results obtained for attitudes 5 and 6 indicate that the interactive vignettes were able to display a side of chemistry not often present in chemistry classes, which had a positive effect on the students in the experimental group. T-test analysis of the individual attitude items for attitudes 5 and 6 showed a significant difference in two particular statements; students' interest in belonging to a chemistry club ($p=0.015$, 95% CL); and, doing chemistry experiments at home ($p=0.0081$. 99% CL) (see appendix J and K). Both these activities demonstrate student interest in pursuing chemistry outside of the classroom. This is quite remarkable, considering students' were only introduced to ten short interactive vignettes. If more interactive vignettes were dispersed throughout their semester, it is possible that even greater extra-curricular interest in chemistry would be generated.

T-tests comparing pre- and post-test data for both the control and experimental groups were also performed. The results for the control group indicated that there were no differences in the means for any of the six attitudes, at confidence levels of 90% and up (see appendix L). This was expected, as the students were not exposed to any of the interactive vignettes in their chemistry class. Instead they continued with the regular curriculum and the activities related more to the concept of the mole and stoichiometry.

The t-tests comparing the pre- to post- test data for the experimental class also did not have any difference in means for attitudes 1, 2, 4, and 6. However, the t-test for attitude 3 indicated that the means were different at a confidence level of 95% (but not at 99%) (see appendix M). Attitude 3 tested for students' openness to new ideas. These results imply that the interactive vignettes had some affect on students' willingness to listen to new ideas in chemistry. The interactive vignettes exposed the students to some earlier conflicting theories in chemistry and explained how new theories were developed over lengthy periods of time, often with much opposition. After being presented with alternative theories to experimental results, and seeing how some resolution was obtained, students might be more apt to question what they are told and observe in chemistry class.

For attitude 5, students' attitude toward chemistry for leisure, the means were different at a confidence level of 90%, but not at 95%. As mentioned previously, this subscale measures student interest in joining a chemistry club or reading or watching chemistry-related information. The interactive vignettes were successful in making chemistry interesting enough to want to pursue outside the classroom.

The interactive vignettes showed no significant changes to Attitude 4, students' attitude toward chemistry class. I find this unfortunate, but believe the lack of change is due to the fact that the interactive vignettes were not tightly tied to the material the students were learning during the remainder of the class following the presentation of the interactive vignette, due to the nature of the curriculum. Some of the material presented to the students in the interactive vignettes (e.g. Dalton's Atomic Theory) had been introduced in senior 2 science, and other material (e.g. Gay Lussac's Law, Avogadro's Hypothesis, Einstein...) is not found at all in the curriculum for the course. The curriculum focuses on the definition of the mole and its use in stoichiometric problem solving. No time is provided for students to learn where the mole concept developed, nor how Avogadro's number was determined. Without seeing the connection between the interactive vignettes and the subsequent classroom activities and work, I can understand why student attitude toward their chemistry class would be unaffected.

5:4: Open-Ended Responses

In order to get an impression of the value of using interactive vignettes in chemistry, the students who were exposed to the ten interactive vignettes were asked an open-ended question at the end of their attitudes test. This question was as follows:

"In the space below, please give your opinion about the use of the interactive vignettes in teaching the history of the mole concept in chemistry. Please consider several factors, such as: how they affected your interest in the class and topic, their effectiveness in relaying concepts, how they affected your motivation to learn more, and, whether activity based or non-activity based would be better."

Three students chose not to write any comments, and a few answered in ways that did not correspond to the factors suggested, but the majority did describe how they felt the interactive vignettes affected them, both in interest and in learning about the mole concept. A complete summary of the responses is available in appendix N. Some of the responses were as follows:

Student 5: "It was interesting to hear how we came about our current knowledge, but it didn't affect my motivation. Non-activity based worked fine."

Student 8: " I felt that it didn't make a difference to me or benefit me in any way. I was interested in it but I didn't feel that it made that much of a difference."

Student 15: "It was interesting to hear about the scientists and history. But it did not really help me concentrate on the main idea. I thought that maybe the time spent studying the scientists could have been used to learn the basics and improve our test marks. Maybe after an understanding of the mole has been reached, we could study who made these discoveries."

Student 18: " I thought it was a good idea. The whole concept of the mole is difficult to grasp but knowing were it comes from and how long it took to discover it, it becomes easier to understand. It was fun to learn about all the different chemists that made a difference in chemistry and changed the way we look at chemistry."

Student 20: "Helped me to understand better about what we're learning (mole) and the demos were really interesting! (the microscope one and bubble one)

Of the 22 students that chose to respond to this question, 16 students (72%) said the interactive vignettes were interesting (see appendix O). Nine students (41%) specifically indicated that the interactive vignettes helped with some aspect of learning the mole concept in class. However, of the 22 students who wrote a response, six students (27%) mentioned that the interactive vignettes has no effect on their motivation in class, and only 7 (32%) indicated that they preferred the activity (interactive) based vignettes over 2 who said there was no preference between activity and non-activity based vignettes.

Overall, the majority of students indicated that the interactive vignettes were an interesting part of the class, and close to a third of the students indicated that they helped with the understanding of some aspect of the mole concept. In terms of motivation, close to one quarter of the class stated that interactive vignettes had little effect on their motivation in chemistry class. What was apparent, when analyzing the open-ended responses, was that many students did not put a lot of thought and effort into their answer. Only four students of twenty-two commented on all four factors they were asked to consider when discussing the value of the interactive vignettes. When writing their opinions of the interactive vignettes, ten students (45%) did not comment on their effectiveness in learning the mole concept, 12 (55%) didn't comment on their effect on motivation, and 13 (60%) didn't comment on whether they preferred activity or non-activity based vignettes.

5.5: Unit Test Results: Multiple Choice

After the unit on the mole and stoichiometry, the overall percentages for the control class and for the experimental class were 76.9% and 77.9% respectively. Comparing to the class averages prior to the unit of study, which were 79% and 78% respectively, there is only a small change. The control class average dropped 1.6 percentage points after the unit, whereas the class exposed to the interactive vignettes had no change to their overall grades. It is important to note that no pretest for students' understanding of the mole concept and stoichiometry was given, so we do not have any indication of their prior knowledge in this area. Students in Senior Two science are taught how to write chemical formulae and balance equations, but coefficients refer to the number of atoms or molecules of a particular substance. The concept of the mole is left for grade 11 Chemistry.

Another consideration is the focus of the chemistry curriculum on calculations, using the mole concept and Avogadro's number primarily as bridge between various quantities. Since students are not expected to learn the derivation of Avogadro's number and the mole concept, and the stoichiometry of chemical reactions is not part of the interactive vignettes, the connection between the interactive vignettes and the unit test is limited. As mentioned previously, the interactive vignettes discussed atoms, molecules, relative atomic mass, and Avogadro's number, and offered examples of how these relate to each other. For example, in discussing Gay-Lussac's law of combining volumes, the stoichiometry of a chemical equation was shown and related to atoms/molecules and volume, but there were no practice calculations. The same is true of Avogadro's number, as it was mentioned that the relative atomic mass of a substance would contain Avogadro's number of entities, but again, students were not shown any calculations. Therefore, if the interactive vignettes had any effect on students' understanding of the mole concept, it would be in the understanding of the underlying concepts such as atom, molecule, and the quantity of Avogadro's number.

The multiple-choice test consisted of 24 questions that ranged from simple recall and one-step calculations to more complex levels of understanding of the concepts taught. Of the 24 multiple choice questions, ten related to the concepts presented in the interactive vignettes at some level. The ten multiple-choice questions chosen for analysis were 3A/23B (question 3 on test "A", question 23 on test "B"), 8A/4B, 10A/6B, 11A/7B, 14A/10B, 18A/14B, 19A/15B, 20A/16B, 23A/19B, and 24A/20B. Each question was worth one mark and no partial marks were given. The multiple-choice questions were analyzed by first examining the number of correct answer, followed by analysis of how students responded if they were incorrect. T-tests comparing the control and experimental group scores were completed. Results can be found in appendix P.

A t-test comparing total marks obtained on all questions resulted in no statistical difference between the two groups. This indicates that there was no difference in students' understanding of the information presented during the unit on the mole and stoichiometry, regardless of whether they were involved in the interactive vignettes. A second t-test, this time comparing student totals on only the ten questions that relate more closely to the interactive vignettes, also showed no statistical difference (see appendix P). Therefore, the interactive vignettes seemed to have no impact on student understanding of the mole concept in chemistry.

Student results on the multiple-choice portion of the test are provided in appendix Q. Although the t-test showed no significant difference between the two classes, there are some differences on a few individual questions. What follows is an analysis of how students responded to the ten questions related to the interactive vignettes.

Question 3A/23B:

In the chemical equation $2H_{2(g)} + O_{2(g)} \rightarrow 2H_2O_{(g)}$ the term to the right of the arrow means

a. 2 atoms of water   c. 2 litres of water

b. 2 grams of water   d. 2 moles of water

The question has students distinguish between various descriptions of an amount of matter as found in a chemical equation, such as atoms, grams, litres and moles. This question relates to the first three interactive vignettes. In the first IV students built molecules of FsR, and in the third IV they worked with Berzelius' symbols, so they should recognize that H_2O represents two types of elements forming a compound. The second IV showed students submicroscopic pictorial representations of atoms versus molecules, so students would be able to exclude the possibility of H_2O being an atom. All of these should help students avoid answer "a". Four more students in the experimental group answered this question correctly (answer "d"), over the control group. Of the students who got this question wrong, 7 out of 8 in the control group chose the answer with "atoms" instead of "moles", and 1 chose "grams". In the experimental group, 2 students chose "atoms" and 2 chose "litres". Therefore, it is possible the additional information from the vignettes was responsible for the fact that half as many students answering incorrectly in the experimental group as in the control group, and only one-quarter as many students in the experimental group gave "atoms" as the erroneous answer.

Question 8A/4B:

A mole of oxygen molecules consists of

a. oxygen atom	c. 6.02×10^{23} oxygen atoms
b. oxygen atoms	d. 12.04×10^{23} oxygen atoms

To answer this question correctly (answer "d"), students need to be able to distinguish between atoms and molecules and must also understand the quantity associated with a mole. The second vignette, through pictorial representation, distinguished between atoms and molecules. Students should recognize that two oxygen atoms make up one oxygen molecule. The quantity of particles in a mole, 6.02×10^{23}, was discussed in the final interactive vignettes, where Perrin's determination of Avogadro's number was described. Applying these two concepts together, students should be able to determine that each molecule has 2 atoms of oxygen, so there would be $2(6.02 \times 10^{23}) = 12.04 \times 10^{23}$ atoms.

The difficulty of this question is indicated by the low number of students who answered it correctly, with only 5 in the control group, and 9 in the experimental group getting it right. Although the question is difficult, nearly twice as many students in the experimental group came up with the correct answer as in the control group. In the control group, 16 out of the remaining 20 students chose answer "c", indicating that they realize that a mole is equal to 6.02×10^{23}, but they have not made the distinction between an atom and a molecule. In the experimental group, 12 of the remaining 16 students also chose answer c, showing their inability to distinguish between atoms and molecules. All but one of the remaining students in both classes chose answer B, demonstrating a distinction between atoms and molecules, but no knowledge of the quantity in a mole.

Question 10A/6B:

What is the approximate total number of hydrogen atoms in one mole of CH_3OH?

a) 24×10^{23} b) 6×10^{23} c) 18×10^{23} d) 36×10^{23}

For this question, students need to understand that a mole of any substance consists of approximately 6×10^{23} molecules, Avogadro's number of particles, of that substance. One mole of CH_3OH would be equivalent to 6×10^{23} molecules of CH_3OH. Students also need to be able to recognize that each molecule has four hydrogen atoms within, so there would be $4\ (6 \times 10^{23})$ atoms of hydrogen, answer "a". This question relates to interactive vignettes number one and two where Dalton's constant composition of compounds and the distinction between atoms and molecules were debated and represented symbolically and submicroscopically in diagram form. If students had to "build" this compound, like they built FsR, they would realize they need four hydrogen atoms for each molecule. This question also relates to the last two interactive vignettes where determinations of Avogadro's number are introduced and discussed. The experimental class had three more students answer this question correctly than students in the control class. Although this is not a large difference, the choice of alternative answers seems to indicate that the experimental class tried to factor in the number of hydrogen atoms per molecule, but calculated it incorrectly. Only six students in the experimental class chose the incorrect answer "b", versus eleven students in the control class. By choosing this answer, it indicates that they know a mole consists of 6×10^{23} particles, but have not made the distinction between atoms and molecules.

Question 11A/7B:

Which sample of hydrogen gas occupies the largest volume at STP?

a) 2 moles b) 2 litres c) 2 grams d) 2×10^{23} molecules

Only two fewer students in the control class answered this question correctly when compared to the experimental class. This question, once again, has the student differentiating among moles, molecules, mass and volume, much like the first question analyzed. Parts of interactive vignettes one, two and six either discussed the relative atomic mass of hydrogen, and/or offered a visual representation or explanation of the diatomic nature of hydrogen. Also, the number of molecules in a mole was discussed in the last two interactive vignettes presented. Therefore, students should know that 2 grams of hydrogen is one mole and that 6×10^{23} molecules would be the equivalent to one mole (2×10^{23} would be less). The only uncertainty in this question might be the relationship of volume to the other quantities, answer b, since molar volume, in litres, was not formally introduced. When looking at the results, 7 students in the control group, and 5 in the experimental group chose answer b, 2 litres, as their response.

Question 14A/10B:

Under ordinary conditions, which substance exists as a diatomic molecule?

a. zinc
b. bromine
c. iron
d. helium

Seven more students in the experimental group (22) answered this question correctly, than did students in the control group. Once again, the second interactive vignette clearly depicted diatomic molecules when showing Avogadro's hypothesis and his distinction between atoms and molecules, although bromine was not used as an example. It seems that the submicroscopic representation of a molecule in the second IV did have an affect on the students in the experimental class. Eight of the twelve students that answered this incorrectly chose helium for their response.

Question 18A/14B:

There are 6.02×10^{23}

a. atoms/moles in 1 litre
b. moles in an atom
c. atoms/molecules in a mole
d. grams in one mole

This is a simple recall question, and out of both classes, only three students did not chose "c" as the correct answer. Two of those students were in the experimental group. Of the students that chose the incorrect response, two chose "b", which is the inverse of the correct response, and one chose "atoms/moles in 1 litre".

Question 19A/15B:

The mass of two moles of nitrogen gas is

a. 56 g b. 2 g c. 17 g d. 14 g

One less student in the experimental group answered this correctly than did the control class. To answer this question correctly, students need to realize that relative atomic mass is the mass of one mole of a substance, but since nitrogen gas is diatomic, it will be twice as much. Students that answered this incorrectly tended to choose answer d, which is the relative atomic mass of one mole of nitrogen atoms.

Question 20A/16B:

What amount of matter contains the largest number of atoms?

a. 40 g of K b. 54 g of Al c. 200 g of Xe d. 200 g of Ba

This question has students relating an element's relative atomic mass to number of atoms. Students do not have to calculate the number of atoms, but need to understand that a mole of any element would have an equal number of atoms, so the substance with the greatest amount of moles would have the largest number of atoms. Both classes had only 14 out of 25 students answer “b”, the correct answer. The most common incorrect answer in both groups was “d”, 200g of Ba. This may have been chosen because is has the highest atomic number and atomic mass out of the four possible responses. The other incorrect responses were evenly divided among the remaining students, with two students in the experimental group omitting this question.

Question 23A/19B:

A mole of H_2O and a mole of O_2

a. have the same mass

b. contain one molecule each

c. have a mass of 1 g each

d. contain the same number of molecules

Eight more students in the experimental group, compared to the control group, answered this question correctly. This question requires students to identify that the term “mole” refers to an amount of substance that is equivalent, independent of the substance being discussed. Therefore, the correct answer for this question is “d”. Of the students in the control group that answered incorrectly, ten chose “b”, 2 chose “a” and 2 chose “c”. Of the students in the experimental group who answered incorrectly, answers “a”, “b”, and “c” were each chosen twice. This question relates directly to interactive vignette number two where Avogadro’s Hypothesis is first presented. It is stressed that equal volumes of gases, at the same temperature and pressure, will have the same number of particles (atoms/molecules), labeled Avogadro’s number, and later referred to as a “mole”. Since the experimental group did much better on this question, it may be due to mention of Avogadro’s hypothesis, and not the rote memorization of the term “mole”.

Questions 24A/20B:

One mole of oxygen molecules contains more independent units (O_2) than one mole of oxygen atoms (O).

a. True, because there are two atoms of O for every molecule of O_2.

b. True, because one mole of O_2 weighs more than one mole of O.

c. False, because both of them have the same number of particles.

d. False, because one mole of O has the same mass as one mole of O_2.

This question relates to interactive vignette 2 where the terms atom and molecule were defined by Avogadro's hypothesis and both were represented in drawing. Avogadro's hypothesis, that equal volumes of gas contain the same number of particles, if temperature and pressure and constant, was also presented during this interactive vignette. Therefore, the correct answer is "c". Both classes found this question quite difficult, with only eight students in total answering it correct. Of those 8 students, five were from the experimental class, where they would have seen drawings of atoms versus molecules. Of the students in the control class who answered this question incorrectly, 18 chose "a", 2 chose "b", and 2 chose "c". In the experimental class, 11 incorrectly chose "a" and 7 chose "b". The difficulty in this question might be due to the phrase "independent units", despite molecules (O_2) and atoms (O) being identified in brackets in the question. If students considered "O" to be an "independent unit", then answer "a" would have been correct.

Overall, when looking at the comparisons between the two classes for all other questions, the results tend to be very similar, with one class only outperforming the other by a few students. For example, out of twenty-four questions, two had equal numbers of students from the control and experimental groups answer them correct. For the remaining twenty-two questions, ten were answered marginally better by the control group and ten were answered marginally better by the experimental group. Only two questions, number 14 (determining which substance is diatomic) and number 23 (comparing a mole of water and a mole of oxygen gas) had the experimental group outperform the control group by seven and eight students respectively. Since both of these questions relate to material presented in the interactive vignettes, we could assume that they did have some, although not statistically significant, effect on the students' knowledge of these particular concepts.

In terms of Johnstone's three levels of representation, the results of the multiple choice questions analyzed (3, 8 10, 11, and 24) would indicate that students exposed to more information on all three levels gain a slightly better understanding of the underlying concepts related to the mole. Interactive vignettes one, two and three had students working on all three levels of representation. Students discussed macroscopic properties of substances (e.g. ratios of volume of gases, comparison of two different elements), represented them symbolically (e.g. Fs, R and FsR), and drew submicroscopic representation of the atoms or molecules. Although analysis involved a small number of questions, and the number of students achieving higher scores is also small, these results show that students in the experimental group were more able to distinguish between atoms and molecules, leading them, more often, to the correct response.

