Evolution of a Nontraditional Freshman Chemistry Curriculum

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Overview: This presentation will describe efforts by the author to go beyond standard lecture and demonstration / recipe-type laboratory formats in a college freshman chemistry course with a large student population (100+ students). Approaches include using active learning strategies, coupling content to the development of reasoning skills, restructuring topic sequences so that observations precede definitions and theories, modifying laboratories so that students must rely on observations and Socratic question sequences to make conclusions, and using multiple representations (verbal, mathematical, pictorial, and graphical) to probe for concept understanding. This work is based on an action research model in which one first plans and implements specific classroom activities, and then observes and evaluates the results before revising the activities and performing another cycle of the process. Evaluative feedback comes from listening to students during interactive problem-solving sessions in the classroom, help sessions and the laboratoy, reading written responses to assignments given in class and lab, studying student feedback from questionnaires, and testing for concept understanding and reasoning skills. A brief history of the curriculum evolution, including unsuccessful strategies, will be included.

Background Information

Freshman chemistry at the Massachusetts College of Pharmacy and Health Sciences (MCPHS) comprises a sequence of two, four-credit courses with a large classroom environment (100+ students). Students attend four, 50-minute classroom periods, including an integrated prelab period, and one three-hour laboratory session each week. The instructor and one or two learning facilitators attend each class. Sections of approximately 40 students interact with the instructor and two or three assistants during laboratory sessions, which are coordinated with classroom activities as much as possible. Student majors include pharmacy, chemistry, pre-med, and various allied health programs. Almost all students have had high school chemistry and biology, and many have had high school physics. In recent years, average combined Scholastic Apptitude Test (SAT) scores have been in the vicinity of 1050, but a diagnostic examination given to students during orientation week indicates a wide range in level of preparation.

Educational Research

Educational research findings have been an important guide in the development of this curriculum. During the past three decades, research in teaching and learning has uncovered discrepancies between the way students learn and the traditional methods used to teach them. Some of the key findings are summarized here for interested readers:

- Learners construct understanding. They do not simply mirror what they read or are told.
- An environment in which students actively work with material and obtain rapid feedback is better than one in which they passively listen.

Students must be able to link new information to what they already know.
Understanding is related to how knowledge is organized.

- Misconceptions (beliefs based on prior experience or instruction) are easy to develop and difficult to dislodge.

Qualitative understanding of concepts is as important as the ability to perform quantitative calculations.
Many students come to college with poorly developed formal reasoning skills.

- It takes time to develop formal reasoning skills and to construct understanding of science concepts, suggesting that less information should be presented, but in more detail.

Important skills necessary for success in college-level courses include observing, comparing, and classifying, using symbolic representations, proportional reasoning, controlling variables, drawing inferences, predicting consequences, formulating and testing hypotheses, and evaluating arguments.
Traditional classroom presentations in science courses can be inconsistent with educational research findings, and often present students with barriers to learning by

presenting too much information, unsystematically, in a passive lecture fashion
equating qualitative understanding with the ability to perform quantitative calculations
not addressing student misconceptions
ignoring the students cognitive level
Specific references to the work of a number of educational researchers, which support statements made in this portion of the presentation can be found in papers by the presenter (**1, 2, 3**).

Some History

The following is an outline tracing the evolution of the freshman chemistry curriculum at MCPHS. More detail can be found in papers by the presenter (**1, 2, 3**).

early 1980s:
there are no problems (the dark ages)
the presenter lectures and is largely unaware of the nature of student difficulties
late 1980s:
efforts begin to find ways of improving presentations and student learning:
delay the presentation of quantitative problem solving
use integrating themes (energy transformation, equilibrium, rates of change)
give tangible examples first, cycle back to ideas for progressively richer elaboration
integrate chemistry and biology courses at MCPHS
create handouts to supplement the text
1990:
author is introduced to educational research findings
does away with commercial textbook; handouts drive classroom activities
early 1990s:
introduce active learning strategies
put experimental evidence before theory
cut content
stress interpretation of ratios
present multiple representations of concepts - verbal, mathematical, pictorial, graphical
late 1990s-present:
coupling content to the development of reasoning skills
creating a logical sequence of topics (for students) in a survey course in chemistry
pay attention to the development of vocabulary
follow historical developments when possible
pay attention to three domains: world of macroscopic observation, world of submicroscopic phenomena, and domain of symbolic representation

Efforts to improve the learning environment began in the late 1980s. Frustration with the poor performance of many students in prior years, a growing appreciation of principles that span and unify the natural sciences, and the willingness of a biologist colleague to join the experiment, were factors that catalyzed the process. Since many ideas in biology depend on understanding fundamental physical and chemical principles, the instructors reasoned that students should be introduced to these in the chemistry course, prior to their use in biology. A summary of important physics principles was introduced in the first few meetings of the chemistry course in the late 1980s. The work eventually led to an integrated chemistry and biology curriculum (**1**), which was taught until 1992. Initially, the concept of energy transformation was chosen as the integrating theme for this curriculum, based on its universal importance.
Although the integrated curriculum was a step in the right direction, evaluation indicated that major problems remained. With regard to the physics summary, even though the emphasis was on qualitative understanding of concepts, and not on cranking out numerical answers from equations, this approach amounted to a preconstructed summary of ideas presented in a vacuum. When the concepts were drawn upon later in the year, many students still struggled with them. In addition, many complained that initially the course seemed more like one in physics than one in chemistry. Another major challenge appeared in the area of quantitative problem solving. Initial efforts in the integrated curriculum of the late 1980s centered on postponing quantitative treatments of stoichiometry one term

(trimester) until weaker students had the chance to complete a basic mathematics course. A modified version of dimensional analysis was then used in chemistry calculations, but this overall approach proved to be of little use in helping students to improve in the area of quantitative problem solving. In addition, it was apparent to the instructors that in a number of places material was being presented at too rapid a pace.

By 1990, the textbook was abandoned in the chemistry curriculum, because its conventional topic sequence and development had become inconsistent with the approach being used. Classroom presentations from that time on have been based on handouts (now an informal textbook) created by the author, while commercial sources are still used for about one third of the laboratory activities. In that year, the presenter was also introduced to constructivist learning theory (**4**), with its key points, summarized in the last section. Although the integrated curriculum came to an end in 1992 with the departure of the biologist, efforts throughout the 1990s have centered on using constructivist learning theory to guide curriculum development in freshman chemistry. Important issues include choice and sequence of topics (including time spent on each topic and which topics to omit), nurturing an active learning environment, coordinating laboratory and classroom activites, and coupling content to the development of specific reasoning skills. In addition to helping students connect observable phenomena with inferences and hypotheses about the atomic world, stress is placed on mastering scientific vocabulary, working comfortably with symbolic representations, and connecting qualitative descriptions of phenomena with quantitative representations.

The approach used in the instructor-generated text and the classroom can be described as *guided* inquiry, since it relies on sequences of questions that provide direction and focus. These have been formulated based on the instructors efforts to create pathways from observation and experimental evidence to definitions, concepts, and theories, and modified based on feedback obtained through years of Socratic dialogs conducted with students during active learning sessions. In the text, students are encouraged to attempt answers before reading those provided. Applications are given in assigned homework problems. Answers are not provided until several days later, to encourage interaction with classmates, and attendance at help sessions. (See the Appendix for a sample of material from the text.)

Active Learning

Active learning strategies have been incorporated into presentations since 1990. Think-aloud sessions are used in the classroom, laboratory, and daily help sessions, and include rapid feedback provided by the instructor. During these sessions in the classroom and laboratory, the instructor and one or two learning facilitators circulate among students, listening to their conversations or engaging them in Socratic dialogs. The daily help session is the instructors office hour, which is held in a classroom, is usually attended by 5 to 30 students, and is very interactive. Listening to students as they engage in these activities continues to serve as the primary source of feedback to guide curriculum evolution. The instructor-generated reading materials cover all points addressed in class, allowing students to focus on classroom presentations and activities, rather than note taking. Writing for understanding is used extensively in the laboratory, and sometimes in the classroom to help students formulate their ideas, and to provide feedback for the instructor. Throughout the year, and particularly in the first semester, an effort is made to help students develop a positive attitude toward learning, and an awareness of the learning process. Students are encouraged to view the instructor as a facilitator, reflection and discussion as important modes of learning, and science as a process, rather than a collection of facts. Through informal discussion, it is stressed that the learning process involves working through uncertainty and conflict, that reasoning ability comprises attainable skills, and that generating and testing ideas is more important than producing the correct answer the first time one tries a problem. The need for repetition and making summaries is stressed, as well as reflecting upon ones own behavior while studying. A critical application of this last point in physical science courses centers on avoiding meaningless symbol manipulation when engaged in quantitative problem solving.