5.6: Unit Test Results: Long Answer

The long answer portion of the students' chemistry test consisted of nine questions that related to some aspect of the interactive vignettes presented. Although stoichiometry and algorithmic problem solving were not part of the interactive vignettes, some of the terminology and relationships between amounts were briefly mentioned. For example, in the second IV, students looked at the volume ratios between reactants and products. All but one of the long answer questions involved either one-step or two-step calculation(s) using Avogadro's number or the determination of the number of moles of a substance, either using molar mass, number of particles, or molar volume. Students' total marks on the long answer portion of the unit test were determined and a comparison was made between the control group and the experimental group using paired t-tests.

Two different t-tests were used to compare the student scores on the long answer test. First, total marks on all questions were evaluated, followed by a t-test only using those questions that fit more closely to the interactive vignettes. The results for these tests can be found in appendix R. Both tests showed no statistical difference between the two classes, indicating that the interactive vignettes had no discernable effect on student understanding of the mole concept and Avogadro's number.

Student responses for each question were evaluated and their full or partial scores were also compared on a question-by-question basis. The questions, their answers, and the student scores are available in appendix S. The majority of the questions show small variations in how the two classes responded. What follows is a description of some of the questions and the answers given.

Question 1 had students differentiate between mass, moles and atoms versus molecules. Most of these distinctions were identified in the first two interactive vignettes. For part b, the experimental class had four more students answer correctly, citing Cl_2 molecules, instead of the monatomic gallium atoms. Three more students in the experimental group, for part c, also gave the correct mass of one mole of nitrogen molecules as 28.02 g, versus the more common incorrect response of 14.01 g for the single nitrogen atom. However, for all of question one, the experimental class only scored eight more marks, out of a total of 75 marks, than the control class.

Questions two and four, converting from mass to moles, each had only one more student in the control class answer it correctly. Questions five, using molar mass, six, and seven, both using Avogadro's number, also showed no major difference between these two groups, with the experimental class obtaining only 1.5, 2, and 0.5 overall marks more on each question respectively. On question eight, finding moles using molar volume, the control class earned two more marks than the experimental group. However, multi-step question three, requiring students to first convert from number of molecules to moles and then multiply by the number of atoms per molecule, had seven more students in the control class earn full marks. The majority of the students who did not get full marks on this question only completed the first part of the calculations. This only resulted in the control class earning 6.5 more marks, out of 25, on this question than the experimental group.

Questions nine and ten, not included in the t-test looking at the effect of the interactive vignettes, involved the students working with whole chemical equations, converting amounts of reactants to moles, setting up appropriate ratios between two substances, and converting the final amount of product from moles to another requested quantity. Question ten was slightly more difficult, because students were required to determine which reactant was limiting in amount. Overall, the experimental class obtained four more marks on question nine, but the control group earned eight more marks on question ten, mainly due to more partial marks for determination of the limiting reactant. Therefore, student performance on the stoichiometric aspect of chemical equations remains quite similar.

The final question of the long answer portion of the test presented students with a balanced chemical equation and then a series of molecular diagrams showing possible products of the reaction. Only a very few number of students in either class were able to chose the correct response and explain their choice properly based on the ratio of S to O atoms and the presence of excess sulfur atoms. The equation indicated that 2 SO_3 would be produced. Twenty-one students out of fifty chose the product that showed molecules of S_2O_6, whereas only fourteen students chose the correct molecular diagram with one sulfur and three oxygen atoms per molecule. Only nine students (5 control and 4 experimental) knew there should be excess sulfur left over. Overall, the experimental class earned two extra marks on this test question. The poor results indicate a much greater need to include more atom and molecular diagrams when teaching chemical reactions, and not just when introducing the associated terminology such as atoms, molecules and ions.

5.7: Summary

When comparing the pretest to post attitude t-test results, the experimental group showed a slight increase in attitude three (CL95%), their openness to new ideas, and a somewhat smaller increase in attitude 5, their attitude toward chemistry leisure (CL90%). A comparison of the post-attitudes tests of each class showed statistical increases in the experimental class attitudes' toward chemistry in leisure (CL99%) and chemistry careers (CL90%). In particular, students responded more favorably to the statement "I would like to belong to a chemistry club" and "I would like to do chemistry experiments at home". This would suggest that the interactive vignettes did have a slight effect on the students' interest in chemistry.

Student results on their final unit test on stoichiometry and the mole did not show any substantial difference between the control and experimental groups. There was a small advantage for the experimental group on the multiple choice questions, and it seemed to be related to the use of both the symbolic and submicroscopic representation of atoms and molecules in the interactive vignettes. Generally, the overall similarity between the control and experimental groups on the unit test was expected, since the interactive vignettes dealt more with the history of the concept of the mole than stoichiometric calculations.

CHAPTER 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to investigate the use and effectiveness of interactive vignettes in teaching the mole concept in senior high chemistry. An interactive vignette is a brief historical story that includes both quantitative and qualitative aspects of a topic that provide an opportunity for better conceptual understanding and practical application. The three specific research questions were:

1. Does an historical presentation of the mole concept, in the form of interactive vignettes, increase students' conceptual understanding of this concept in chemistry?

2. Will this conceptual understanding occur on all three levels of representation in chemistry: the macro, symbolic and the sub-micro?

3. Does the use of history, with emphasis on the central mole concept, improve students' attitude toward, and interest in chemistry?

Interactive vignettes were inserted at the beginning of the experimental group's chemistry class, for ten consecutive classes. With the exception of these interactive vignettes, the two classes in the study were taught the same chemistry curriculum by the same instructor during the same semester. In order to answer the first two research questions, a unit test on stoichiometry and the mole concept, administered after the completion of the section, was analyzed. In particular, student responses and achievement in both the control class and the experimental class were compared. Since the interactive vignettes did not relate to all aspects of the unit, a closer analysis was done on those questions that were connected.

The third research question dealt with student attitudes toward, and interest in, chemistry. Therefore, students involved in the study were given a chemistry attitudes test at the beginning and end of the vignette period. The attitudes test was a five point Likert-style questionnaire that looked at students' attitudes toward six different perceptions towards chemistry. Students in the experimental group were also asked their opinion of the effectiveness of the interactive vignettes, in both their interest in class and on their understanding of the material. The attitude tests were analyzed using paired t-tests, and their responses categorized and tallied.

In response to the first two research questions, the students exposed to the interactive vignettes had no significant statistical difference in their unit test marks than did the class that followed the regular curriculum. The overall average for the experimental class remained the same, whereas the control class dropped by less than 2%. Therefore, the interactive vignettes did not improve students' understanding of the mole concept, as evaluated by their unit test. Analysis of individual questions also did not reveal any specific area of study where one class achieved much better or worse than the other. For example, students in the experimental class did not do any worse in calculations, even though they had slightly less class time to practice due to the introduction of the interactive vignettes at the start of their class. However, that being said, the experimental class did seem to have a slight advantage (although not statistically so) answering multiple choice questions that involved comparing or choosing between atoms and molecules. These two terms were clearly represented on all three levels during the presentation of the interactive vignettes.

One possible reason the interactive vignettes did not improve students' conceptual understanding of the mole could be related to the chemistry curriculum itself. As mentioned previously, the chemistry curriculum places a lot of emphasis on mathematical problem solving in this unit, with many outcomes specifically stating that students should be able to calculate or solve for unknowns. For example, students should be able to; "solve problems requiring the inter-conversion between mass, volume, and number of particles, and moles", or, "solve mole-mole problems given reactants and products". By contrast, in the non-quantitative area, the curriculum only asks that students be able to "describe the concept of the mole and its importance to measurement in chemistry", after calculating the mass of compounds and before calculating the volume of gases. Although this statement provides educators the chance to expand and incorporate the historical aspect of Avogadro's number and the mole concept, it emphasizes measurement over theory. The highly algorithmic nature of the curriculum leads to rote memorization of Avogadro's number and its use as a bridge between the various measures of an amount of substance. Therefore, since the main focus of the class is the introduction and practice of calculations, the interactive vignettes at the start of the class are essentially unrelated to what is being done during the remainder of the class.

Furthermore, the mismatch between the curriculum outcomes for this unit and the historical information contained in the interactive vignettes makes it difficult to place the interactive vignettes appropriately within the unit where they would have the most affect. The research for this study is embedded within the existing chemistry curriculum which, in actual fact, places little emphasis on the qualitative understanding of the mole. Therefore, the introduction and discussion of the mole concept usually occurs during a portion of one class, with the majority of time afterwards being spent on calculations and conversions between different quantities of substances. Therefore, the best placement for the interactive vignettes would be as a precursor to the introduction of the mole concept. However, presented this way the interactive vignettes would only be isolated pieces of information, seemingly unrelated to the topic being covered in class, since much of the introduction to chemistry - such as Dalton's atomic theory, learning to calculate formula mass, write chemical formulas, and balance equations - begins in 20S Science, if not earlier. Therefore, some of the interactive vignettes fit more appropriately with previously learned material.

The nature of the unit test also limits how students are able to express their understanding of the mole concept, even if their understanding was influenced by the interactive vignettes. For example, since the curriculum emphasizes quantitative problem solving, much of the unit test is calculation-based problem-solving, making it difficult to conclude whether any differences between the groups are based on better understanding of the underlying concepts, or just better memorization of how to solve certain types of problems. Therefore, a recommendation would be to use a different form of assessment to better determine whether interactive vignettes had an effect on students' understanding of the mole concept. This could be a written test with questions requiring students to write out their explanations, or students could be interviewed individually. This process would allow the investigator to gain a deeper understanding of what students know, and would allow further questioning to determine where any difficulty with the mole concept might exist. In order to better assess if students understand the concepts on all three levels of representation, questions that only require a numeric answer should be avoided and, instead, students should be required to problem solve using the different levels of representation, providing written or verbal explanations of their reasoning. This, again, would provide the educator more information on where students are having difficulty with the concepts being tested.

One additional problem with using students' chapter tests to assess the effectiveness of the interactive vignettes is the fact that the students are informed that they will not be tested on the history discussed during these presentations, since it is not a specific outcome of the transitional grade 11 Chemistry curriculum. Being typical high school students, many will not pay as close attention to the material as they might have if they knew the interactive vignettes counted towards their final assessment in the course. One way to overcome this setback is to inform them that they will be assessed on the material. However, in the end, it seems that the best way to get students undivided attention is to make the interactive vignettes compelling and activity-based, so they are involved in every aspect of the historical material presented. Equally important is to clearly provide as many connections between the interactive vignettes and the material they are currently being taught in class.

The information in the interactive vignettes was provided to students on all three levels of representation in chemistry, the macroscopic, the symbolic and the submicroscopic. However, only two IVs utilized all three levels when describing one phenomenon. These were the vignettes on Dalton's atomic theory and Avogadro's Hypothesis. When looking at the questions that related to these two interactive vignettes, in particular differentiating between atoms and molecules, the students in the experimental class seemed to have a slight advantage. However, the final question of the long-answer portion of the unit test clearly indicated that all students had difficulty working between the symbolic and submicroscopic levels of representation in chemistry. Although the interactive vignettes focused on the three levels of representation for atoms and molecules and simple chemical reactions, it is evident that students do not transfer this information from the three levels when working on more difficult stoichiometric problems. It is also interesting to note that students had difficulty defending, in words, why they chose a specific answer. It seems that students have become accustomed to answering quantitative questions in chemistry, and are relying upon memorized algorithms to find the final answer. A recommendation that arises from this would be to assess how an increase in the use of pictorial representation, when teaching and solving more complex concepts such as stoichiometric problems, affects student understanding.

In addressing the third research question, the interactive vignettes did have a positive effect on some of the chemistry related attitudes of the students in the experimental group. Students' attitude toward chemistry in leisure increased, with a noticeable response to the statement that they would like to belong to a chemistry club. To a lesser extent, there was an increase in students' attitudes towards chemistry as a career. This is encouraging, as it suggests that more students, by being involved in the interactive vignettes, see chemistry as a possible part of their future, either in their career or simply on a general basis. Perhaps the interactive vignettes made chemists seem more human, and the career more accessible to the average student, since the theories presented were not arrived at in a short period, nor without problems.

An increase in chemistry-related attitudes was expected since the interactive vignettes were meant to highlight some of the main ideas behind the development of

Avogadro's number and the concept of the mole by providing students with an interesting story and activity that would get them involved with the material. What was unknown, however, was which particular attitudes might show change. The interactive vignettes presented chemistry as a human endeavor, fraught with controversy and unforeseen problems. Students heard how some theories originated through intuition, and progressed through hard work and luck, only to be dismissed due to societal beliefs or a lack of evidence. They also were able to follow how the concept of the atom started as a simple belief by a few, and became something tangible many years later. This description of chemistry is quite unlike the usual way instructors and textbooks present only the final form of science, requiring endless calculations and repeated experiments to obtain already-known results. This leaves out the excitement of new discoveries and human achievement, which invariably will be more compelling. A recommendation might be to assess a larger population of chemistry students using more items for each of the attitude subscales. This would enable researchers to more clearly identify what specific items within each attitude category are affected with the use of an historic approach.

The fact that an historical approach, using ten short interactive vignettes presented over ten chemistry classes, had an effect on student attitudes has implications for the teaching of chemistry, especially when this increase was shown when there was only a marginal correlation between the material in the interactive vignettes and the course curriculum. Through this study I have personally learned a lot about the history of Avogadro's number and the mole concept, and have incorporated the interactive vignettes into my current grade 11 Chemistry classes. Anecdotally, I have witnessed an increase in student interest and involvement in the class. There could be a significantly greater effect if the course material was structured to better incorporate historical discussions and appropriate hands-on activities. The challenge now is to incorporate the history of science, though the use of interactive vignettes, into other areas of the curriculum.

An historic approach is already being implemented in a few sections of the new chemistry curriculum that is being adopted over the next few years. For example, in the unit "Gases and The Atmosphere", teachers are to outline the historical development of the measurement of pressure, and then students are to experiment with pressure, temperature, and volume to determine the relationships previously determined by Boyle, Charles, and Gay-Lussac. In the unit on Organic Chemistry, the historical contributions of Fredrik Wöhler to overturn vitalism is to be discussed. However, in the unit on "Chemical Reactions", where the concept of the mole is taught, the outcomes have changed very little. Students are once again asked to describe the concept of the mole and its importance to measurement in chemistry before calculating and solving various problems. The notes for instruction do briefly mention Avogadro and Jean Perrin, but the amount of information is insignificant and insufficient if a teacher wishes to effectively describe their contributions without having to look elsewhere for more detail. The curriculum does give some sources for further research and offers an activity for determining Avogadro's number using oleic acid. However, the educator will need to put in extra time preparing if they wish to follow the suggestions for implementation. Therefore, another recommendation arising from this study would be to provide teachers with the necessary resources to help them better incorporate the history of science into their classroom. Material outlining the historical development of the big ideas in chemistry could be developed and then disseminated to chemistry teachers through workshops or attachments to curriculum documents. At a minimum, it would help teachers better understand the background of what they are teaching, and potentially allow them to inject small aspects of history into their existing lesson plans. The workshops would also provide teachers with relevant hands-on activities, if they chose to expand on their instruction of historical elements related to the mole concept.

Another recommendation coming out of the research is for teachers to discourage the rote memorization of facts and algorithms, in favour of developing a deeper understanding of the material. This could be achieved by relying less upon a textbook, or by using a textbook or other material that includes more of the history of science and less final form science. Instruction should include pertinent activities that increase conceptual understanding by involving students as much as possible. However, in order to move away from rote memorization of facts and algorithms, there needs to be a change in the way in which we assess students' understanding of chemistry, with less emphasis on algorithmic problem solving and more of an opportunity for students to express their understanding of the concepts taught in writing.

This research indicates that the use of an interactive historical approach to teaching senior high chemistry has the potential to increase student interest in certain areas of chemistry. Usually students, who are interested in the subject matter being taught, will strive to understand it beyond the simple memorization of facts and equations and will seek out answers to their own questions. Through the use of appropriately placed interactive vignettes, an historical approach could transform the chemistry classroom into a dynamic place where students are open to new ideas and learn to question the information provided to them with the same curiosity as the scientists they have studied.

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Appendix A

Letters to Principal and Assistant Superintendent of School Division

March 9, 2005

Mr. G Bruce, Assistant Superintendent
Pembina Trails School Division
181 Henlow Bay
Winnipeg, MB

Dear Mr Bruce;

Re: Master's thesis research project: "Using Interactive Vignettes in the teaching of the Mole Concept in Senior Chemistry"

I, Heather Teller, am a science/chemistry teacher at Fort Richmond Collegiate. During the past few years I have been working on my Masters of Education degree with Dr. Arthur Stinner (stinner@cc.umanitoba.ca, 474-9068) in the Faculty of Education at the University of Manitoba. I am writing you to request permission from the Division Office to conduct research in two classrooms at Fort Richmond Collegiate. I have cc'd this letter to my principal, Mrs. Lorraine Carter. A description of my research study is presented below. The research project has been approved by the Education/Nursing Research Ethics Board, and any parent and/or student concerns or complaints about the project may be directed to the Human Ethics Secretariat at 474-7122.

In chemistry, the concept of the mole is central to several topics studied (e.g. equations, stoichiometry, solutions, gas laws), but research has shown that students have difficulty with this concept. Knowledge of teaching methods that would enhance students' conceptual understanding of the mole, as well as increase their interest in science, would be beneficial to chemistry and science educators. An historic approach to teaching science, even in small vignettes, has been shown to increase student understanding and interest in science and, enhance critical thinking skills. Therefore, my research aim is to investigate how the inclusion of the history of science affects students' understanding of the mole, a central concept in chemistry, and their attitude towards chemistry.

In order to complete my research, data from two chemistry classes will be compared. To ensure that the two classes are comparable, I will first need to compare students' final science 20S grades, teachers, and chemistry 30S marks up to the point of the study. To keep student identities anonymous this information will be collected by a third party.

For the study, for both classes involved, the prescribed chemistry 30S curriculum will be followed, but the method of instruction will be varied in one class to address my research topic. This variation will include the introduction of historical background, in the form of interactive vignettes, related to the chemistry concept of the mole. These interactive vignettes:

- will provide an opportunity for conceptual development and practical demonstration
- include qualitative and/or quantitative aspects of a topic
- may include a demonstration or activity
- provide relevant and detailed information
- require student interaction and participation.

The interactive vignettes will occur daily for a period of ten consecutive classes. They will each take between five to ten minutes to complete and will not involve a discernable difference in time between the two classes. The estimated total time required for the study would be a maximum of one hundred minutes of class time, spread over eleven classes (ten classes for the vignettes and one for the pre-attitudes test). The history presented will include the theories that led to Avogadro's hypothesis and various steps towards the eventual determination of Avogadro's number. The ten interactive vignettes are attached for your information. Students will not be tested on the history injected into their lessons. Therefore, the new information will not cause any more stress on the students involved than that already associated with learning chemistry.