Topics in Semester I

The two-semester sequence is traditional in the sense that it comprises a survey of important topics, which are presented in the text as a series of units. However, topic development is based on introducing experimental evidence before concepts and theories, and some attempt is made to follow the historical development of ideas. The units are organized around themes that span and unify the sciences. A brief description of the units from semester I is given below. Topics are presented in approximate historical order within a given unit when possible (units 3, 6, 7, and 10), and the sequence of units is consistent with the historical development of concepts in chemistry. In this 30-week

curriculum, topics that are usually found fairly early in standard freshman chemistry courses are delayed. Below are some examples:
mole concept: week 6 nuclear atom / atomic number: week 16
periodic table: week 7 chemical bonding: week 17
electrons: week 12 molecular geometry: week 19

Unit 1: Mathematical Foundations
This unit serves as a reference for topics like logarithms and scientific notation, but the main emphasis is placed on correct interpretation of ratios, and how to use these effectively in quantitative problem solving (**2, 5**). The focus is on helping students to connect the manipulation of objects and the comparison of quantities with the associated symbolic representations. The approach relies on concrete examples that deal with familiar quantities like dollars, gallons, miles, and hours. Class and laboratory time are devoted to this in week one.

Unit 2: Introduction to Measurement
The idea is stressed that all measurement entails comparison with a standard, counting, and reporting a number. The measurement process serves as the basis for operational (and concrete) definitions of important scientific concepts including distance, length, area, volume, gravitational mass, and density, in week two of the course. Gravitational mass is introduced first as a measure of the attraction of the earth for objects, and then as a way to infer that denser objects contain more matter (**6**). In the laboratory, students practice scale reading and reporting values with the appropriate uncertainty, as they make length and volume measurements, and work with density manipulatives. The subject matter provides further opportunity for students to practice their proportional reasoning skills as applied to unit conversions.

Unit 3: Observations about Matter
Classroom and laboratory discussion (week 3) of the behavior of various samples of matter are used to create a library of terms such as element, compound, and mixture. The presentation avoids making a distinction between chemical change and physical change (**3**), focusing instead on the outcome of a process - is it more likely a mixture, compound, or phase change? Percent composition and limiting reagent via mass ratio are introduced. Evidence suggesting the atomic nature of matter and the qualitative idea of bonding is presented, but with no specifics about atomic structure, chemical formulas, or the mole concept. Some modifications to the definitions are made in the second semester as ideas about atomic structure are introduced.

Unit 4: Ideas about Motion
The concepts of displacement and time interval are developed as a lead-in to those of velocity and acceleration. Multiple representations are used to help students distinguish between the latter two concepts, primarily in laboratory four. These include verbal, mathematical, pictorial, and graphical representations. The material serves as a general introduction to quantitative descriptions of change, and provides students with an opportunity to construct graphs.

Unit 5: The Concept of Force
Stress is placed on the qualitative idea that a force is an interaction (**7**). Various activities help the student use the word properly in describing physical situations in the classroom and in laboratory 4 (**8**). The relationship between inertial mass, acceleration, and force is introduced.

Unit 6: Making Inferences about the Atomic Realm
Ideas about pressure and temperature measurement precede discussion of the gas laws, and kinetic theory. Qualitative questions about the behavior of gas molecules are included as well as the usual gas law calculations (laboratory 5). Avogadros law is avoided, since there is no experimental evidence for it at this point. Relative atomic masses for the elements (laboratory 6) and formulas for simple compounds, based on the law of definite proportions and Daltons Rule of Simplicity, are contrasted with those based on the law of combining volumes and Avogadros hypothesis. The mole concept is introduced. Experimental evidence leads to Avogadros law, and the values of relative atomic masses in the modern periodic table (laboratory 7, a dry lab) (**3**). The molar mass of a volatile hydrocarbon is determined by the Dumas method in laboratory 8.

Unit 7: Introduction to the Periodic Table
The concept of the mole, molar mass, and molar volume are developed using a doughnut-dozen analogy. Periodic behavior based on increasing atomic mass is introduced. (This is modified in semester 2 when the concept of atomic

number is introduced). The combining ability (based on mole ratios), not electron configuration, of the representative elements is used to rationalize their placement in families, and then introduce some descriptive chemistry. Molar mass information is used in determining formulas of compounds (laboratory 9), in studying stoichiometry, and in expressing solution concentration. Avogadros number is estimated in laboratory 10.

Unit 8: The Concept of Energy
Gravitational potential energy, kinetic energy, internal energy, and their interconversion are discussed in macroscopic systems. The concepts of work and specific heat capacity are introduced **(8).** The relationship between temperature and molecular motion, introduced in unit 6, is reinforced. Thermal interactions are explored in the laboratory in week 11.

Unit 9: Gradients and Equilibrium
The concepts of gradient and dynamic equilibrium are introduced via pressure and temperature differences. The creation of gradients in osmosis experiments is discussed. A system is observed as it comes to thermal equilibrium (laboratory 12), and its behavior is described using an exponential function.

Unit 10: Matter with a Charge
The concepts of charge and electric fluid are introduced through experiments in which glass rods are rubbed with silk and fur. A hypothesis is developed about the direction of electric fluid flow when different metals are touched together. The continuous flow of electric fluid in electrochemical cells is introduced; the direction of flow and its particulate nature are inferred through the description of experiments with a Geissler (Crookes) tube. The term electron is introduced. Evidence for the existence of ions in solution is presented, and products of electrolysis are discussed. Current and charge measurement are described based on force, and on mass of metal deposited at an electrode. The determination of relative charge on different ions is presented. Students identify solutions of ionic substances and determine the relative acidities of others in the laboratory in weeks 13-15. Details of atomic structure are not presented until the second semester.

Semester two units include atomic structure, bonding, reaction rates and energetics, chemical equilibrium, acid-base chemistry and redox chemistry.

Arranging Topics and Cutting Content

In recent years, poor class performance on the first test in semester one has led to a steady decrease in the number of concepts that are introduced in the first few weeks of the curriculum. Some have been eliminated entirely, while others have been moved to more appropriate places. For example, prior to academic year 1997-98, the concept of energy was introduced before ideas about chemical processes and gases, but students complained that the course seemed more like a physics course than a chemistry course, and it was evident that they were being overwhelmed with too many ideas in too little time. In particular, not enough time was spent on evidence supporting the atomic theory, and how to distinguish between compounds, mixtures, and elements. The current presentation avoids any mention of the concept of energy until after the introduction of the periodic table.

In an effort to help students articulate the meaning of ratios and apply this skill to quantitative problem solving, the mole concept has been delayed. Students first work with familiar quantities like dollars and gallons in week one, followed by concepts like density and percent composition by mass in weeks two and three. The mole concept is not introduced until week six, and not used extensively until weeks seven and eight. This approach is also consistent with the historical fact that knowledge of percent composition preceded knowledge of chemical formulas by many years.

These changes reflect an increased awareness, on the part of the instructor, about the concepts that are essential and those that are not for students to explore a certain aspect of chemistry. For example, while the details of electron configurations may provide insight on stoichiometric relationships, knowledge of atomic masses and how to balance equations is sufficient to conduct lessons on calculations involving moles.

Topics like quantum numbers and orbitals have been eliminated, and replaced in semester two by presentations that use comparison of ionization energies to suggest the existence of different energy levels in atoms. Coverage of descriptive chemistry and colligative properties has become more restricted, and focused on supporting other topics like stoichiometry and equilibrium. Responding to student difficulties is producing a curriculum that is more in line with the historical evolution of chemistry. Presentations are also evolving so that experimental observations are better coordinated with relevant theory.

Delaying the Topic of Atomic Structure

Reasons for delaying this topic (**3**):
1) Chemistry entails linking observations in the see-touch world with inferences about the sub-microscopic world, and with symbolic representations. Since observations and inferences precede models and theories, an approach that delays the details of atomic models and theories is more consistent with the way in which science actually proceeds.
2) Knowledge of the behavior of substances, relative atomic masses, chemical formulas, and molecular geometry all preceded knowledge of atomic structure. Presenting topics roughly in the order in which they were historically elucidated can provide greater insight into how the science of chemistry developed, and greater appreciation of some of the uncertainties faced by the scientists who brought this knowledge to light.
3) Research indicates that students are easily overwhelmed by too much information, and that it takes time to develop reasoning skills. Therefore, an approach that delays topics like atomic structure can provide students with a better opportunity to develop the skills that are at the heart of connecting the see-touch world with the sub-microscopic world.