In order to eliminate my position of power as the teacher of the students in the study, Troy Scott, fellow colleague, has expressed interest in helping me by using his two chemistry classes in the study. Student involvement would be entirely voluntary and anonymous. A neutral third party would describe the purpose of the study to the students and then recruit them in an anonymous way. Troy Scott has no formal background in the history of science, so he will receive outlines for this portion of his lesson plans from me for the duration of the study. All other classroom information will be identical between the two classes and we will meet on an ongoing basis throughout the study to discuss any issues that might arise. Interested students and their parents/guardians would need to sign assent/consent forms allowing me to keep copies of the chemistry tests for the unit involved and their results on a science attitude test. Identities would be kept unknown, with transcription of answers being completed if recognition of handwriting is possible. I will not request access of any student's files, other than their Sr2 science grades and teachers, in order to complete this study.

At the end of the unit, copies of tests (maintaining anonymity) will be analyzed. A neutral teacher will also administer a pre and post-test of chemistry related attitudes (attached for your information). Participation in the study will not require any extra time, outside of class. All data obtained will be seen only by me and will be destroyed after completion of my thesis. Participation in the study is entirely voluntary and anonymous. Students participating in the study will receive a summary of the research results when available if interest is indicated on their assent form.

Attached are copies of the assent form for the students, the consent for the parents, the Test of Science Related Attitudes, and a brief summary of the ten interactive vignettes that will be used in the classroom.

If you have any further questions regarding my research, or my thesis, I would be happy to discuss them with you. My email is ____________ and my phone number is
. If you grant your permission for me to conduct the research, please indicate so by signing below.

Thank you

Heather Teller

Good luck in your research. I would be very interested in the results of your research.

____
Signature

cc: Lorraine Carter, Principal, Fort Richmond Collegiate

March 9, 2005

Mrs. L. Carter, Principal
Fort Richmond Collegiate
99 Killarney Rd.
Winnipeg, MB

Dear Mrs. Carter;

Re: Master's thesis research project: "Using Interactive Vignettes in the teaching of the Mole Concept in Senior Chemistry"

Earlier this year we met to discuss my Master of Education thesis project. As you are aware, I am working on my Masters of Education degree with Dr. Arthur Stinner (stinner@cc.umanitoba.ca, 474-9068) in the Faculty of Education at the University of Manitoba. I have requested permission from Mr. Bruce at the Division Office, to conduct research in the classroom, and have cc'd you on the request letter. I would also like to ask your permission to carry out the proposed research at Fort Richmond Collegiate. A description of my research study is presented below. The research project has been approved by the Education/Nursing Research Ethics Board, and any parent and/or student concerns or complaints about the project may be directed to the Human Ethics Secretariat at 474-7122.

In chemistry, the concept of the mole is central to several topics studied (e.g. equations, stoichiometry, solutions, gas laws), but research has shown that students have difficulty with this concept. Knowledge of teaching methods that would enhance students' conceptual understanding of the mole, as well as increase their interest in science, would be beneficial to chemistry and science educators. An historic approach to teaching science, even in small vignettes, has been shown to increase student understanding and interest in science and, enhance critical thinking skills. Therefore, my research aim is to investigate how the inclusion of the history of science affects students' understanding of the mole, a central concept in chemistry, and their attitude towards chemistry.

In order to complete my research, data from two chemistry classes will be compared. To ensure that the two classes are comparable, I will first need to compare students' final science 20S grades, teachers, and chemistry 30S marks up to the point of the study. To keep student identities anonymous this information will be collected by a third party.

For the study, for both classes involved, the prescribed chemistry 30S curriculum will be followed, but the method of instruction will be varied in one class to address my research topic. This variation will include the introduction of historical background, in the form of interactive vignettes, related to the chemistry concept of the mole. These interactive vignettes:

- will provide an opportunity for conceptual development and practical demonstration
- include qualitative and/or quantitative aspects of a topic
- may include a demonstration or activity
- provide relevant and detailed information
- require student interaction and participation.

The interactive vignettes will occur daily for a period of ten consecutive classes. They will each take between five to ten minutes to complete and will not involve a discernable difference in time between the two classes. The estimated total time required for the study would be a maximum of one hundred minutes of class time, spread over eleven classes (ten classes for the vignettes and one for the pre-attitudes test). The history presented will include the theories that led to Avogadro's hypothesis and various steps towards the eventual determination of Avogadro's number. The ten interactive vignettes are attached for your information. Students will not be tested on the history injected into their lessons. Therefore, the new information will not cause any more stress on the students involved than that already associated with learning chemistry.

In order to eliminate my position of power as the teacher of the students in the study, Troy Scott, fellow colleague, has expressed interest in helping me by using his two chemistry classes in the study. Student involvement would be entirely voluntary and anonymous. A neutral third party would describe the purpose of the study to the students and then recruit them in an anonymous way. Troy Scott has no formal background in the history of science, so he will receive outlines for this portion of his lesson plans from me for the duration of the study. All other classroom information will be identical between the two classes and we will meet on an ongoing basis throughout the study to discuss any issues that might arise. Interested students and their parents/guardians would need to sign assent/consent forms allowing me to keep copies of the chemistry tests for the unit involved and their results on a science attitude test. Identities would be kept unknown, with transcription of answers being completed if recognition of handwriting is possible. I will not request access of any student's files, other than their Sr2 science grades and teachers, in order to complete this study.

At the end of the unit, copies of tests (maintaining anonymity) will be analyzed. A neutral teacher will also administer a pre and post-test of chemistry related attitudes (attached for your information). Participation in the study will not require any extra time outside of class. All data obtained will be seen only by me and will be destroyed after completion of my thesis. Participation in the study is entirely voluntary and anonymous. Students participating in the study will receive a summary of the research results, when available, if interest is indicated on their assent form.

Attached are copies of the assent form for the students, the consent for the parents, the Test of Science Related Attitudes, and a brief summary of the ten interactive vignettes that will be used in the classroom.

If you have any further questions regarding my research, or my thesis, I would be happy to discuss them with you. If you grant your permission for me to conduct the research, please indicate so by signing below.

Thank you,

Heather Teller

Signature

Appendix B

Student Assent Form

Assent Form

March 22, 2005.

Research Project Title:
Using Interactive Vignettes in the teaching of the Mole Concept in Senior Chemistry
Researcher: Mrs. H. Teller

Dear Student,

In chemistry, the concept of the mole is central to several topics studied (e.g. equations, stoichiometry, solutions, gas laws), but research has shown that students have difficulty with this concept. Knowledge of teaching methods that would enhance students' conceptual understanding of the mole, as well as increase their interest in science, would be beneficial to chemistry and science educators. My research aim for my Master of Education thesis for the Faculty of Education at the University of Manitoba, is to investigate how the inclusion of the history of science in the curriculum affects students' understanding of the mole and their attitude towards chemistry generally. The research project has been approved by the Education/Nursing Research Ethics Board, and any student or parent concerns or complaints about the project should be directed to the Human Ethics Secretariat at 474-7122.

In order to complete my research, data from two chemistry classes will be compared. To ensure that the two classes are comparable, I will first need to compare students' final science 20S grades, teachers, and chemistry 30S marks up to the point of the study. To keep student identities anonymous, a third party will collect this information. One class will be the control class, being taught the standard lesson plan, and the other will have some history injected into their lessons. This will occur daily for a period of ten consecutive classes, and will only take about ten minutes a class. The total amount of time will be approximately one hundred minutes of class time, spread over eleven classes. The new information introduced will not cause any more stress on students than that already associated with learning chemistry since participants will not be tested on the history presented.

At the end of the unit, copies of chapter tests (maintaining anonymity) will be analyzed. A pre and post-test of chemistry related attitudes would also be administered. There will be no extra time required, outside of your regularly scheduled chemistry class. All data obtained in this study will be destroyed after completion of my thesis. Participation in the study is entirely voluntary and anonymous. Any students participating in the study may have a summary of the research results mailed out to them by completing the attached portion on the consent form.

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project, and agree to participate as a subject. You are free to withdraw from the study at any time without prejudice or consequence. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation.

Thank you for your consideration. Please feel free to contact me, through the neutral teacher, if you have any questions.

Sincerely,

Mrs. H. Teller

Date: ________________

I, ___________________, agree to participate in the research project. I understand that my final science 20S grade and my initial chemistry 30S marks will be looked at, and a copy of my unit test will be kept anonymously for analysis. I will take a science attitudes test at the beginning and end of the instructional unit.

If you are interested in receiving a copy of the project summary once it is available. Please provide your full name and mailing address below.

Appendix C

Parental Consent Form

Consent Form

March 22, 2005

Research Project Title:
Using Interactive Vignettes in the teaching of the Mole Concept in Senior Chemistry
Researcher: Mrs. H. Teller

Dear Parent/Guardian,

Your son/daughter has expressed an interest in being part of a research study to be conducted at the school. This study, which is part of my Masters of Education thesis for the Faculty of Education at the University of Manitoba, focuses on how the inclusion of the history of science affects students' understanding of the mole, the central concept in chemistry, and their attitude towards chemistry. The research project has been approved by the Education/Nursing Research Ethics Board, and any student or parent concerns or complaints about the project should be directed to the Human Ethics Secretariat at 474-7122.

In chemistry, the concept of the mole is central to several topics studied (e.g. equations, stoichiometry, solutions, gas laws), but research has shown that students have difficulty with this concept. Knowledge of teaching methods that would enhance students' conceptual understanding of the mole, as well as increase their interest in science, would be beneficial to chemistry and science educators.

In order to complete my research, data from two chemistry classes will be compared. To ensure that the two classes are comparable, I will first need to compare students' final science 20S grades, teachers, and chemistry 30S marks up to the point of the study. To keep student identities anonymous this information will be collected by a third party.

For the study, for both classes involved, the prescribed chemistry 30S curriculum will be followed, but the method of instruction will be varied in one class to address my research topic. This variation will include the introduction of historical background, in the form of interactive vignettes, related to the chemistry concept of the mole. These interactive vignettes:

- will provide an opportunity for conceptual development and practical demonstration
- include qualitative and/or quantitative aspects of a topic
- may include a demonstration or activity
- provide relevant and detailed information
- require student interaction and participation.

The interactive vignettes will occur daily for a period of ten consecutive classes. They will each take between five to ten minutes to complete and will not involve a discernable difference in time between the two classes. The estimated total time required for the study would be a maximum of one hundred minutes of class time, spread over eleven classes (ten classes for the vignettes and one for the pre-attitudes test). The history presented will include the theories that led to Avogadro's hypothesis and various steps towards the eventual determination of Avogadro's number. The ten interactive vignettes are attached for your information. Students will not be tested on the history injected into their lessons. Therefore, the new information will not cause any more stress on the students involved than that already associated with learning chemistry.

At the end of the unit, copies of tests (maintaining anonymity) will be analyzed. A neutral teacher will also administer a pre and post-test of chemistry related attitudes. Participation in the study will not require any extra time, outside of class. All data obtained will be seen only by me and will be destroyed after completion of my thesis. Participation in the study is entirely voluntary and anonymous. Students participating in the study will receive a summary of the research results when available.

Your signature on this form indicates that you have understood to your satisfaction the information regarding your son's/daughter's participation in the research project, and agree to allow him/her to participate as a subject. Your son/daughter is free to withdraw from the study at any time without prejudice or consequence. His/her continued participation should be as informed as his/her initial consent, so you should feel free to ask for clarification or new information throughout his/her participation.

Thank you for your consideration. Please feel free to contact me at the school (275-7520) or by email (________________) if you have any questions.

Sincerely,

Mrs. H. Teller

Date: ________________

I, ____________________, agree to having my son/daughter __________________ participate in the research project. I understand that a copy of his/her unit test will be kept anonymously for analysis and that he/she will take a science attitudes test at the beginning and end of the instructional unit. I also understand that his/her science 20S final mark will be noted, as will his/her chemistry 30S mark prior to the study.

____

parent/guardian signature

The Ten Interactive Vignettes

1. John Dalton's Atomic Theory (1808)
   - In this interactive vignette, students will:
     - Be re-introduced to the four postulates of John Dalton's atomic theory.
     - See how Dalton viewed atoms and determined his relative atomic weights and chemical formulae.

2. Avogadro's Hypothesis (~1811)
   - This interactive vignette will present the conflicting theories of John Dalton and Gay-Lussac, and will introduce the students to Amadeo Avogadro and his hypothesis.
   - Students will be presented with a visual thought experiment involving observed volumes of gases found in a reaction between two gases.

3. Berzelius' Scientific Notation (~1813)
   - This interactive vignette will be an account of how Jacob Berzelius introduced the modern system of chemical notation and helped establish some consistency in the world of chemistry.
   - Students will be shown comparisons of Dalton's and Berzelius' chemical symbols.

4. Brownian Motion (~1828)
   - The fourth interactive vignette will describe one of the first observations in support of atoms by Robert Brown.
   - Students will observe Brownian motion either on video, through a microscope attached to a camera, or through a computer simulation.

5. Faraday's Laws of Electrolysis (~ 1834)
   - The fifth interactive vignette will outline how Michael Faraday's data from electrolysis gave more credibility to the existence of atoms and could have led to one of the first determinations of Avogadro's number.
   - An electrolytic cell will be set up for students to observe the production of an element at one of the electrodes.

6. Cannizzaro's Quest (~1860)
   - Cannizzaro, after Avogadro's death, tried to convince the scientific world of the importance and truth of Avogadro's hypothesis.
   - Through this story, science will be humanized and students will see how one man's viewpoint and persistence can change the face of science.

7. Loschmidt's Number (1865)

- This interactive vignette will be introduced using a soap bubble demonstration and the principles of interference of light, to show students how the approximate size of a molecule can be determined.
- Students will be provided with a description of one of the first estimates of Avogadro's number as done by Josef Loschmidt in 1865.

8. Einstein the Chemist (1905)
   - The eighth interactive vignette will tell a story that celebrates Albert Einstein, the chemist.
   - Students will hear how Einstein described a method by which Avogadro's number could be determined by studying Brownian motion.
   - Students will be exposed to Einstein's idea of "random walk" by the use of a computer simulation.

9. Jean Perrin and Brownian Motion (~1910)
   - The ninth interactive vignette will show students the method by which Perrin, guided by Einstein's work, studied Brownian motion and came to a value for Avogadro's number.
   - Students will use a video on Brownian motion to make similar calculations to Perrin's, and actually determine Avogadro's number.

10. Jean Perrin and the Vertical Distribution of Particles in Emulsions
    - The final interactive vignette will explain Perrin's examination of gamboge emulsions that led him to values for Avogadro's number.
    - Jean Perrin received the Nobel Prize for this work in 1926.

Appendix D

Interactive Vignettes

Interactive Vignette 1: JOHN DALTON (1766-1844)

Read to students: John Dalton: The Law of Definite Proportions and the Atomic Theory

In the 1300s, an Egyptian Chemist (Aidamir al-Jildaki) introduced the idea that elements combine in fixed amounts to form new substances. Hundreds of years later, in 1794, the idea, "the Law of Definite Proportions", was re-introduced by a French chemist, Joseph Proust. Despite over **eight** years of constant urging by Proust, the idea was generally not accepted by the scientific community. Other distinguished chemists at that time maintained that the composition of chemical compounds varied and that proportions in compounds were not absolutely rigid.

In the early 1800s, chemists were beginning to provide evidence for the existence of atoms, although not all realized what they had done. One of these people was John Dalton, a mathematics and philosophy tutor in England, who devoted all his free time to scientific research. Although he taught chemistry for six years, John Dalton had no experience in chemical research. His laboratory equipment was very basic as it was homemade, but he approached his research with intuitiveness and independence, and was a genius in putting facts and ideas together. Many questioned his data, but they were good enough to give his alert and creative mind clues to the probable answer. Over several years he worked with the idea of atoms and published his Atomic Theory in 1808.

This theory, if you recall, had four main points: (overhead)

1) All matter is made of atoms. Atoms are indivisible and indestructible.

2) All atoms of a given element are identical in mass and properties (atoms of different elements are different (in properties and mass)

3) Compounds are formed by a combination of two or more different kinds of atoms.

4) A chemical reaction is simply a *rearrangement* of atoms.

Student Activity: Definite Proportions: Open Discussion of Fs and R

Quickly toss out the Ziploc bags and have students dump the contents of their bag on the table. (Questions to guide them are on overhead)

Explain to students:

- although you cannot see atoms directly, this activity is meant to illustrate parts of the atomic theory and the Law of Definite Proportions. In this activity you will be using indirect evidence of atoms of two different "elements":

  Fs, are paper fasteners; R, are rubber rings

- If you look at all the fasteners, they are alike, just like all atoms of an element are similar to each other. Similarly, all the rings are alike, although they differ from the fasteners because they are meant to represent atoms of another element.

1. How many Fs do you have? _________

2. How many R do you have? _________

3. Do other groups have the same amount? _______

- Now you are going to put together two elements (Fs and R) to produce a compound (FsR). To do this you simply slide a ring on the fastener. (This would be like reacting an atom of copper with an atom of oxygen to make copper oxide).

Make your compound by placing one ring one each fastener.

$Fs + R \rightarrow FsR$

- note that the number of rings and the number of fasteners do not change, neither do their individual masses, just as stated in Dalton's atomic theory. This is just a rearrangement of atoms. If there are any extra's of fasteners or rings, they don't form any compound.

4. How many molecules of FsR, did you make? _______

   Is this the same as other groups?

- Guide them through a simplistic determination of the mass ratio of fasteners to rings. Briefly discuss their findings, mentioning the Law of Definite Proportions, which states that a given chemical compound always contains the same proportion by mass of its constituent elements. In this case, the mass ratio of Fs to R was the same, independent of the number of "atoms" of each type each group had at the start.

If each fastener has a mass of 0.3g and each ring has a mass of 0.2g, calculate the following:

5. Total mass of Fs in compound? (# of fasteners x 0.3 g)
   Total mass of R? (# of fasteners x 0.2g)

6. What is your mass ratio of Fs to R in your compound?

$$\frac{\text{Total mass of Fs}}{\text{Total mass of R}} = \_\_\_\_\_\_\_\_ =$$

7. How does your mass ratio compare to other groups?

8. Does the mass ratio depend on the sample size?

9. If you were to "decompose" the compound FsR, do you get back all the atoms with which you began?

Mass of Fasteners are 0.3 g and the mass of rings are 0.2 g. Therefore the mass ratio of Fs: R is 1.5/1 (the mass of the fasteners in the compound will always be 1.5X the mass of rings).

Extension: To make the compound water, H_2O, one atom of oxygen is required for every two atoms of hydrogen. Therefore: the ratio of

$$\frac{\text{mass of oxygen}}{\text{mass of hydrogen}} = \frac{16.0\text{ g}}{2.0\text{ g}} = \frac{8}{1}$$

or, the mass of oxygen is **always** 8 times heavier than the mass of hydrogen.

Continue with the story:

Using the assumptions of his atomic theory, John Dalton experimentally determined the composition of some compounds and found the relative atomic weights for some elements. He believed that the best explanation for an observation is most likely the simplest one. Therefore, when atoms combined to form compounds, they combined in small whole numbers to produce compounds. Therefore, if two elements made only one compound, the compound simply contained one atom of each.

Show overhead of atomic weights:

(Looking at Dalton's atomic weights it is obvious that his experimental results were flawed. This was mainly due to his false assumption with regards to the ratio of element atoms in a compound. If Dalton had a way of determining the constituents of a molecule, he would have had very close results to those accepted today.)

Unfortunately, chemistry professors, even in 1868 (60 years later), were still teaching their students that the existence of atoms was a hypothesis and not very probable. Even in 1910, Wilhelm Ostwald a Nobel Prize winner in chemistry, wanted to do away with the atomic theory. However, until new evidence arose, Dalton's Atomic Theory and simple laws of chemical combination (Conservation of Mass, Definite Proportions and Multiple Proportions) lent themselves to the test of experiment and gave some evidence for the existence of atoms.

Dalton's Atomic Theory will be revisited at the end of our historical venture.

Determination of Dalton's Relative Atomic Weights

Elements	# of Compounds known at the time	Given Formula	Weight Ratio	Assigned Relative Atomic Weights
hydrogen and oxygen	1	HO	H:O 1:8	H = 1 0 = 8
hydrogen and nitrogen	1	HN	H:N 1:5	H = 1 N = 5
carbon and oxygen	2	CO CO_2	O known	C = 5 O = 8

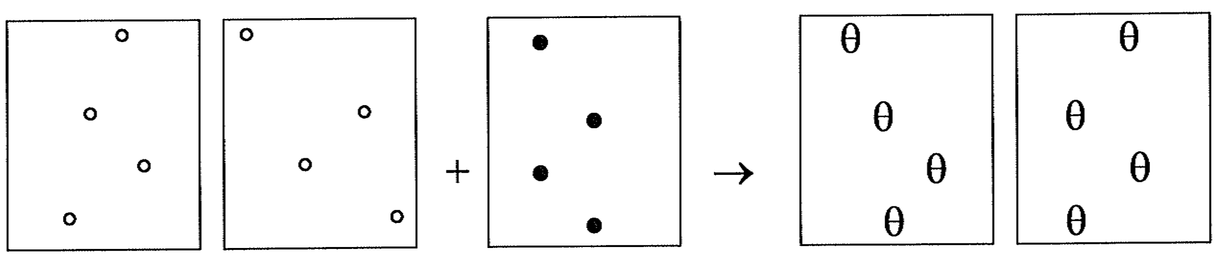
Dalton's Atomic Weights.

Hydrogen	1	Iron	38
Nitrogen	5	Zinc	56
Carbon	5	Copper	56
Oxygen	7	Lead	95
Phosphorous	9	Silver	100
Sulphur	13	Mercury	167

Interactive Vignette 2:
JOHN DALTON Vs. JOSEPH GAY-LUSSAC
Winner: AMADEO AVOGADRO

Thought Experiment:

It was found that two volumes of a gas (°) reacted with one volume of a different gas (•) to produce 2 volumes of gaseous product (θ). How can you explain these results? How can they combine to give the two volumes of product?



Have students give suggestions as to how the volume observations could be obtained. Students might suggest that 2 of the first gas combine with one of the second. Ask them why there would be two volumes of the product then.

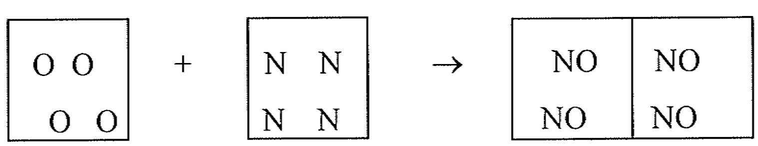
Story:

Remind them that John Dalton's atomic theory was ~1808.

The thought experiment that you just tried introduces us to some of the problems that existed in the early 1800's. Several different domains of thought about the composition of gases existed, and because of this, scientists seemed to be at odds with each other. Two such individuals were Joseph Gay-Lussac and John Dalton.

John Dalton believed that equal volumes of gases did not always contain equal numbers of atoms. His evidence arose from the fact that when two volumes of nitric oxide was decomposed, it yielded one volume of oxygen and one volume of nitrogen ($2 \rightarrow 1:1$). If there are x atoms of oxygen and x atoms of nitrogen, then there should only be ½ x atoms of nitric oxide per volume, because each particle of nitric oxide will yield one atom of oxygen and one nitrogen atom.

Overhead:



X atoms/volume X atoms/volume X/2 atoms /volume

On the other hand, Joseph Gay-Lussac, a French chemist, found that, at constant temperature and pressure, gases combine in very simple numerical proportions by volume (1 to 1, 1 to 2…), and that these volumes are related to the volume of gaseous product. This idea (that gases combine in small whole number ratios) became known as Gay-Lussac's Law (overhead).

Gay-Lussac hypothesized that the ratio of the volumes of reacting gases must resemble the ratio of the numbers of atoms in those volumes of these gases. He published his findings in 1808 – the same year that Dalton published his Atomic Theory.

Avogadro's Hypothesis

The scientist that made sense of both scientists' data was the Italian scientist Amedeo Avogadro. By simply making a clear distinction between the ultimate chemical particle of an element, the "**atom**", and the ultimate physical particle of a substance, which Avogadro called the "**molecule**", both ideas could be reconciled and, support given to Dalton's atomic theory.

Avogadro's hypothesis, published in 1811, simply stated that equal volumes of all gases at the same temperature and pressure contain equal numbers of molecules. Therefore, the weights of these equal volumes have to be in the ratio of the weights of the individual molecules of the gases. Avogadro had no positive evidence of his hypothesis and could not verify it, no did he have no way of determining how many molecules were present in a sample of gas, but he understood that the number must be quite large.

Return to Thought Experiment – Telling them the gases in the problem are hydrogen and oxygen and showing the distinction between atoms and molecules.

Previous work had indicated that one volume of hydrogen reacts with one volume of chlorine, producing two volumes of hydrochloric acid. It was believed that each atom of hydrogen and chlorine split in half during the reaction to produce hydrochloric acid. Avogadro explained this occurrence by predicting that the basic particles of hydrogen and chlorine were molecules instead of atoms, as previously believed.

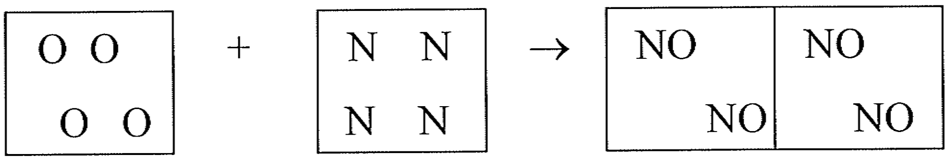
Avogadro's hypothesis made the large distinction between atoms and molecules, and provided a key to the structure of matter. It was now known that the smallest, normally existing particle of hydrogen was not H, as Dalton assumed, but actually H_2, consisting of two atoms joined together. Combining Gay-Lussac's Law with Avogadro's hypothesis, Dalton's "ultimate particles" could be correctly established and atomic weights could correctly be obtained.

Avogadro's hypothesis allowed relative weights of the molecules of two gases to be determined simply by weighing equal volumes of the gases at the same temperature and pressure and calculating the ratio between them. Unfortunately the simplicity of Avogadro's work was not appreciated because:

- it called for the acceptance of Dalton's Atomic Theory, which was still not appreciated by the scientists of this time.
- Avogadro was not a part of an active community of chemists, as Italy was located far from the main centers of chemistry, so it was easy for his hypothesis to be overlooked.

John Dalton:

- equal volumes do not need to contain equal number of atoms



X atoms/volume X atoms/volume X/2 atoms /volume

Gay-Lussac:

- gases combine in small whole number ratios

i) two volumes of carbon monoxide will combine with one volume of oxygen to yield two volumes of carbon dioxide (2:1:2)

ii) one volume of hydrogen will combine with one volume of chlorine to produce two volumes of hydrochloric acid gas (1:1:2)

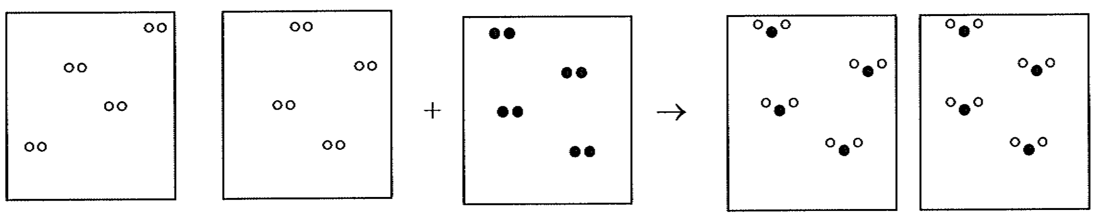
Therefore: the ratio of the volumes of reacting gases must resemble the ratio of the numbers of atoms in those volumes of these gases → equal volumes of gases contain equal numbers of atoms.

Avogadro's hypothesis: (1811)

- *equal volumes of all gases at the same temperature and pressure contain equal numbers of molecules*

Avogadro: The ultimate particles of hydrogen and oxygen are molecules consisting of two atoms each.

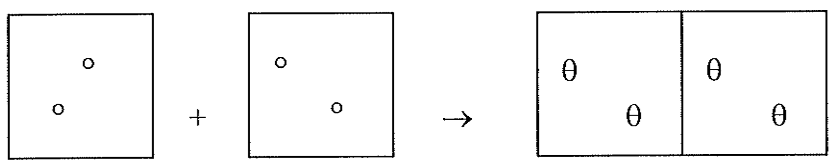
two volumes of hydrogen + one vol. of oxygen → two volumes of water
(diatomic molecules) (diatomic molecules) molecules



Example:

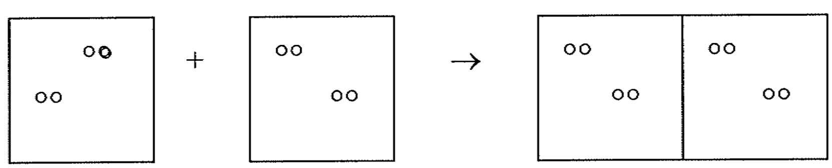
1 vol. hydrogen + 1vol. chlorine → 2 vol. hydrogen chloride

Previous Beliefs



Each reacting atom split in half for the reaction to occur.

Avogadro's Reasoning



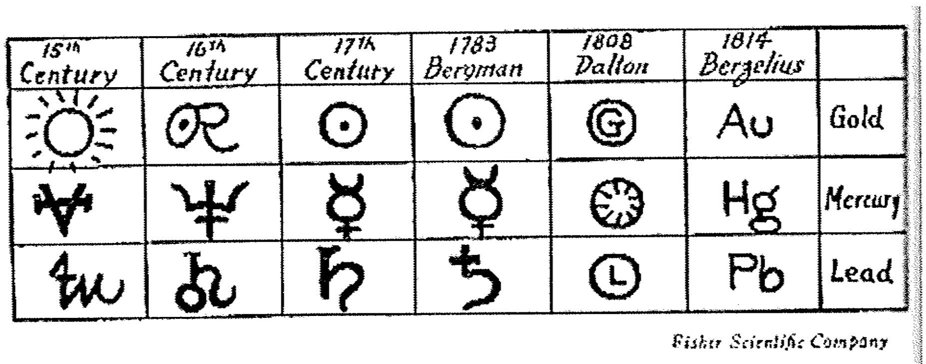
Each molecule of gas contained two atoms.

Interactive Vignette 3: BERZELIUS (1779 – 1848)

When John Dalton developed his Atomic theory some chemical symbols were already being used for some substances. There was no uniformity within the scientific community though, causing quite a bit of confusion amongst the scientific community. John Dalton even developed his own symbols for some of the elements and compounds. Most of his symbols consisted of circles with lines or shapes inside. (see overhead)

In 1813, a simple and logical system was adopted by the international society for chemistry. Berzelius, a Swedish chemist, is responsible for the modern system of chemical notation which uses the first or first two letters of the element's name to represent an atom of that element. For example: H = 1 atom of hydrogen, Zn = 1 atom of zinc. (Lead was Plumbum, thus symbol was Pb, Gold was auric – Au). This eventually was applied to compounds as well, except superscripts, instead of subscripts, were used to indicate proportions (CO^2 vs. CO_2). HO = water, NH = ammonia, CO = carbonic oxide and CO_2 = carbonic acid. Since Berzelius was a firm believer in the John Dalton and his atomic theory, the uncertainty that existed with Dalton's atomic weights soon also existed in Berzelius' method of nomenclature, but now there was a uniformity amongst chemists and an easier method of chemical notation.

The History of Atomic Symbols



(Source: Couke et al, 1958)

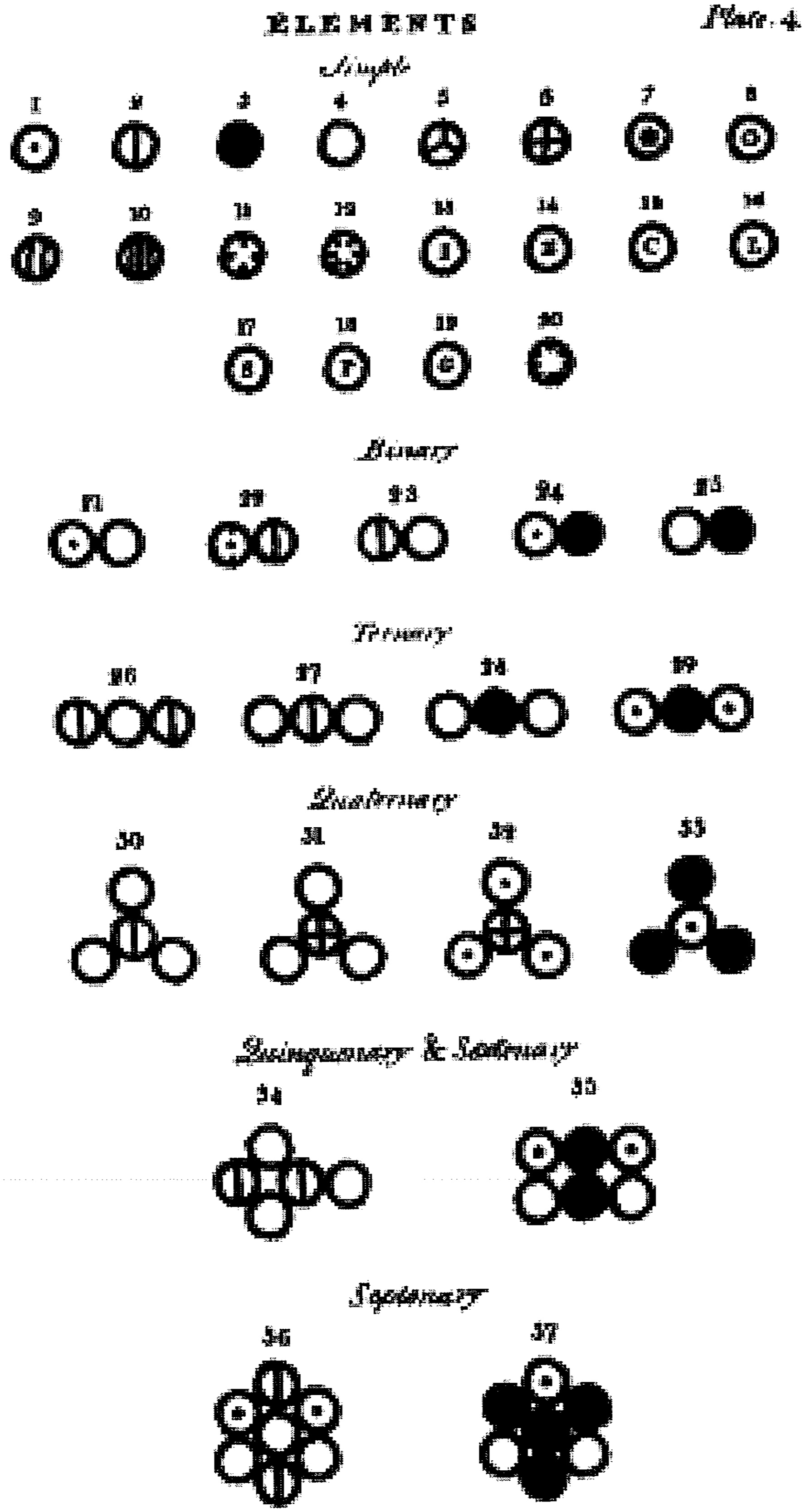
Student Activity

Write out the chemical reaction between hydrogen and nitrogen to produce ammonia (NH_3) using both Dalton's and Berzelius' chemical symbols.

Which is easier to write? Understand?

Dalton's Symbols

(Source: Carmen Giunta, Excerpts from *A New System of Chemical Philosophy*)



Ineractive Vignette 4: BROWNIAN MOTION (~1828)

Read to class:

In 1828, Robert Brown, a London doctor and botanist observed that plant pollen particles, suspended in water, seem to be in a constant state of motion when observed under the microscope. He also found that inorganic materials such as carbon and various metals were equally subject to it, but he could not find the cause of the movement. The cause of this movement was doubtful for a long period of time and remained an unknown until Einstein studied it almost eighty years later.

Have students observe Brownian Motion through one of the following ways:

- video (in the kinetic theory of gases in library)
- a microscope (possibly attached to a camera)
    - a solution with small particles (may be milk, India ink, or powdered carmine) on a slide and set up under a microscope at high power (400X)
    - carbon suspension in water

Interactive Vignette 5: FARADAY'S LAWS OF ELECTROLYSIS (~ 1834)

Preparation:

Have several electrolytic cells set up around the classroom. Choose ones that will show a definite product that can be easily observed by the students:

- Electrolysis of copper sulfate
- Electrolysis of water

Read to class:

In 1834, Michael Faraday studied the effect of electric currents on water solutions of a variety of different substances. He determined that chemical compounds could be separated into their elemental components by passing an electric current through them, and called this process "electrolysis". He completed many quantitative studies on electrolysis, and from analysis of the data proposed that a fixed quantity of electricity would produce a definite amount of an element at one of the electrodes.