Example of a Teaching Activity

Throughout the course, activities in the laboratory include observing properties of materials, interpreting experimental results in terms of a posed hypothesis, a known law, or a definition, and obtaining experimental data and using it to calculate quantitative properties of substances. Simple activities that are usually used to demonstrate concepts have been turned into more challenging experiments by withholding some of the facts, and including a Socratic line of questioning (**3**). Although laboratory manipulations are relatively simple, most students fill the entire period with discussions among themselves, or Socratic dialogs with instructors. These help students when they are interpreting phenomena, repeating procedures to reinforce ideas, and writing up their findings and interpretations. Students usually work in pairs, but hand in separate laboratory reports.
Parts of a laboratory from Semester I, week 3 (Unit 3):
Activity 1: Students are shown a pair of processes, and asked to determine which is more likely a chemical reaction, based on observations like thermal energy or gas evolution. One activity entails observing a piece of zinc dropped into a solution of dilute hydrochloric acid, and another piece dropped into some water. Another activity entails mixing dilute acid with water vs. mixing dilute acid with dilute base. It is stressed that such limited investigations lead to conclusions that are suggestive, rather than definite.
Activity 2: (Students are given the following to read.)
When certain types of metallic substances are heated in an open container (called a crucible), they become a type of substance called **calx**. Calx is a powder, and does not exhibit metallic properties. Consider the following hypothesis to explain the experimental observations: Heating removes something from the metallic substance to make calx.
Answer the following questions: Is this a reasonable hypothesis? How could you test the hypothesis? Can you think of an alternative hypothesis that could also explain the observations? If you have trouble, conduct the next activity first, then return to this one.
Activity 3: You will now perform an experiment in which you heat a piece of metal in an open crucible, producing calx. Your instructor will tell you what size piece of metal to use. (The procedure and data sheets are omitted here.)
Answer the following questions:
Did your sample of metal gain mass or lose mass?
What was the increase (or decrease) in mass of your sample in grams?

> Does this result support the original hypothesis about what happens when calx is formed? If not, suggest a new hypothesis based on your experimental results.
> Which is more likely an element, the piece of metal or the calx? Explain your reasoning
> Make the ratio: mass increase (or mass decrease) / original mass of metal. Check with other students who had different starting masses of metal. Did they get about the same **ratio** as you? Based on your findings, is calx more likely an element, a compound, or a mixture? Explain your reasoning.

A similar set of activities is used during this lab period to determine that an unknown liquid is most likely a mixture.

For activity 3, students are given a piece of magnesium to heat, but the identity of the metal and the fact that the term calx is an archaic name for a metal oxide are omitted. After completing the procedure in which calx is formed, students often say that this proves the initial hypothesis is correct, because they have created calx. The fact that this procedure alone does not confirm whether the metal has lost or gained something seems to escape them. It is common to find students who cannot decide whether or not the original hypothesis is reasonable, who cannot produce an alternative hypothesis, who do not think of using mass measurements to test the hypothesis, and who struggle when asked to apply appropriate terms like element, compound, and mixture. This is in spite of the fact that most students appear in lab with a set of written definitions, including these terms, which they were required to complete prior to arrival.

Evaluation

These efforts in curriculum development are based on an action research methodology (**9, 10**), which consists of planning and implementing specific classroom activities, observing and evaluating the results, and then using conclusions to revise the activities and perform another cycle of the process. The most valuable source of feedback on how students are progressing in their understanding of material, and how the intructor can improve future presentations continues to be observation of students as they engage in active learning during problem-solving sessions in class, help sessions, and the laboratory. Other sources include student responses to written assignments, and performance on tests.

The students willingness to interact enables the instructor to clarify points, and uncover misconceptions that might otherwise go undetected. The construction of more useful sequences of questions for the classroom, text, and laboratory is an ongoing process. Carefully listening to students and reflecting upon the phenomena within which concepts are rooted has allowed the instructor to anticipate the degree of disequilibrium that students face as they are introduced to new material. Introducing material so that it produces only moderate disequilibrium is a major challenge, given the diverse population of learners.

For example, limiting the quantitative treatment of compound composition in Unit 3 to discussion of mass ratios is important because it reduces the number of ideas that students must consider. Many students are extremely challenged by questions that ask them to interpret and use ratios in a fashion that goes beyond plugging numbers into proportions or cancelling units (**2**). Given the additional demands of mastering vocabulary and hypothetico-deductive reasoning that are also placed upon them at this time, an approach that delays the mole concept is justified.

This method of curriculum evaluation and development is qualitative by nature. No opportunity exists to employ control groups, since only one section of the course exits, and several factors vary from year to year. These include class size, average SAT scores, number and sequence of topics, transition from a trimester format with no laboratory in trimester one, to a semester format with laboratory in both semesters, different number of questions on exams from one year to another, and different learning facilitators with different skill levels. While course content and sequence have remained almost constant in semester one for the past four years, class size is increasing, from a past average of about 115 students, to 187 students this year, and a projected 230 students for academic year 2003-04.