Faraday called these masses of elements produced, "electrochemical equivalents", and found that for many elements, the equivalents were the same as Dalton's reported atomic masses. Faraday was able to measure the total charge (1 Faraday = 96,500 coulombs) required to deposit a mass of an element, equal to its atomic mass. Michael Faraday was aware that this mass of element would contain a definite number of atoms according to Avogadro's hypothesis, and knew that this number of atoms, multiplied by the unit of charge, e, should equal one faraday, but was unable to find Avogadro's number or the unit of charge separately. Faraday was not able to prove that atoms actually existed, but his quantitative experimental data from electrolysis was clearly explained using the ideas of atomism. By so doing, he gave more credibility to the existence of atoms.

For Reference (or expansion):

- The Faraday constant, F, is the quantity of electricity carried by Avogadro's number of electrons.

  F = Avogadro's Number x charge on electron (coulombs)

Interactive Vignette 6: STANISLAO CANNIZZARO (1826 – 1910)

Read to Students:

The mid-1800's proved to be very confusing for the scientific community. Dalton's law of definite proportions and Gay-Lussac's Law of Combining Volumes were being used independently without a consideration of Avogadro's hypothesis. This led to different interpretations of quantitative results from chemical reactions and a variety of atomic mass tables. In 1860, the first International Chemical Congress was held in Germany.

What follows is a tape recording of some of the proceedings of the congress:

Narrator:

First Session of the Congress

Mr. Weltzien, General Commissioner, opened the first session with the following speech:

Mr. Weltzien:

Gentlemen:

I have the honor to inaugurate a Congress which has no precedent for its kind, the nature of which has never before met.

For the first time, the representatives of a single Natural Science have assembled. These representatives belong to nearly every nationality. We may be of differing ethnic origin and speak different languages, but we are related by professional specialty, are bound by scientific interest, and are united by the same design. We are assembled for the specific goal of attempting to initiate unification around points of vital concern for our science. Due to the extraordinarily swift development of Chemistry, and because of the massive accumulation of factual materials, and the means of expression, both in words and symbols, theoretical viewpoints have begun to differ more than is expedient for mutual understanding, and, especially, more than is suitable for instruction. Considering the importance of Chemistry, it seems advisable to cast our science in a more rigorous form, so that it will be possible to communicate it in a relatively more concise manner.

In order to achieve this, we should not only review various viewpoints and writing conventions, and we should not be burdened with a nomenclature, which lacks any rational basis, and which, is derived, for the most part, from a theory whose validity can hardly be maintained today. The ample attendance at this Congress is surely a clear indication that these problems are universally recognized and that their resolution is desirable. The achievement of this end is well worth the effort to undertake the task here.

I do not doubt that this Congress will be called upon to lay the foundations for an important era in the history of our science, and hope that our science will one day look back with satisfaction upon our assembly.

Narrator: First Session of the Commission, September 3, 1860 at 11 A.M.

The chairman suggests that the discussion begin with the notions of molecule and atom, and he asks Mr. Kekulé and Mr. Cannizzaro, whose studies have especially encompassed this issue, to take the floor.

Cannizzarro:

For those of you who do not know me, I am Stanislao Cannizzarro, a professor of chemistry and physics at the university of Genoa where I teach a course in theoretical chemistry.

"I believe that the progress of science made in these last years has confirmed the hypothesis of Avogadro… that is, that equal volumes of these substances, whether simple or compound, contain an equal number of molecules; not an equal number of atoms."

In order to lead my students to the same conviction I have reached myself, I lead them through a historical examination of chemical theories.

I start my first lecture by showing my students how, from the examination of the physical properties of gases, and from the law of Gay-Lussac on the volume relations between components and compounds, that Avogadro's hypothesis contains nothing contradictory to known facts, provided that we distinguish, molecules from atoms.

In the second lecture, I investigate the reasons why Avogadro's hypothesis was not immediately accepted by the majority of chemists. I explain the ideas and work of those individuals who examined the relationships of reacting quantities of substances without concerning themselves with the volumes these substances occupy in the gaseous state. We have only to distinguish atoms from molecules in order to reconcile all the experimental results known.

In the third lecture I review various research and show that all the new research from Gay-Lussac to Clausius confirm the Avogadro's hypothesis. The distances between the molecules, so long as they remain in the gaseous state, do not depend on the their nature, nor on their mass, nor on the number of atoms they contain, but only on the temperature and pressure to which they are subjected.

In the fourth lecture I review chemical theories and explain clearly how discoveries on the constitution of organic compounds further confirm Avogadro's hypothesis.

Thus, from the historical examination of chemical theories as well as from physical researches, I draw the conclusion that to bring harmony to all the branches of chemistry we must resort to the complete application of Avogadro's theory in order to compare the weights and the numbers of the molecules. I propose to show that the conclusions drawn from it are in accordance with all physical and chemical laws discovered.

Teacher Summary:

Cannizzarro proceeded to explain how, by applying Avogadro's hypothesis, weights of molecules could be determined even before their composition was known. He demonstrated how hydrogen, being the lightest gas, could be used as the unit to which others gases are referred.

After much discussion during the congress, the chemists agreed to return home to decide for themselves how to proceed. Many participants had heard young Cannizzarro speak about Avogadro's hypothesis, and others carried away a printed version of Cannizzaro's outline, where Cannizzaro strongly recommended that Avogadro's hypothesis be accepted and used.

Cannizzaro established values for atomic and molecular weight, designating the weight of hydrogen as the universal standard by which other elements should be measured. This led to the 1869 publication of Mendeleev's Periodic Table. The periodic occurrence of similar physical and chemical properties supported the recorded relative masses of the elements. These values soon became widely accepted by the scientific community.

Once an agreement of atomic weights was established, the pathway for determining the number of atoms in Avogadro's number became evident. It was recognized that if the atomic weight of substance A was two times heavier than the atomic weight of substance B, two grams of A would have the same number of atoms as one gram of B.

Interactive Vignette 7: JOSEPH LOSCHMIDT (1821- 1895)

Recall – Chemistry congress was in 1860

Soap Bubble Demonstration:

Briefly explain the idea of light wavelengths and colours and light interference. A laser and grating can be used to help students visualize this effect. This explanation might be enhanced by the use of a computer simulation that shows various wavelengths of light and the resulting colours observed.

Make a large soap bubble and show students how the interference of light from a light bulb (when held in front) causes the production of many different colours.

Explain to students:

Due to the action of gravity on the bubble, producing a wedge, there will be a place where the film is the thinnest, much **shorter** than the wavelength of visible light($<10^{-7}$m). At this spot, there will be no visible reflection and the bubble will look black. The bubble is only about $10^{-7} - 10^{-8}$ m thick (one ten-thousandth of a millimeter at most) at this spot and will soon pop. If we estimate that there are 10 molecules in this thinnest spot on the film, what would be a rough estimate of the size of one molecule? (10^{-8} to 10^{-9} m or one hundredth thousandth of a millimeter to one millionth of a millimeter)

You might choose to provide each student with some bubble solution and small loops so that they can see the colours up close.

Tell Class:

One of the first scientists to make an estimate of the diameter of a molecule was Joseph Loschmidt, in 1865. He assumed that the volume of a substance, when reduced to the liquid form, would not be much greater than the total volume of all its molecules.

He deduced that the following two **ratios** were comparable:

$$\frac{\textbf{the volume of a gas}}{\textbf{total volume of all the molecules}} = \frac{\textbf{the space between one collision and the next of a molecule (the mean free path)}}{\textbf{one-eighth of the diameter of a molecule}}$$

(The value for mean free path was obtained from previous work by Clausius and Maxwell on the determination of average velocity of molecules of gases at different temperatures, and the relationship of total kinetic energy of a gas corresponding to that velocity. It was found that the diameter of a gas molecule was equal to 8X the mean free path.)

Loschmidt determined that an air molecule is one millionth of a millimeter in diameter. Loschmidt's size of a molecule of hydrogen was such that two million arranged in a row would take up one millimeter of space. He found that one cubic centimeter (hold up a sample cube), at normal temperature and pressure, would contain approximately nineteen million million million molecules or 1.9×10^{18}).

These results were supported by the individual results obtained by Stoney (1868) and Thomson (1870). Thomson's estimate was deduced using the thickness of soap bubbles and from the electric properties of metals.

Interactive Vignette 8: EINSTEIN THE CHEMIST (1905)

Recall: Brownian Motion was discovered in 1828.

The first estimate of the size of an atom was in 1865.

Read to class:

Einstein nearly became a chemist, but after many unsuccessful attempts to obtain academic appointments he settled on a job as a patent clerk. This job provided Einstein lots of idle time to think about his chief obsession – finding facts that would guarantee the existence of atoms. During his free time he worked on three different papers in physics and chemistry, and in 1905 (100 years ago, and only at 26 years of age), all three papers were published in the same physics journal and changed the life of science.

In one of these papers Albert Einstein made some very important statements regarding the existence of atoms, although atoms and molecules were still open to objection in the scientific world.

In his paper, Einstein described how the random motions of larger particles in a suspension, as viewed under a microscope, were the result of collisions with the random movement of smaller molecules in a liquid, which moved according to the kinetic theory of liquids. The random bombardment of a particle would cause it to move in the same way Robert Brown had described it years ago and, due to the large size of the particle, measurements could be made more easily than on the water molecules themselves. Einstein determined that the displacement of a Brownian particle would not increase linearly with time but with the square root of time, since the particular motion resembles that of a "random walk".

Show simulation: (Fowler, M. "Einstein and Brownian motion: simulation of random walk, http://galileo.phys.virginia.edu/classes/109N/more_stuff/Applets/brownian/enbrownian.html.)

A "random walk" has some predictability in the same way that certain rolls on dice would be more possible. For example, even though throws of dice are random, a roll of two would be less probable then a roll of seven. This is because you need to roll two ones to get a roll of 2, but several possibilities will give a sum of 7 (a 1 and 6, 2 and 5…). After repeated rolls of the dice, you would expect to see many more 7's than 2's in the long run.

Random walks hold the same sort of predictability. It is quite unlikely, although possible, for a walker to head off in one direction and continue in a straight line. More often, a walker's path will loop back upon itself and, in the end, the walker does not venture too far off from his starting point. It has been proven that after N random steps, such a walker will *on average* end up at a distance of $\sqrt{N}$ from its starting place. For example, a person taking 100 random steps, each one foot in size, will end up only 10 feet ($\sqrt{100}$) *on average* from their starting position.

(reference: http://www.ms.uky.edu/~mai/java/stat/brmo.html)

In his paper, Einstein provided an equation by which Avogadro's number could be determined simply by studying Brownian motion. This equation replaced the number of steps in a random walk with the number of collisions of a particle. The equation also took particle size, temperature and liquid viscosity into consideration. Einstein suggested that a "measurement of the average position of a microscopic particle versus time could be used to make the first direct determination of Avogadro's number" (Salmon, 2002). His paper "gave experimentalists a way to count atoms by looking through an ordinary microscope" and "provided convincing evidence for the physical existence of atom-sized molecules". This almost 100 years after Avogadro made his hypothesis.

Interactive Vignette 9: JEAN PERRIN AND BROWNIAN MOTION (~1910)

Read to Students:

In 1908, guided by Einstein's work, Jean Perrin, a French physicist, set about quantitatively studying Brownian Motion in order to determine Avogadro's number.

This is how he did it:

Perrin first prepared a suspension of similar-sized particles. Then, under the microscope, he followed the movement of a single particle, noting its position after successive, equal time intervals (30 s). (overhead) Plugging-in the obtained value for the mean displacement into Einstein's equation, Perrin was able to calculate a value for Avogadro's number.

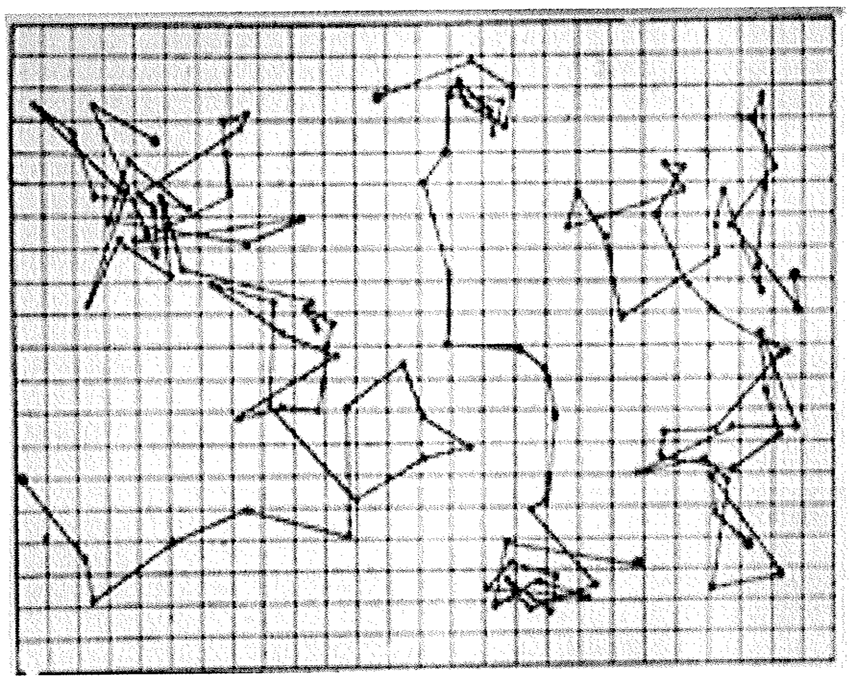
Einstein's equation (not for students)

$$N_A = (t / \lambda_x^2)\ (RT/3\pi\eta\rho)$$

λ_x = displacement (x-axis) η= viscosity ρ= radius of spheres

Perrin repeated this procedure many times, working with various emulsions and variations in grain size and mass. According to Perrin, the emulsion containing the most uniform grains produced the "most accurate measurements" and gave a value of 6.4×10^{23} for Avogadro's number. The similarity in all of Perrin's results gave Einstein's formula considerable support as well as demonstrated the reality of atoms.

Currently, students at the university of Winnipeg are studying Brownian motion using a microscope, a video camera, and video capture software to verify Einstein's calculation of 1905. Avogadro's number is determined by simply taking the slope of a graph of average square displacement vs. time.



From: Perrin: Atoms

Interactive Vignette 10: JEAN PERRIN AND THE VERTICAL DISTRIBUTION OF PARTICLES IN EMULSIONS

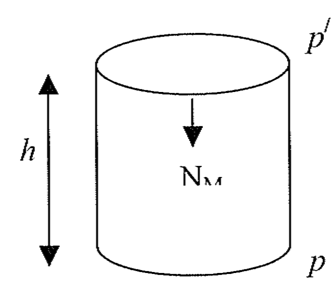
Read story:

Yesterday we described how Jean Perrin followed Brownian motion of particles to get a value for Avogadro's number. Perrin also studied the distribution of particles in a suspension, as another way of determining Avogadro's number.

In our last unit we discussed atmospheric pressure, and, if you recall, how it is greater at sea level, and decreases at higher altitudes. Thus, there are more molecules of air at sea level, than there are at higher altitudes.

Perrin applied this relationship to emulsions (particles suspended in a liquid). There will be more particles near the bottom, fewer near the top. Once the opposing effects of Brownian motion and gravity reach equilibrium, equal height differences in the liquid will correspond to equal differences in the numbers of particles.

p' and p are the two pressures found at different heights
h is the height of the column
N_M is molecular weight of the particles



It was found that the ratio p' to p remains constant if the height is unchanged. For example, for each step you climb going up a staircase, the pressure decreases by the same relative amount independent of the level at which the staircase starts or which step we are on.

The process of preparing of a suitable emulsion was very lengthy. Perrin used a dried vegetable latex (gamboge) which formed a bright yellow emulsion. In order to obtain an emulsion with appropriate sized grains, the emulsion was centrifuged, washed and centrifuged repeatedly.

Once the emulsion was prepared, Perrin determined the density and volume of the individual grains by different methods:

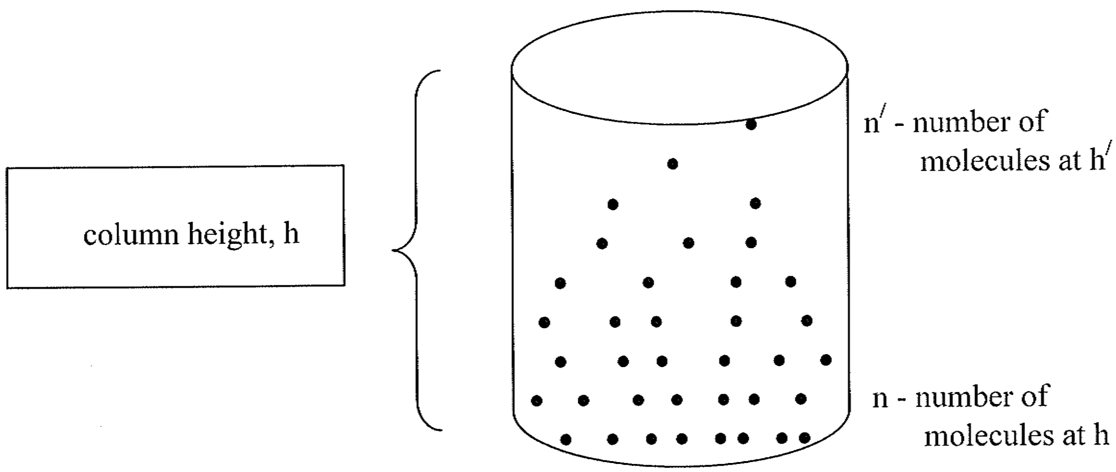
- In the first method he allowed a small amount of the emulsion to nearly evaporate onto a cover slip. The grains ran together almost in rows, allowing Perrin to count the number lying in one row where the length was known.
- The second method involved the introduction of a weak acid solution, which caused the grains of the emulsion to "collect on the walls of the glass without adhering to one another". Once all the grains were fixed, Perrin could again count the grains.

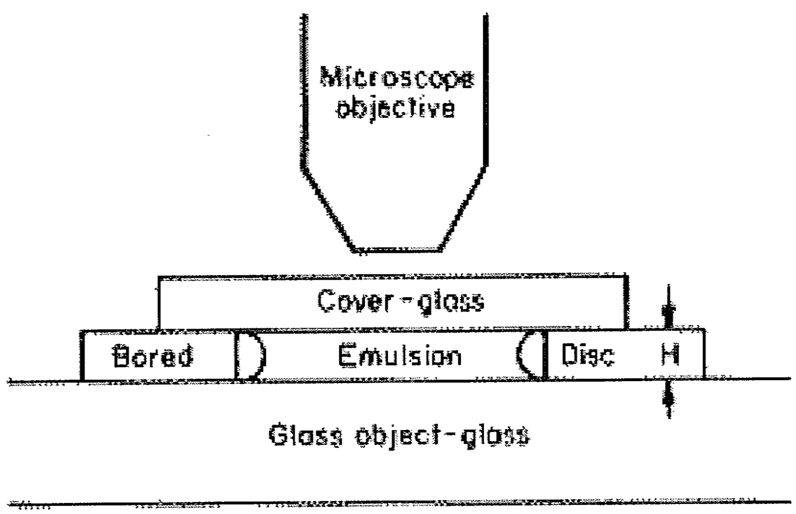
After a very long period of preparation, it finally came time to observe the emulsions and count the grains contained within at two differing heights. To do this a drop of the emulsion was placed in a 0.1 mm hollow section of a glass slide and was covered with a cover glass. To prevent evaporation of the emulsion, paraffin was placed on the edges of the cover glass. The slide could be placed either vertically (with the microscope horizontally), where the complete distribution of the emulsion was observed at once, or horizontally (with the microscope vertically), where the emulsion was observed on one layer of particles at a time as the microscope was raised or lowered.

In order to count the grains, the easiest method involved taking photographs and counting the number of grains observed, but good images were hard to obtain. Therefore, Perrin decreased the field of vision to allow him to quickly count the grains he could see. He would then repeat this at another height in the emulsion. Every hour, Perrin would determine the ratio of the grains at the two fixed heights and found that after one hour the ratios did not change, and they remained the same up to 15 days later. Perrin repeated his findings with emulsions containing particles in varying sizes, a different nature of grain, different liquids, varying grain densities and differing temperature (–9°C and at 60°C).

Despite all the changes, Perrin found that the value for Avogadro's number remained relatively constant between 65×10^{22} and 72×10^{22}.

For his achievement Perrin was honoured with the Nobel Prize for Physics in 1926.





(From Perrin: Atoms)

Interactive Vignettes: SUMMARY

Through the years, many different phenomena have been involved in the determination of Avogadro's number. Whether it was the kinetic theory and gases, charged particles in solution, or radioactive substances, the results for Avogadro's number are surprisingly similar to one another. The table below summarizes the range of studies done, and shows the closeness between the results for N. This gives much support to the atomic theory and Avogadro's hypothesis. (See overhead)

Modern methods of determining Avogadro's number rely on the use of x-ray crystallography to get precise dimensions in crystals. These can produce extremely precise values of N_A with an error of less than 0.000 000 01. The current value for Avogadro's number of particles is $6.022\ 1415 \times 10^{23}$.

Revisiting Dalton's Atomic Theory:

When we first started this historical journey into the history of Avogadro's number, we looked at John Dalton and his introduction of the atomic theory. Let's take a moment to evaluate the points to his theory: (Read out each point and have students comment on the statements – bringing to light the changes that have been made to the theory with time).

1) All matter is made of atoms. Atoms are indivisible and indestructible. (nuclear reactions can change atomic structure…)
2) All atoms of a given element are identical in mass and properties (atoms of different elements are different (in properties and mass). (existence of isotopes)

3) Compounds are formed by a combination of two or more different kinds of atoms.
4) A chemical reaction is simply a *rearrangement* of atoms.

Two of Dalton's main postulates were partially incorrect, yet some of the most important discoveries and foundations in science were based on his atomic theory. This is important as it brings to light the fact that science is a human endeavor. Science does not always provide the correct answers, but theories can, with time, guide us in the right direction.

Also important to note is the length in time it took science to prove, beyond a doubt, that atoms exist. Dalton introduced his theory in 1808, but it wasn't until 1908, that unquestionable evidence for atoms arose. Textbooks and teachers do not always mention the theories that existed before. Instead they teach the theory that is presently believed. Imagine how science might progress over the next one-hundred years!

Summary of Various Methods that have given values for N

Phenomena Observed		$N/10^{22}$
Viscosity of Gases		62 (?)
Vertical Distribution in dilute emulsions		68
Vertical Distribution in concentrated emulsions		60
Brownian Movement	Displacements	64
	Rotations	65
	Diffusion	69
Density fluctuation in concentration emulsions		60
Critical Opalescence		75
Blueness of the Sky		65
Diffusion of light in Argon		69
Black Body Spectrum		61
Charge as microscopic particles		61 (?)
Radioactivity	Projected charges	62
	helium produced	66
	Radium lost	64
	Energy radiated	60

From: Perrin, Jean. Atoms. Constable & Company Ltd., London, England, 1923.

Appendix E

Test of Chemistry Attitudes

Chemistry Attitude

Please read the following sentences and circle the answer that describes your attitude. There are no right answers – please describe yourself as you are, not how you want to be or think you ought to be.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
1	**2**	**3**	**4**	**5**

1. Money spent on chemistry is well worth spending.	1	2	3	4	5
2. I would prefer to find out why something happens by doing an experiment than by being told.	1	2	3	4	5
3. I enjoy reading about things which disagree with my previous ideas.	1	2	3	4	5
4. Chemistry classes are fun.	1	2	3	4	5
5. I would like to belong to a chemistry club.	1	2	3	4	5
6. Chemistry is the world's worst enemy.	1	2	3	4	5
7. Doing experiments is not as good as finding out information from teachers.	1	2	3	4	5
8. I dislike repeating experiments to check that I get the same results.	1	2	3	4	5
9. I dislike chemistry classes.	1	2	3	4	5
10. I get bored when watching programs about chemistry on TV at home.	1	2	3	4	5
11. When I leave school, I would like to work with people who make discoveries in chemistry.	1	2	3	4	5
12. Public money spent on chemistry in the last few years has been spent wisely.	1	2	3	4	5
13. I would prefer to do experiments than to read about them.	1	2	3	4	5
14. I am curious about the world in which we live.	1	2	3	4	5
15. School should have more chemistry classes.	1	2	3	4	5
16. I would like to be given a book on chemistry or a piece of chemistry equipment as a present.	1	2	3	4	5
17. I would dislike a job in a chemistry laboratory after I leave school.	1	2	3	4	5
18. Discoveries in chemistry are doing more harm than good.	1	2	3	4	5
19. I would rather agree with other people than do an experiment to find out myself.	1	2	3	4	5
20. Finding out about new things is unimportant.	1	2	3	4	5
21. Chemistry classes bore me.	1	2	3	4	5
22. I dislike reading books about chemistry during my vacations.	1	2	3	4	5
23. Working in a chemistry laboratory would be an interesting way to earn a living.	1	2	3	4	5
24. The government should spend more money on research in chemistry.	1	2	3	4	5
25. I would prefer to do my own experiments than to find out information from a teacher.	1	2	3	4	5

Turn over …..

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

26. I like to listen to people whose opinions are different from mine.	1	2	3	4	5
27. Chemistry is one of the most interesting school subjects.	1	2	3	4	5
28. I would like to do chemistry experiments at home.	1	2	3	4	5
29. A career in chemistry would be dull and boring.	1	2	3	4	5
30. Too many laboratories are being built at the expense of the rest of education.	1	2	3	4	5
31. I would rather find out about things by asking an expert than by doing an experiment.	1	2	3	4	5
32. I find it boring to hear about new ideas.	1	2	3	4	5
33. Chemistry classes are a waste of time.	1	2	3	4	5

Adapted from: Test of Science-Related Attitudes (TOSRA): Fraser, B.L. (1978). Development of a test of science-related attitudes. *Science Education*, 62, 509-515.

Appendix F

Summary of Individual Attitude Subscales

Attitude 1: Social Importance of Chemistry

1. Money spent on chemistry is well worth spending.
6. Chemistry is the world's worst enemy.
12. Public money spent on chemistry in the last few years has been spent wisely.
18. Discoveries in chemistry are doing more harm than good.
24. The government should spend more money on research in chemistry.
30. Too many laboratories are being built at the expense of the rest of education.

(Results for questions 6, 18, and 30 were reversed for analysis.)

Attitude 2: Preference for Experimentation

2. I would prefer to find out why something happens by doing an experiment than by being told.
7. Doing experiments is not as good as finding out information from teachers.
8. I dislike repeating experiments to check that I get the same results.
13. I would prefer to do experiments than to read about them.
19. I would rather agree with other people than do an experiment to find out myself.
25. I would prefer to do my own experiments that to find out information from a teacher.
31. I would rather find out about things by asking an expert than by doing an experiment.

(Results for questions 7, 8, 19, and 31 were reversed for analysis.)

Attitude 3: Openness to New Ideas

3. I enjoy reading about things which disagree with my previous ideas.
14. I am curious about the world in which we live.
20. Finding out about new things is unimportant.
26. I like to listen to people whose opinions are different from mine.
32. I find it boring to hear about new ideas.

(Results for questions 20 and 32 were reversed for analysis.)

Attitude 4: Attitude Toward Chemistry Classes

4. Chemistry classes are fun.
9. I dislike chemistry classes.
15. School should have more chemistry classes.
21. Chemistry classes bore me.
27. Chemistry is one of the most interesting school subjects.
33. Chemistry classes are a waste of time.

(Results for questions 9, 21, and 33 were reversed for analysis.)

Attitude 5: Attitude Toward Chemistry Leisure

5. I would like to belong to a chemistry club.
10. I get bored when watching programs about chemistry on TV at home.
16. I would like to be given a book on chemistry or a piece of chemistry equipment as a present.
22. I dislike reading books about chemistry during my vacations.
28. I would like to do chemistry experiments at home.

(Results for questions 10 and 22 were reversed for analysis.)

Attitude 6: Attitude Toward Chemistry Careers

11. When I leave school, I would like to work with people who make discoveries in chemistry.
17. I would dislike a job in a chemistry laboratory after I leave school.
23. Working in a chemistry laboratory would be an interesting way to earn a living.
29. A career in chemistry would be dull and boring.

(Results for questions 17 and 29 were reversed for analysis.)

Appendix G

Open-Ended Attitudes Question for Intervention Class Following Study

In the space below, please give your opinion about the use of the interactive vignettes in teaching the history of the mole concept in chemistry. Please consider several factors, such as:

- how they affected your interest in the class and topic
- their effectiveness in relaying concepts
- how they affected your motivation to learn more
- whether activity based or non-activity based was better

Appendix H

Chapter Test

Che30S

Unit 3 Test A: Chemical Reactions and Stoichiometry

Part 1: Multiple Choice – shade in the best answer on the scan sheet provided.

1. In the chemical equation $2\ C_2H_6 + 7O_2 \rightarrow 6\ H_2O + 4\ CO_2$ the number 7 is called a

   a. subscript b. exponent c. superscript d. coefficient

2. The symbol (s) is used in a chemical equation to represent

   a. the solid phase b. a catalyst c. a spectator ion d. a solution

3. In the chemical equation $2H_{2(g)} + O_{2(g)} \rightarrow 2\ H_2O_{(l)}$, the term to the right of the arrow means

   a. 2 atoms of water
   b. 2 grams of water
   c. 2 liters of water
   d. 2 moles of water

4. Chemical equations become balanced by

   a. eliminating spectator ions from chemical formulas
   b. adjusting coefficients of chemical formulas
   c. rearranging the parentheses of chemical formulas
   d. adjusting subscripts of chemical formulas

5. How many substances are reactants in the equation
   $2Cl_2 + 6KOH \rightarrow 5\ KCl + KClO_3 + 3\ H_2O$

   a. 2 b. 5 c. 9 d. 18

6. In the balanced equation $2\ Na + 2\ H_2O \rightarrow H_2 + 2\ X$

   a. Na_2O_2 b. Na_2O c. NaH d. NaOH

7. When the equation $Al_2(SO_4)_3 + BaCl_2 \rightarrow AlCl_3 + BaSO_4$ is balanced using the smallest whole number coefficients, what is the coefficient of $Al_2(SO_4)_3$?

   a. 1 b. 2 c. 3 d. 4

8. A mole of oxygen molecules consists of

   a. 1 oxygen atom
   b. 2 oxygen atoms
   c. 6.02×10^{23} oxygen atoms
   d. 12.04×10^{23} oxygen atoms

9. What is the total number of atoms represented by one unit of $(NH_4)_2HPO_4$?

   a. 22 b. 11 c. 16 d. 5

10. What is the approximate total number of hydrogen atoms in one mole of CH_3OH?

   a. 24×10^{23} b. 6×10^{23} c. 18×10^{23} d. 36×10^{23}

11. Which sample of hydrogen gas occupies the largest volume at STP?

   a. 2 moles
   b. 2 litres
   c. 2 grams
   d. 2×10^{23} molecules

12. What is the minimum number of moles of $O_{2(g)}$ needed to produce 1.0 mole of CO_2 according to the reaction whose balanced equation is $2CO_{(g)} + O_{2(g)} \rightarrow 2\ CO_{2(g)}$

a. 0.25 mole b. 0.5 mole c. 1 mole d. 2 moles

13. How many atoms are there in 4.5 g of CO_2?

a. 1.8×10^{23} b. 6.2×10^{22} c. 6.0×10^{23} d. 1.2×10^{26}

14. Under ordinary conditions, which substance exists as a diatomic molecule?

a. zinc b. bromine c. iron d. helium

15. As aluminum burns in oxygen according to the equation $4Al_{(s)} + 3O_{2(g)} \rightarrow 2Al_2O_{3(s)}$ the number of aluminum atoms present

a. increases b. decreases c. remains the same

16. In the reaction whose balanced equation is: $N_{2(g)} + 3H_{2(g)} \rightarrow 2NH_{3(g)}$. What mass of $H_{2(g)}$ is needed to produce one mole of ammonia?

a. 1 g b. 2 g c. 3 g d. 4g

17. Adding the atomic masses of all elements in a molecule provides the ______.

a. formula unit b. formula mass c. molar mass d. grams in one mole

28. There are 6.02×10^{23}

a. Atoms/moles in 1 liter
b. moles in an atom
c. atoms/molecules in a mole
d. grams in one mole

19. The mass of two moles of nitrogen gas is _____

a. 56 g b. 2 g c. 17 g d. 14 g

20. What amount of matter contains the largest number of atoms?

a. 40 g of K b. 54 g of Al c. 200 g of Xe d. 200 g of Ba

21. The number of molecules present in 25 grams of nitrogen gas is equal to

a. $25 \times 6.02 \times 10^{23}$

b. $\frac{25 \times 6.02 \times 10^{23}}{28}$

c. $\frac{25}{6.02 \times 10^{23}}$

d. $\frac{25 \times 6.02 \times 10^{23}}{14}$

22. In a mass-mass problem, grams must first be converted to moles by
a. using the mole ratios from the balanced equation
b. using the molar mass of the substance
c. dividing molar mass by grams
d. none of the above methods

23. A mole of H_2O and a mole of O_2

a. have the same mass
b. contain one molecule each
c. have a mass of 1 g each
d. contain the same number of molecules

24. One mole of oxygen molecules contains more independent units (O_2) than one mole of oxygen atoms (O).

a. True, because there are two atoms of O for every molecule of O_2.
b. True, because one mole of O_2 weighs more than one mole of O.
c. False, because both of them have the same number of particles.
d. False, because one mole of O has the same mass as one mole of O_2.

Che30S **Test A: Long Answer: Chemical Reactions** Name: ___________

A: For the reactions that occur, write down the formulas for the products of the following chemical reactions (including phases), balance the equation and give the name of the reaction type. If the reaction does not occur, state why. (8 x 3 = 18)

1. ____ $C_6H_{14(g)}$ + ____ $O_{2(g)} \rightarrow$ ______________________________

   Type: ______________________

2. ____ $H_2CO_{3\,(aq)}$ + NaOH $_{(aq)} \rightarrow$ ______________________________

   Type: ______________________

3. ____ $I_{2(s)}$ + $CaBr_{2(aq)} \rightarrow$ ______________________________

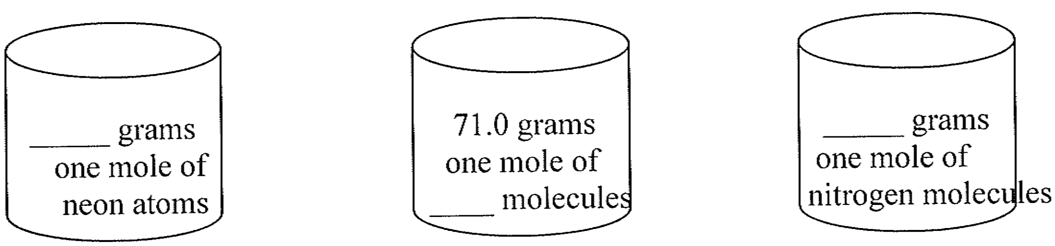
   Type: ______________________

4. ____ $Na_{(s)}$ + ____ $O_{2(g)} \rightarrow$ ______________________________

   Type: ______________________

B Calculations (Show all work)

1. The following three containers have identical capacities. Each contains Avogadro's number of molecules of a gaseous element. Fill in the blanks with the missing information. (3)



2. What mass of chlorine atoms contains the same number of atoms as does 24.0 grams of carbon? (1)

3. How many moles of atoms are there in 1.20×10^{25} carbon tetrachloride, CCl_4 molecules? (1)

4. How many moles of nickel atoms are needed to supply the same number of atoms as does 10.0 grams of neon? (2)

5. 0.500 mole of an element has a mass of 31.75 grams. Identify the element.(1)

6. Each carbon atom contains 6 electrons. How many carbon atoms will contain one mole of electrons?(1)

7. What is the volume of 3.0 x 10^{24} molecules of CO_2 at STP?(2)

8. At STP, how many moles of neon gas in a 11.5 L sample? (1)

C. 9. Nitrogen gas and hydrogen gas react at S.T.P. to make ammonia.

$$N_{2(g)} + 3H_{2(g)} \rightarrow 2NH_{3(g)}$$

a) If 24.0 g of nitrogen gas reacts, what volume of ammonia is produced? (2)

b) What mass of hydrogen gas is needed to produce 450. g of ammonia? (2)

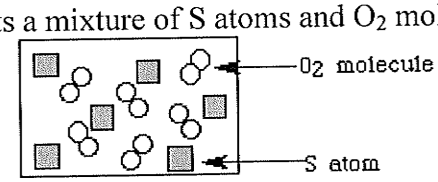
10. Given the following unbalanced equation:

$$C_2H_6 + O_2 \longrightarrow CO_2 + H_2O$$

a) Given 10.5g of ethane gas reacting with 26.88L of oxygen gas at STP. Determine the limiting reactant. (3 marks)

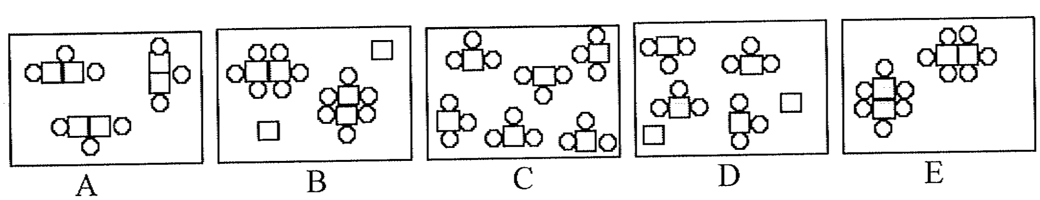
b) What is the mass of water produced in this reaction(1 mark)

11. The diagram represents a mixture of S atoms and O_2 molecules in a closed container.



Chose and explain which diagram shows the results after the mixture reacts as completely as possible according to the equation:

$2S + 3O_2 \text{ --> } 2SO_3$



Appendix I: Analysis of Pretest Attitudes Tests

Attitude 1	Time	M	SD	N	t	p
Social Importance of Chemistry	Control Pretest	16.577	2.626	26	0.209	0.835
	Exp. Pretest	16.741	3.046	27		
	difference	-0.164	-0.42			

Attitude 2	Time	M	SD	N	t	p
Preference for Experimentation	Control Pretest	22.346	2.884	26	0.566	0.574
	Exp. Pretest	21.889	2.991	27		
	difference	0.457	-0.107			

Attitude 3	Time	M	SD	N	t	p
Openness to new Ideas	Control Pretest	14.5	2.702	26	1.24	0.221
	Exp. Pretest	13.63	2.404	27		
	difference	0.87	0.298			

Attitude 4	Time	M	SD	N	t	p
Chemistry classes.	Control Pretest	17.038	2.522	26	0.343	0.733
	Exp. Pretest	16.778	2.979	27		
	difference	0.26	-0.457			

Attitude 5	Time	M	SD	N	t	p
Chemistry Leisure	Control Pretest	13.538	2.486	26	0.237	0.814
	Exp. Pretest	13.741	3.601	27		
	difference	-0.203	-1.115			

Attitude 6	Time	M	SD	N	t	p
Chemistry Careers	Control Pretest	11.385	2.137	26	0.0256	0.980
	Exp. Pretest	11.37	1.904	27		
	difference	0.015	0.233			

None of these results show any statistical significance (no p scores < 0.05).