In addition to the variables mentioned above, contact with students varies. Some seek extensive help, attending many daily help sessions, while others do not. The performance level for each of these groups spans a wide range, and includes students who struggle, as well as those who do well. While instructors seek to interact with all students in the laboratory, the amount of help received by each student is different. In order to reach a conclusion, some students require more extensive interaction with an instructor than others. Some students actively engage in dialog with instructors, while others prefer to keep this to a minimum. In addition, different instructors have different levels of expertise in guiding students in the right direction.

The administration of a relatively large number of tests during the semester is consistent with a correlation between frequent testing and student performance **(11)**. The five, hour-long tests currently comprise 20 multiple choice questions, while the two-hour final exam comprises 40 of these questions. The advantages of carefully constructed multiple choice questions over open-ended essay questions in focusing students on specific information and skills has been discussed (**12**). Testing focuses more on concept understanding and application of reasoning skills rather than recognition and recall. There are usually more qualitative than quantitative questions. (For examples, see reference **3**.) However, the survey nature of the course leads to limited testing of each topic on the final exam (some topics are not revisited at all on the final), making it hard to judge how much students have retained throughout the semester.

Student responses to the curriculum in recent years have been very favorable. Even among students who struggle, the consensus opinion is that the approach is helping them to learn to think. (This was not always the case!) Most students find it challenging when asked to reason through situations, and many find it particularly challenging to distinguish between facts, inferences, hypotheses, and deductions. (See material in the Appendix.) As a consequence, students are given the opportunity to practice this as much as possible. On the positive side, a number of students with little or no chemistry background have done quite well, suggesting that a reasonable sequence of topics is emerging. When the instructor had access to SAT scores some years ago, it was observed that more students with lower scores tended to hold their own, or improve in performance going from one term to the next, *after* active learning strategies had been added to the curriculum. This suggests that these interventions are helping the students who need it most. On the negative side, about 20% of the class still performs poorly. In some cases, this is due to insufficient study time, or failure to embrace active learning. In others, the struggle to develop reasoning skills while trying to master content appears to be too much. The latter situation keeps the instructor constantly on the lookout for ways to improve the presentation. This can be through cutting content or rearranging topic sequences, or more likely in semester one, through improved question sequences, in an effort to better engage and lead students toward understanding. The instructor intends to follow the progress of more of the students who perform poorly, but who do go on to their second year, to see if they show improvement. Informal discussions with a number of these students indicate that this is the case.

In spite of the many uncontrollable factors, extensive feedback from students during the past ten years has driven and will continue to drive the evolution of a chemistry curriculum that is more consistent with the logical structure of the discipline, and that anticipates the needs of novice learners.

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Appendix

Here is a sample of reading material from the informal text used for classroom presentation and laboratory discussion on the concepts of relative atomic mass and chemical formulas. In this chapter, students are introduced to the concepts and practice hypothetico-deductive reasoning, an important thinking skill. In later chapters, students compare predictions made using Avogadros hypothesis with those using Daltons. These lead to Avogadros law and the actual relative atomic masses of the elements found in the modern periodic table.

Unit 6: Making Inferences about the Atomic Realm

Chapter 7: Deducing Relative Atomic Masses and Compound Formulas (I) Daltons Hypothesis

The experiments performed in the late 1700s and early 1800s gave information about the mass of one element that

would combine with the mass of another. These experiments led to the law of conservation of matter, and the law of definite proportions (also called the law of constant composition). At the time when Dalton proposed the atomic theory, a major goal was to determine the relative atomic masses of the elements (how massive the atoms of one element are compared to the atoms of another), and the formulas of their compounds (how many of each type of atom are coming together when a particular compound is formed).
Since nobody can directly see what is going on at the atomic level, the masses of elements that combine with one another do not give any clue to how many of each atom are coming together and binding to one another when a compound is formed. Therefore, it was necessary to start with some assumptions about what might be going on at the atomic level. Along with the five points of the atomic theory that were listed earlier (Unit 3, chapter 6), Dalton proposed a sixth point, a hypothesis called the rule of simplicity.

Dalton makes a Hypothesis

Dalton **hypothesized** that the simplest compound that would form from the combination of two elements would contain diatomic molecules, made from one atom of each element (diatomic means two atoms). This hypothesis is called **Daltons Rule of Simplicity**. For example, in the case of water, he suggested that each water molecule was made of one hydrogen atom and one oxygen atom.