Analysis of Post Attitudes Tests

Attitude 1	Time	M	SD	N	t	p
Social Importance of Chemistry	**Control Posttest**	17.654	2.799	26	0.207	0.837
	Exp. Posttest	17.5	2.55	26		
	difference	0.154	0.249			

Attitude 2	Time	M	SD	N	t	p
Preference for Experimentation	**Control Posttest**	22.154	3.209	26	0.760	0.451
	Exp. Posttest	22.769	2.597	26		
	difference	-0.615	0.612			

Attitude 3	Time	M	SD	N	t	p
Openness to new Ideas	**Control Posttest**	14.962	2.441	26	0.499	0.620
	Exp. Posttest	15.308	2.558	26		
	difference	-0.346	-0.117			

Attitude 4	Time	M	SD	N	t	p
Chemistry classes.	**Control Posttest**	17.731	2.127	26	0.296	0.769
	Exp. Posttest	17.5	3.362	26		
	difference	0.231	-1.235			

Attitude 5	Time	M	SD	N	t	p
Chemistry Leisure	**Control Posttest**	13.538	2.083	26	2.936	**0.00502**
	Exp. Posttest	15.885	3.502	26		
	difference	-2.347	-1.419			

Attitude 6	Time	M	SD	N	t	p
Chemistry Careers	**Control Posttest**	11.038	1.399	26	1.99	**0.0524**
	Exp. Posttest	11.923	1.787	26		
	difference	-0.885	-0.388			

Attitude 5 shows a significant score at CL 99%.
Attitude 6 shows a significant score at CL 90%.

Analysis of All Attitudes Pre and Post-Tests

All Attitudes	Time	M	SD	N	t	p
	Control Pretest	95.385	10.666	26	0.438	0.663
	Exp. Pretest	94.146	9.883	27		
	difference	1.239	0.783			

All Attitudes	Time	M	SD	N	t	p
	Control Posttest	97.077	9.761	26	1.338	0.187
	Exp. Posttest	100.885	10.742	26		
	difference	-3.808	-0.981			

Neither of these results shows any statistical significance (no t scores < 0.05).

Appendix J: T-test Analysis of Items for Attitude 5
Attitude toward Chemistry Leisure

Question 5:	Time	M	SD	N	t	p
I would like to belong to a chemistry club.	Pretest control	1.923	1.017	26	0.0827	0.412
	Pretest expt.	2.185	1.272	27		
	Difference	-0.262	-0.255			
	Time	**M**	**SD**	**N**	**t**	**p**
	Posttest control	2.077	0.796	26	2.520	***0.0149** (CL95%)
	Posttest exp.	2.815	1.272	27		
	difference	-0.738	-0.576			

Question 10:	Time	M	SD	N	t	p
I get bored when watching programs about chemistry on TV at home.	Pretest control	2.731	1.251	26	0.526	0.601
	Pretest expt.	2.926	1.439	27		
	Difference	-0.195	-0.188			
	Time	**M**	**SD**	**N**	**t**	**p**
	Posttest control	2.923	1.129	26	0.432	0.638
	Posttest exp.	2.778	1.311	27		
	difference	0.145	-0.182			

Question 16:	Time	M	SD	N	t	p
I would like to be given a book on chemistry or a piece of chemistry equipment as a present.	Pretest control	2.308	1.123	26	0.187	0.852
	Pretest expt.	2.370	1.305	27		
	Difference	-0.062	-0.182			
	Time	**M**	**SD**	**N**	**t**	**p**
	Posttest control	2.577	1.06526	26	0.737	0.465
	Posttest exp.	2.815	1.272	27		
	difference	-0.238	-0.207			

Question 22:	Time	M	SD	N	t	p
I dislike reading books about chemistry during my vacations.	Pretest control	2.192	1.059	26	0.748	0.458
	Pretest expt.	2.444	1.368	27		
	Difference	-0.252	-0.309			
	Time	**M**	**SD**	**N**	**t**	**p**
	Posttest control	2.654	1.325	26	0.776	0.441
	Posttest exp.	2.370	1.334	27		
	difference	0.284	-0.009			

Question 28:	Time	M	SD	N	t	p
I would like to do chemistry experiments at home.	Pretest control	2.231	0.863	26	2.222	***0.0308 (CL 95%)**
	Pretest expt.	2.889	1.251	27		
	Difference	-0.658	-0.288			
	Time	**M**	**SD**	**N**	**t**	**p**
	Posttest control	2.615	1.098	26	2.752	***0.00812 (CL99%)**
	Posttest exp.	3.481	1.189	27		
	difference					

Appendix K: T-test Analysis of Items for Attitude 6
Attitude Toward Chemistry Careers

Question 11:	Time	M	SD	N	t	p
When I leave school, I would like to work with people who make discoveries in chemistry.	Pretest control	2.654	1.164	26	0.334	0.740
	Pretest expt.	2.556	0.974	27		
	Difference	0.098	0.190			
	Time	**M**	**SD**	**N**	**t**	**p**
	Posttest control	2.885	1.033	26	1.056	0.296
	Posttest exp.	3.185	1.039	27		
	difference	-0.300	-0.006			

Question 17:	Time	M	SD	N	t	p
I would dislike a job in a chemistry laboratory after I leave school.	Pretest control	3.269	1.041	26	0.375	0.709
	Pretest expt.	3.148	1.292	27		
	Difference	0.121	-0.251			
	Time	**M**	**SD**	**N**	**t**	**p**
	Posttest control	3.192	0.849	26	0.154	0.878
	Posttest exp.	3.148	1.199	27		
	difference	0.044	-0.350			

Question 23:	Time	M	SD	N	t	p
Working in a chemistry laboratory would be an interesting way to earn a living.	Pretest control	3.115	1.336	26	1.253	0.216
	Pretest expt.	3.556	1.219	27		
	Difference	-0.441	0.117			
	Time	**M**	**SD**	**N**	**t**	**p**
	Posttest control	3.038	0.774	26	1.529	0.132
	Posttest exp.	3.444	1.121	27		
	difference	-0.406	-0.347			

Question 29:	Time	M	SD	N	t	p
A career in chemistry would be dull and boring.	Pretest control	3.192	1.201	26	1.107	0.273
	Pretest expt.	3.556	1.188	27		
	Difference	-0.364	0.013			
	Time	**M**	**SD**	**N**	**t**	**p**
	Posttest control	3.346	0.689	26	0.310	0.758
	Posttest exp.	3.259	1.259	27		
	difference	0.087	-0.570			

Appendix L: Analysis of Control Group pre to post Attitudes Tests

Attitude 1	Time	M	SD	N	t	p
Social Importance of Chemistry	Pretest	16.52	2.663	25	1.38	0.172
	Posttest	17.6	2.843	25		
	difference	1.08	0.18			

Attitude 2	Time	M	SD	N	t	p
Preference for Experimentation	Pretest	22.52	2.801	25	0.562	0.577
	Posttest	22.04	3.221	25		
	difference	-.48	0.42			

Attitude 3	Time	M	SD	N	t	p
Openness to new Ideas	Pretest	14.56	2.74	25	0.595	0.555
	Posttest	15.0	2.483	25		
	difference	0.44	-.257			

Attitude 4	Time	M	SD	N	t	p
Chemistry classes.	Pretest	17.0	2.566	25	1.071	0.289
	Posttest	17.72	2.17	25		
	difference	0.72	-0.396			

Attitude 5	Time	M	SD	N	t	p
Chemistry Leisure	Pretest	13.6	2.517	25	0.183	0.856
	Posttest	13.48	2.104	25		
	difference	0.120	0.413			

Attitude 6	Time	M	SD	N	t	p
Chemistry Careers	Pretest	11.44	2.162	25	0.852	0.399
	Posttest	11.0	1.414	25		
	difference	0.440	0.748			

None of these results show any statistical significance (no p scores < 0.05).

Appendix M: Analysis of Experimental Group Attitudes Tests

Attitude 1	**Time**	**M**	**SD**	**N**	**t**	**p**
Social Importance of Chemistry	**Pretest**	16.667	3.212	24	0.912	0.366
	Posttest	17.417	2.43	24		
	difference	0.75	-0.782			

Attitude 2	**Time**	**M**	**SD**	**N**	**t**	**p**
Preference for Experimentation	**Pretest**	21.917	3.161	24	1.083	0.284
	Posttest	22.833	2.681	24		
	difference	0.916	-0.48			

Attitude 3	**Time**	**M**	**SD**	**N**	**t**	**p**
Openness to new Ideas	**Pretest**	13.583	2.501	24	2.424	***0.0193**
	Posttest	15.375	2.618	24		
	difference	1.792	0.117			

Attitude 4	**Time**	**M**	**SD**	**N**	**t**	**p**
Chemistry classes.	**Pretest**	16.792	3.134	24	0.695	0.491
	Posttest	17.458	3.501	24		
	difference	0.666	0.367			

Attitude 5	**Time**	**M**	**SD**	**N**	**t**	**p**
Chemistry Leisure	**Pretest**	13.792	3.776	24	1.912	***0.062**
	Posttest	15.833	3.62	24		
	difference	2.041	-0.156			

Attitude 6	**Time**	**M**	**SD**	**N**	**t**	**p**
Chemistry Careers	**Pretest**	11.375	1.996	24	0.978	0.333
	Posttest	11.917	1.84	24		
	difference	0.542	-0.156			

Attitude 3 shows a significant t score ($p<0.05$) at CL 95%
Attitude 5 shows a significant score at CL 90%.

Appendix N

Attitude Test Comments: Response to Open Ended Question

Experimental Group Post Test

Student 1: I was taught more about the scientists esp. Avogadro and how they sort their numbers.

Student 2:

- just made a background on the info
- helps you understand the concepts
- I dunno
- Activity, because it's more hands on, which is easier to learn from

Student 3: They have no effect on the level of interest in class. Basic concepts were effectively related, yet definition was unclear (ex. Molar volume). No effect on motivation, I learn all I could. Activity based could provide visual learning, but un-necessarily better.

Student 4: They didn't really affect me, not at all, they did not effect it, activity based were better

Student 5: It was interesting to hear how we came about our current knowledge, but it didn't affect my motivation. Non-activity based worked fine.

Student 6: It was good to learn about history of molecule it gave extra information about moles which I felt curious about. However it didn't affect my modifation to learn more.

Student 8: I felt that it didn't make a difference to me or benefit me in any way. It was interested in it but I didn't feel that it made that much of a difference.

Student 9: They were interesting and got me thinking, but I don't really remember what it was about. I think they should add these history-based activities to classes.

Student 10: - made it boring, not effective, made me not want to learn more, same

Student 13: Some what, yes, more than before, activity

Student 14: fun, fun, a lot, activity

Student 15: It was interesting to hear about the scientists and history. But it did not really help me concentrate on the main idea. I thought that maybe the time spent studying the scientists could have been used to learn the basics and improve our test marks. Maybe after an understanding of the mole has been reached, we could be studied who made these discoveries.

Student 16: It was interesting to learn what/who founded the thing your learning about! It makes it more interesting. It is easier to remember than. It sort of wanted to make me learn more. Activity based was maybe better because more interactive.

Student 17: The program offered additional information that was quite interesting. It really increased students' background knowledge. The concepts were useful to know although they were sometimes hard to understand. There was a lot of interesting facts given, i.e. random motion; makes students want to get more details. Activity based.

Student 18: I thought it was a good idea. The whole concept of the mole is difficult to grasp but knowing where it comes from and how long it took to discover it it becomes easier to understand. It was fun to learn about all the different chemists that made a difference in chemistry and changed the way we look a chemistry.

Student 19: The I.V.s were a good way to help me understand the concept of what the mole is. They also helped make the class more interesting, as we could just sit back and listen to the stories rather than doing work. I definitely think I would find the concept of the mole confusing had we not done the I.V.s.

Student 20: Helped to understand better about what we're learning (mole) and the demos were really interesting! (the microscope one and bubble one)

Student 21: It has made class interesting by providing information of how the concept of the mole was introduced in chemistry. Learning the people who provided bits of information into the concept of the mole was very knowledgable.

Student 22: The picture and a little lab are affected me interest in the class and topic. I think chemistry is really effect us for everything, so sometime I am very surprise that chemical can do and change many thing. Also, I feel thankful to the people who do chemistry. They need to try and try the lab again. Some of them just spend a whole time to it. I hope next time can have more activity, maybe a big lab and group work, that is more fun.

Student 23: They were interesting topics.

Student 24: I found it pretty interesting to learn new ideas and concepts that I never knew about. Didn't affect much with the interest in the class. Scientist's stories affect me to have more interest in chemistry, I found experiments more amusing.

Student 25: I find it interesting to learn about them I would like to know more about history of science but I wouldn't be interested to have them as one of the curriculums

Appendix O: Summary Table for Individual Comments

Student	*Effect on interest*	*Effectiveness in relaying concepts*	*Effect on motivation*	*Activity or non-activity based*
1				
2		√		
3	*X*	√	*X*	*No pref.*
4		*X*	*X*	*A*
5	√		*X*	*N*
6			*X*	
8	√		*X*	
9	√			
10	*boring*	*X*	*X*	
13	√	√	√	*A*
14	√	√	√	*A*
15	√	*X*		
16	√	√	√	*A*
17	√	√	√	*A*
18	√	√		
19	√	√		
20	√	√		
21	√			
22	√			*A*
23	√			
24	√			*A*
25	√			
summary	*16*	*9Y/3N*	*4Y/6N*	*7A/1N*

Appendix P:

T-test results: Multiple Choice Questions

All questions:

	M	SD	N	t	p
Control	15.875	6.11	24	0.785	0.436
Experimental	17.167	5.256	24		
difference	-1.262	0.854			

Questions pertaining to interactive vignettes:

	M	SD	N	t	p
Control	13.6	6.328	10	1.032	0.316
Experimental	16.4	5.797	10		
difference	-2.9	0.531			

Results show for both comparisons show no statistical significance.

Appendix Q: Comparison of Multiple Choice Test Results

Q test A (Q test B) Answers are in a / b format. Correct answer is bolded.

1A(21B): In the chemical equation 2 C_2H_6 + 7 $O_2 \rightarrow$ 6 H_2O + 4 CO_2 the number 7 is called a

	Control responses		Expt. (IV) responses	
a/a subscript	2/0=2	(8%)	1/0=1	(4%)
b/c exponent	0/0		0/0	
c/d superscript	0/0		0/1=1	(4%)
d/b coefficient	**11/12=23**	**(92%)**	**13/10=23**	**(92%)**

2A(22B): The symbol (s) is used in a chemical equation to represent

	Control responses		Expt. (IV) responses	
a/c the solid phase	**13/12=25**	**(100%)**	**13/9=22**	**(88%)**
b/d a catalyst	0/0		0/1=1	(4%)
c/a a spectator ion	0/0		0/0	
d/b a solution	0/0		1/1=2	(8%)

3A(23B): In the chemical equation $2H_{2(g)} + O_{2(g)} \rightarrow 2\ H_2O_{(l)}$, the term to the right of the arrow means

	Control responses	Expt. (IV) responses
a/b 2 atoms of water	4/3=7 (28%)	0/2=2 (8%)
b/a 2 grams of water	0/1=1 (4%)	0/0=0 (0%)
c/d 2 liters of water	0/0=0 (0%)	1/1=2 (8%)
d/c 2 moles of water	**9/8=17 (68%)**	**13/8=21 (84%)**

4A(24B): Chemical equations become balanced by

	Control	Expt. (IV)
a/c eliminating spectator ions from chemical formulas	0/0	0/0
b/d adjusting coefficients of chemical formulas	**11/12=23 (92%)**	**14/11=24 (96%)**
c/a rearranging the parentheses of chemical formulas	0/0	0/0
d/b adjusting subscripts of chemical formulas	2/0=2 (8%)	0/0

5A(1B): How many substances are reactants in the equation

$$2\ Cl_2 + 6\ KOH \rightarrow 5\ KCl + KClO_3 + 3\ H_2O$$

	Control responses		Expt. (IV) responses	
a/d 2	**9/10=19**	**(76%)**	**10/7=17**	**(68%)**
b/c 5	2/1=3	(12%)	3/2=5	(20%)
c/b 9	1/1=2	(8%)	1/2=3	(12%)
d/a 18	1/0=1	(4%)	0/0	

Comparison of Multiple Choice Test Results: Continued

6A(2B): In the balanced equation 2 Na + 2 H_2O → H_2 + 2 X, X refers to

	Control responses	Expt. (IV) responses
a/a Na_2O_2	3/0=3 (12%)	1/0=1 (4%)
b/c Na_2O	8/5=13 (52%)	8/8=16 (64%)
c/d NaH	0/0	0/0
d/b NaOH	**2/7=9 (36%)**	**5/3=8 (32%)**

7A(3B): When the equation $Al_2(SO_4)_3$ + $BaCl_2$ → $AlCl_3$ + $BaSO_4$ is balanced using the smallest whole number coefficients, what is the coefficient of $Al_2(SO_4)_3$?

	Control responses	Expt. (IV) responses
a/d 1	**10/10=20 (80%)**	**12/11=23 (92%)**
b/c 2	3/1=4 (16%)	1/0=1 (4%)
c/b 3	0/1=1 (4%)	1/0=1 (4%)
d/a 4	0/0	0/0

8A(4B): A mole of oxygen molecules consists of

	Control responses	Expt. (IV) responses
a/c 1 oxygen atom	1/0=1 (4%)	0/0=0 (0%)
b/b 2 oxygen atoms	2/1=3 (12%)	4/0=4 (16%)
c/a 6.02×10^{23} oxygen atoms	7/9=16 (64%)	5/7=12 (48%)
d/d 12.04×10^{23} oxygen atoms	**3/2=5 (20%)**	**5/4=9 (36%)**

9A(5B): What is the total number of atoms represented by one unit of $(NH_4)_2HPO_4$?

	Control responses	Expt. (IV) responses
a/d 22	0/0	0/0
b/c 11	0/1=1 (4%)	1/2=3 (12%)
c/b 16	**13/10=23 (92%)**	**13/8=21 (84%)**
d/a 5	0/1=1 (4%)	0/1=1 (4%)

10A(6B): What is the approximate total number of hydrogen atoms in one mole of CH_3OH?

	Control responses	Expt. (IV) responses
a/c 24×10^{23}	**6/6=12 (48%)**	**11/4=15 (60%)**
b/d 6×10^{23}	6/5=11 (44%)	2/4=6 (24%)
c/a 18×10^{23}	1/0=1 (4%)	1/0=1 (4%)
d/b 36×10^{23}	0/1=1 (4%)	0/2=2 (8%)

Comparison of Multiple Choice Test Results: Continued

11A(7B): Which sample of hydrogen gas occupies the largest volume at STP?

		Control responses	Expt. (IV) responses
a/b	**2 moles**	**6/9=15 (60%)**	**11/6=17 (68%)**
b/a	2 litres	4/3=7 (28%)	1/4=5 (20%)
c/d	2 grams	1/0=1 (4%)	0/0=0 (0%)
d/c	2×10^{23} molecules	2/0=2 (8%)	2/1=3 (12%)

12A(8B): What is the minimum number of moles of $O_{2(g)}$ needed to produce 1.0 mole of CO_2 according to the reaction whose balanced equation is $2CO_{(g)} + O_{2(g)} \rightarrow 2\ O_{2(g)}$

		Control responses	Expt. (IV) responses
a/a	0.25 mole	0/0	0/2=2 (8%)
b/b	**0.5 mole**	**8/8=16 (64%)**	**11/4=15 (60%)**
c/c	1 mole	5/3=8 (32%)	0/4=4 (16%)
d/d	2 moles	0/1=1 (4%)	3/1=4 (16%)

13A(9B): How many atoms are there in 4.5 g of CO_2?

		Control responses	Expt. (IV) responses
a/c	1.8×10^{23}	2/2=4 (16%)	1/1=2 (8%)
b/a	**6.2×10^{22}**	**10/8=18 (72%)**	**10/5=15 (60%)**
c/b	6.0×10^{23}	1/2=3 (13%)	3/4=7 (28%)
d/d	1.2×10^{26}	0/0	0/1=1 (4%)

14A(10B): Under ordinary conditions, which substance exists as a diatomic molecule?

		Control responses	Expt. (IV) responses
a/a	zinc	0/0	0/0
b/b	**bromine**	**7/8=15 (60%)**	**13/9=22 (88%)**
c/c	iron	2/1=3 (12%)	1/0=1 (4%)
d/d	helium	4/2=6 (24%)	0/2=2 (8%)

15(11B): As aluminum burns in oxygen according to the equation $4Al_{(s)} + 3O_{2(g)} \rightarrow 2Al_2O_{3(s)}$ the number of aluminum atoms present

		Control responses	Expt. (IV) responses
a/b	increases	2/1=3 (12%)	1/2=3 (12%)
b/a	decreases	3/1=4 (16%)	1/1=2 (8%)
c/c	**remains the same**	**8/10=18 (72%)**	**12/8=20 (80%)**

Comparison of Multiple Choice Test Results: Continued

16A(12B): In the reaction whose balanced equation is: $N_{2(g)} + 3H_{2(g)} \rightarrow 2NH_{3(g)}$. What mass of $H_{2(g)}$ is needed to produce one mole of ammonia?

	Control responses	Expt. (IV) responses
a/d 1 g	2/1=3 (12%)	3/0 =3 (12%)
b/c 2 g	3/1=4 (16%)	1/3=4 (16%)
c/b 3 g	**8/9=17 (68%)**	**10/8=18 (72%)**
d/a 4g	0/1=1 (4%)	0/0

17A(13B): Adding the atomic masses of all elements in a molecule provides the ______.

	Control responses	Expt. (IV) responses
a/a formula unit	0/0	0/0
b/b formula mass	3/1=4 (16%)	2/2=4 (16%)
c/c molar mass	**10/10=20 (80%)**	**9/7=16 (64%)**
d/d grams in one mole	0/1=1 (4%)	3/2=5 (20%)

18A(14B): There are 6.02×10^{23}

	Control responses	Expt. (IV) responses
a/a atoms/moles in 1 liter	0/0	1/0=1 (4%)
b/b moles in an atom	0/1=1 (4%)	1/0=1 (4%)
c/c atoms/molecules in a mole	**13/11=24 (96%)**	**12/11=23 (92%)**
d/d grams in one mole	0/0	0/0

19A(15B): The mass of two moles of nitrogen gas is _____

	Control responses	Expt. (IV) responses
a/a 56 g	**8/12=20 (80%)**	**11/8=19 (76%)**
b/b 2 g	0/0	1/1=2 (8%)
c/c 17 g	0/0	0/0
d/d 14 g	5/0=5 (20%)	2/2=4 (16%)

20A(16B): What amount of matter contains the largest number of atoms?

	Control responses	Expt. (IV) responses
a/a. 40 g of K	1/1=2 (8%)	1/2=3 (12%)
b/b 54 g of Al	**5/9=14 (56%)**	**8/6=14 (56%)**
c/c 200 g of Xe	2/1=3 (12%)	1/1=2 (8%)
d/d 200 g of Ba	5/1=6 (24%)	3/1=4 (16%)

Comparison of Multiple Choice Test Results: Continued

21A(17B): The number of molecules present in 25 grams of nitrogen gas is equal to

	Control responses	Expt. (IV) responses
a/a $25 \times 6.02 \times 10^{23}$	3/1=4 (16%)	2/0=2 (8%)
b/b $(25 \times 6.02 \times 10^{23})/28$	**5/6=11 (44%)**	**10/5=15 (60%)**
c/c $25/6.02 \times 10^{23}$	2/1=3 (12%)	1/1=2 (8%)
d/d $(25 \times 6.02 \times 10^{23})/14$	3/4=7 (28%)	1/5=6 (24%)

22A(18B): In a mass-mass problem, grams must first be converted to moles by

	Control resp.	Expt. (IV) resp.
a/a using the mole ratios from the balanced equation	0/0	2/2=4 (16%)
b/b using the molar mass of the substance	7/6=13 (52%)	3/7=10 (40%)
c/c dividing molar mass by grams	4/3=7 (28%)	2/1=3 (12%)
d/d none of the above methods	2/3=5 (20%)	7/1=8 (32%)

23A(19B): A mole of H_2O and a mole of O_2

	Control responses		Expt. (IV) responses	
a/a have the same mass	1/1=2	(8%)	2/0=2	(8%)
b/b contain one molecule each	5/5=10	(40%)	2/0=2	(8%)
c/c have a mass of 1 g each	1/1=2	(8%)	0/2=2	(8%)
d/d contain the same number of molecules	**6/5=11**	**(44%)**	**10/9=19**	**(76%)**

24A(20B): One mole of oxygen molecules contain more independent units (O_2) than one mole of oxygen atoms (O).

a/a True, because there are two atoms of O for every molecule of O_2.
b/b True, because one mole of O_2 weighs more than one mole of O.
c/c False, because both of them have the same number of particles.
d/d False, because one mole of O has the same mass as one mole of O_2.

Control responses		Expt. (IV) responses	
12/6=18	(72%)	6/5=11	(44%)
0/2=2	(4%)	3/4=7	(28%)
0/3=3	**(12%)**	**3/2=5**	**(20%)**
1/1=2	(4%)	0/0=0	(0%)

Appendix R:

T-test results: Long Answer Questions

Total All questions:

	M	SD	N	t	p
Control	23.68	6.336	25	0.696	0.490
Experimental	22.08	9.596	25		
difference	1.60	-3.26			

Questions pertaining to interactive vignettes (#1 – 8, 11):

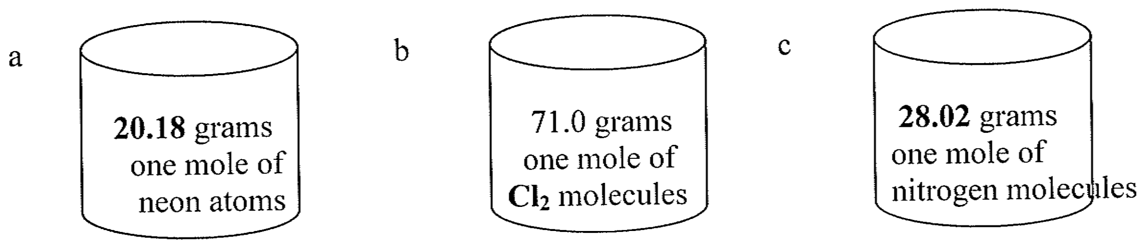
	M	SD	N	t	p
Control	8.98	2.71	25	0.371	0.713
Experimental	8.62	4.032	25		
difference	0.360	-1.322			

The results show no statistical significance between the two groups.

Appendix S:

Unit Test: Long Answer Analysis

1. The following three containers have identical capacities. Each contains Avogadro's number of molecules of a gaseous element. Fill in the blanks with the missing information (3).



	Control Responses		**Experimental (IV) Responses**	
Part a	20/25	(80%)	21/25	**(84%)**
Part b	8/25	(32%)	12/25	**(48%)**
Part c:				
Full marks:	8	(32%)	11	(44%)
Part marks:	11 (1/2 marks)	(44%)	11 (1/2 marks)	(44%)
Total marks (c):	13.5/25	(54%)	16.5/25	**(66%)**

2. What mass of chlorine atoms contains the same number of atoms as does 24.0 grams of carbon? (1)

$24.0 \text{ g} / 12.01 \text{ g/mol} = 2.00$ moles of carbon (half marks)

$(2.00 \text{ moles})(34.45 \text{ g/mol}) = 68.9 \text{ g}$ (full marks)

	Control Responses		**Experimental (IV) Responses**	
Full marks:	12	(48%)	11	(44%)
Half marks:	8	(32%)	8	(32%)
Total marks:	16/25	**(64%)**	15/25	(60%)

Unit Test: Long Answer Analysis: Continued

3. How many moles of atoms are there in 1.20×10^{25} carbon tetrachloride, CCl_4 molecules? (1)

   $(1.20 \times 10^{25}$ molecules$)$ / $(6.02 \times 10^{23}$ molecules/mole$) = 19.9$ moles
   (19.9 moles of CCl_4)(5 atoms/mole) = 99.5 moles of atoms

	Control Responses		Experimental (IV) Responses	
Full marks:	19	(76%)	12	(48%)
Half marks:	3	(12%)	4	(16%)
Total marks:	20.5/25	**(82%)**	14/25	(56%)

4. How many moles of nickel atoms are needed to supply the same number of atoms as does 10.0 grams of neon? (2)

   (10.0 g) / (20.18 g/mol) = 0.496 mol of Ne atoms ∴ 0.496 mol of Ni atoms since a mole always contains the same number of atoms (whether Ne or Ni).

	Control Responses		Experimental (IV) Responses	
Full 2 marks:	11	(44%)	17	(68%)
1 ½ marks:	2	(6%)	0	
1 mark:	6	(12%)	3	(6%)
Total marks:	31 /50	(62%)	37 /50	**(74%)**

5. 0.500 mole of an element has a mass of 31.75 grams. Identify the element.(1)

   31.75 grams /0.500 mole = x grams / 1.00 mole
   x = 63.5 grams per mole.
   copper since relative atomic mass is 63.5 g

	Control Responses		Experimental (IV) Responses	
Full marks:	15	(60%)	15	(60%)
Half marks:	0		3	(6%)
Total marks:	15/25	(60%)	16.5 /25	**(66%)**

6. Each carbon atom contains 6 electrons. How many carbon atoms will contain one mole of electrons?(1)

   $(6.02 \times 10^{23}$ atoms/ mole$)$ / (6 electrons/atom) $= 1.00 \times 10^{23}$ atoms

	Control Responses		Experimental (IV) Responses	
Full marks:	6	(24%)	9	(36%)
Half marks:	2	(4%)	0	
Total marks:	7/25	(28%)	9/25	**(36%)**

Unit Test: Long Answer Analysis: Continued

7. What is the volume of 3.0×10^{24} molecules of CO_2 at STP?(2)

$(3.0 \times 10^{24}$molecules) / 6.02×10^{23} molecules/mole) = 5.0 moles
(5.0 moles) (22.4L/mole) = 112 L

	Control Responses		**Experimental (IV) Responses**	
Full 2 marks:	18	(36%)	13	(26%)
1 ½ marks:	2	(6%)	7	(21%)
1 mark:	2	(4%)	0	
Total marks:	23/50	(46%)	23.5 /50	**(47%)**

8. At STP, how many moles of neon gas in a 11.5 L sample? (1)

(11.5 L) / (22.4L/mole) = 0.513 mole

	Control Responses		**Experimental (IV) Responses**	
Full marks:	21	(84%)	20	(80%)
Half marks:	3	(6%)	1	(0.05%)
Total marks:	22.5/25	**(90%)**	20.5/25	(82%)

C. 9. Nitrogen gas and hydrogen gas react at S.T.P. to make ammonia.

$$N_{2(g)} + 3H_{2(g)} \rightarrow 2NH_{3(g)}$$

b) If 24.0 g of nitrogen gas reacts, what volume of ammonia is produced? (2)

(24.0 g of N_2) / (28.02 g/mol) = 0.857 mol N_2
Ratio N_2:NH_3 is 1: 2 therefore (0.857 x 2) = 1.71 mole NH_3 produced
(1.71 mole NH_3)(22.4L/mol) = 38.3 L

	Control Responses		**Experimental (IV) Responses**	
Full 2 marks:	18	(72%)	13	(52%)
1 ½ marks	2	(6%)	6	(18%)
1 mark:	1	(2%)	1	(2%)
½ mark:	2	(2%)	0	
Total marks:	41/50	**(82%)**	36/50	(72%)

Unit Test: Long Answer Analysis: Continued

b) What mass of hydrogen gas is needed to produce 450. g of ammonia? (2)

(450. g) / (14.01 + 3(1.01)) = 26.4 moles NH_3
Ratio H_2 : NH_3 is 3:2 therefore 39.6 moles of hydrogen needed
(39.6 moles)(2.02 g/mole) = 80.0 g of hydrogen needed.

	Control Responses		Experimental (IV) Responses	
Full 2 marks:	10	(40%)	15	(60%)
1 ½ marks	4	(12%)	2	(6%)
1 mark:	3	(6%)	6	(12%)
½ mark:	2	(2%)	0	
Total marks:	30/50	(60%)	39/50	**(78%)**

10. Given the following unbalanced equation:

$$2C_2H_6 + 7O_2 \longrightarrow 4CO_2 + 6H_2O$$

a) Given 10.5g of ethane gas reacting with 26.88L of oxygen gas at STP. Determine the limiting reactant. (3 marks)

moles ethane = (10.5 g) / 30.08 g/mol) = 0.349 mol
moles oxygen = (26.88L) / (22.4L/mol) = 1.20 mol
Ratio is 2:7 if we use all the 1.20 mol of oxygen, we need 0.343 mol of ethane
Since we have enough, oxygen is the limiting reactant.

	Control Responses		Experimental (IV) Responses	
Full 3 marks:	13	(52%)	13	(52%)
2 ½ marks:	4	(13%)	0	
2 marks:	2	(5%)	2	(5%)
1 ½ marks	2	(4%)	3	(6%)
1 mark:	1	(1%)	2	(3%)
½ mark:	1	(1%)	0	
Total marks:	57.5/75	**(77%)**	49.5/75	(66%)

Unit Test: Long Answer Analysis: Continued

b) What is the mass of water produced in this reaction? (1 mark)

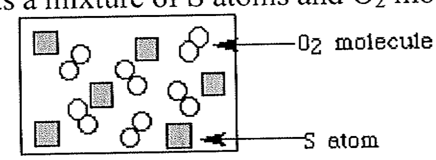
$7O_2 \rightarrow 6H_2O$

1.20 mol = x = 1.03 mol of water is produced

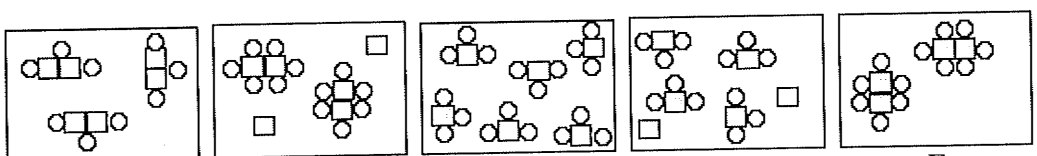
(1.03 mol)(18.02 g/mol) = 18.6 g

	Control Responses		Experimental (IV) Responses	
Full marks:	13	(52%)	9	(36%)
Half marks:	6	(12%)	7	(14%)
Total marks:	16/25	(64%)	16/25	(64%)

11. The diagram represents a mixture of S atoms and O_2 molecules in a closed container.



Chose and explain which diagram shows the results after the mixture reacts as completely as possible according to the equation: $2S + 3O_2 \rightarrow 2SO_3$



A B C D E

Answer: D – you need one sulfur atom for every three oxygen atoms (SO_3)

- according to the starting amount (6 S : 12 O), and the combining ratio (1 sulfur : 3 oxygen) there should be 2 sulfur atoms in excess.

	Control Responses		Experimental (IV) Responses	
2 marks:	2	(8%)	3	(12%)
1 marks:				
(D/wrong expl.)	3	(6%)	1	(2%)
(not D/right expl.)	12	(24%)	14	(28%)
Total marks:	19/50	(38%)	21/50	**(42%)**

Multiple choice:	Control Responses		Experimental (IV) Responses	
A S_2O_3	0		5	(20%)
B S_2O_6 + excess	3	(12%)	2	(8%)
C SO_3	1	(4%)	4	(16%)
D SO_3 + excess	**5**	**(20%)**	4	**(16%)**
E S_2O_6	9	(36%)	7	(28%)