It is an experimental **fact** that 1 g of hydrogen reacts **completely** with 8 g of oxygen to form 9 g of water. This hydrogen / oxygen mass ratio of 1 / 8 is observed no matter what the quantity of water. We can symbolize these statements as follows:
1 g hydrogen + 8 g oxygen ----> 9 g water **experimental fact** (observation)
H atom + O atom ----> HO (water molecule) **hypothesis** (assumption)
Question 1: If the 1 / 8 mass ratio is always maintained, even for one molecule of water, what must we conclude about the mass of one oxygen atom compared to the mass of one hydrogen atom, if we assume the formula for water is OH?

An O atom must be eight times as massive as an H atom.

Such a conclusion is called a **deduction**. In this case, we are forced to make the deduction that an oxygen atom is eight times as massive as a hydrogen atom, based on the experimental facts, and the hypothesis we are using.

Since atoms are so small, there was no way to determine how many atoms there are in 1 g of hydrogen and 8 g of oxygen. For now **we** will make an assumption and say there are one million hydrogen atoms in 1 g of hydrogen. If we use Daltons rule of simplicity and assume that hydrogen and oxygen atoms are reacting 1:1, then there also must be one million oxygen atoms in 8 g of oxygen.

If we guess that 10^6 atoms are in 1g of hydrogen and 10^6 atoms are in 8 g of oxygen, then when they react completely, we would get 10^6 molecules of water:
H + O ----> HO
10^6 atoms + 10^6 atoms ----> 10^6 molecules

Question 2: Based on this information, what would be the mass in grams of one H atom? one O atom? one OH molecule?
1 g H atoms / 10^6 atoms = 1×10^{-6} g for 1 H atom
8 g O atoms / 10^6 atoms = 8×10^{-6} g for 1 O atom
9 g OH molecules / 10^6 molecules = 9×10^{-6} g for 1 OH molecule

Scale of Relative Atomic Masses

Having no way to determine the actual mass of a single atom, a scale of relative masses was developed. The mass of one H atom was **arbitrarily** set at 1 **a**tomic **m**ass **u**nit (abbreviated as 1 amu), and therefore 1 O atom was 8 amus **based on the above experimental evidence**, **and the rule of simplicity**. One water molecule would then have a mass of 9 amus.

It is important to realize that we can use the equation H + O ----> HO, to symbolize two things:
1) one atom of H reacting with one atom of O, to yield one molecule of OH.
or 2) the number of atoms in one gram of hydrogen reacting with the number of atoms in eight grams of oxygen, to form the same number of water molecules, which totals 9 g in mass.

Recognizing the Hypothesis

It is important to realize that we cannot prove the relative atomic masses of hydrogen and oxygen are 1 and 8 amus respectively based only on the fact that 1 g of hydrogen combines with 8 g of oxygen. If Daltons hypothesis is wrong, and the formula for water is not OH, then the relative masses would be different. For example, lets see what we can deduce if we hypothesize that 1 g of hydrogen contains half as many atoms as are in 8 g of oxygen:
Since 1 g of hydrogen reacts completely with 8 g of oxygen, then we must use up all the atoms of both elements when the water is formed. If there are twice as many O atoms as H atoms, we must take 2 O atoms for every H atom. We conclude that the formula for water would be HO_2.

Question 3: What must we conclude about the relative atomic mass of an O atom compared to an H atom if the formula for water is HO_2?

> Remember that it is an experimental fact that the mass ratio of hydrogen to oxygen in water is always 1 / 8, no matter how much water we have. So even in one molecule of water it must be 1 / 8. If we assign a hydrogen atom a mass of 1 amu, and **if** the formula for water were HO_2, then **2** oxygen atoms would have a mass of 8 amus. So one O atom would have a mass of 4 amus.

Determining Relative Atomic Masses Using the Rule of Simplicity

1) It is an experimental fact that 1 g of hydrogen + 8 g of oxygen yield 9 g of water.
Dalton assumed that this was happening at the atomic level: H + O ---> HO
If this is so, then the H atom to O atom mass ratio is 1 / 8.

2) It is an experimental fact that 3 g of carbon + 1 g of hydrogen yield 4 g of a compound.
If we assume the rule of simplicity for this compound, then we would write: H + C ---> HC

Question 4: If the mass of an H atom is assigned the value 1 amu, what should we assign as the mass of a carbon atom based on the **fact** that 1 g of hydrogen reacts with 3 g of carbon, and the **hypothesis** that the atoms combine 1 to 1?

A carbon atom would have a mass of 3 amus.

3) We can use the previous facts and assumptions to predict that a compound made from carbon and oxygen that obeyed the rule of simplicity would have 3 g of carbon + 8 g of oxygen, yielding 11 g of CO.

Question 5: Explain why this is consistent with the above data.

> The carbon atom / oxygen atom mass ratio should be 3 amus / 8 amus based on points 1 and 2 above. If carbon and oxygen make a compound in which one atom of each combine, then the 3 / 8 ratio must be preserved (law of constant composition) no matter what the amount of compound that is made. Therefore, if 3 g of carbon combine, then 8 g of oxygen must combine.

The experimental evidence supports this prediction, lending support to the rule of simplicity!

4) It is an experimental fact that 7 g of nitrogen plus 8 g of oxygen yield 15 g of nitrogen oxide.
Using the rule of simplicity, we assume that this is happening at the atomic level: N + O ---> NO

Question 6: If an O atom has a mass of 8 amus, then what would be the mass of an N atom? What mass of nitrogen should react with 1 g of hydrogen?

N atom =7 amus;

If the rule of simplicity is true, then the compound of nitrogen and hydrogen would have the formula NH. Since an H atom has a mass of 1 amu and an N atom has a mass of 7 amus, the 1 / 7 ratio must be preserved, no matter what the amount of compound. Therefore, 7 g of nitrogen would be expected to react with 1 g of hydrogen.

Unit 6: Making Inferences about the Atomic Realm
Chapter 7: Daltons Hypothesis
Questions:

1. Knowing that water is composed of the elements hydrogen and oxygen and using Dalton's rule of simplicity, we assume the formula for water is HO. What would be the formula for water if:
a) 8 g of oxygen contained half as many atoms as are in 1 g of hydrogen?
b) 8 g of oxygen contained twice as many atoms as are in 1 g of hydrogen?

For OH we concluded that the ratio of the mass of a hydrogen atom to that of an oxygen atom was 1 amu / 8 amus, if we assign an H atom a mass of 1 amu. What would be the formula for water if:
c) an oxygen atom were only 4 times as massive as a hydrogen atom?
d) an oxygen atom were 16 times as massive as a hydrogen atom?
e) an oxygen atom were as massive as a hydrogen atom?

2. Given the fact that the hydrogen / oxygen mass ratio is 1 / 8 in water, if the formula for water is a) HO, what is the mass of an O atom compared to that of an H atom?
b) H_2O, what is the mass of an O atom compared to that of an H atom?
c) HO_2, what is the mass of an O atom compared to that of an H atom?
d) H_2O_2, what is the mass of an O atom compared to that of an H atom?

3. Assuming relative atomic masses of 1 amu for an H atom, and 8 amus for an oxygen atom, but not the rule of simplicity, what other formulas are possible for water?

4. When the compound ammonia is made, 1 g of hydrogen reacts completely with 4.67 g of nitrogen to make 5.67 g of ammonia. If the rule of simplicity is true, what is the formula for ammonia? If a hydrogen atom is assigned a mass of 1 amu, what would be the mass of a nitrogen atom? If 4.67 g of nitrogen contained twice as many N atoms as there are H atoms in 1 g of hydrogen, what would the mass of an N atom be compared to the mass of an H atom (H = 1 amu)? If an N atom had a mass of 9.34 amu and an H atom were 1 amu, what would the formula of ammonia be?

5. It is an experimental fact that 1 g of hydrogen combines with 35.5 g of chlorine to yield 36.5 g of hydrogen chloride. If hydrogen and chlorine atoms combine 1 to 1 to make HCl molecules, what is the relative atomic mass of a chlorine atom compared to a hydrogen atom? (assume H = 1 amu)

6. Since 1 g of hydrogen reacts with 35.5 g of chlorine, and 1 g of hydrogen reacts with 3 g of carbon, predict the mass ratio of chlorine to carbon when they react. What would the formula of the compound be according to the rule of simplicity?

7. Consider the following statements concerning the composition of the compound water:

1) $\frac{\text{mass of element oxygen}}{\text{mass of element hydrogen}} = \frac{8}{1}$

2) $\frac{\text{mass of total \# of oxygen atoms in one water molecule}}{\text{mass of total \# of hydrogen atoms in one water molecule}} = \frac{8}{1}$

Which of the following is correct about these two statements?
a) They are both true. b) They are both false. c) a is true, but b is false.
d) b is true, but a is false.

8. Assume that Daltons rule of simplicity is correct, but that the mass of an oxygen atom is 1 amu. Then the mass of a hydrogen atom would be
a) 8 amus b) 1 amu c) 1/8 amu d) 64 amus e) 1 / 64 amu

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