CREATING A MODEL-BASED CHEMISTRY CURRICULUM SEQUENCE

by

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A capstone submitted in partial fulfillment of the requirements for the degree of Master of Arts in Education.

Hamline University

St. Paul, MN

December 2020

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MODEL-BASED CHEMISTRY CURRICULUM

Introduction

The purpose of this project is to create a chemistry curriculum that is model-based and supported through guiding questions and relevant experiments in the lab. The outcome is to provide teachers with support that will enhance students' abilities to analyze and make sense of the physical interactions between substances. The first support is spatial modeling that helps focus students' attention on the interacting particles and specific qualities about those particles. The second support is a group of guiding questions to help students inquire about these interactions. The third support contains suggested lab experiments and demonstrations to show real-life interactions. This process and these supports should help to answer the question: *How should core concepts be sequenced in a general high school chemistry course?*

In order to create such a curriculum, it is important to place students at the center of the process. Therefore, the process begins with an examination of the difficulties students currently have with their chemistry curriculum. The students discussed are in 8th grade and 9th grade, since both grades include chemistry concepts in their science courses. The 8th grade teacher and two 9th grade teachers collaborated to compile a list of these misconceptions. An overview of these misconceptions is discussed next. Also included are the historical misconceptions of scientists that discovered keystone theories in related concepts. The comparison of student and scientist misconceptions shows a correlation that helps to map out the sequence of concepts for the curriculum.

After the mapping of sequences, supports are added based on the historical models used. As these models evolve, they help to progress through the understanding of the related concepts. The guided questions are therefore designed to help students travel down similar paths in tandem with these models. The lab experiments are also designed to be as similar as possible to the actual experiments that helped the models evolve.

There is significant influence on this curriculum from prior research, learning theories and curriculum design models. Prior research on cognitive learning theories helped to outline the following guidelines. The first is that students' prior understandings and misconceptions should be taken into account. The initial project steps support this by searching for misunderstandings and necessary knowledge bases for each subunit. The next guideline requires support to help students progress through conceptual understandings. These supports should include simple spatial diagrams. Another guideline requires learning steps be small and explicit. In order to accomplish this the subunits have been mapped out and the progression through each is detailed. The next guideline requires students be given opportunities to create a dialogue about their concept understandings. This is accomplished through the use of guiding questions to help reinforce this dialogue. The next guideline requires students to be given hands-on activities to analyze. These opportunities should include examples of cognitive conflict. Laboratory examples and demonstrations were designed for this reason. An emphasis was placed on finding explicit cognitive conflict that arises from these experiments and demonstrations.

Another prominent influence was from curriculum design models. These showed that good curriculums should be teacher-generated. Additionally, the sequence for this project was outlined. First, student misconceptions need to be identified in order to create a rationale for the concepts. These misconceptions are then analyzed and concepts selected. Concepts are then sequenced and mapped out. Finally, supports are added to each unit and subunit in the concept map. Outside of the scope of this project but still a part of the overall process outlined by these models is the creation of assessment materials and analysis of the curriculum. Both of those activities will be completed after this project is finished, and will be continued since the process as a whole is iterative.

Sequence Mapping Guidelines

It will be important to keep the following rules in mind when creating, finalizing and reviewing the sequence:

- *There is no known 'building block' of knowledge*. We try as best we can to break down the learning process, however, the actual mental steps are unknown and perhaps remain undocumented. A schema is the best guess as to that block. Sequencing itself is a learning process.
- *The concept relevance needs to be reflected in student misconceptions.* If there are none, it is possible that students are either proficient in that area or are so far in experience from it they can not relate. This is a decent bellwether for a student's zone of proximal development.
- *The concept mapping must be created with historical misconceptions in mind.* These are helpful in correlating and discerning concepts and their linkages. Most important, it is expected that these are mirrored in some way with student misconceptions as well. If they are not, further examination should be made into why they exist, and if they should be included in the sequence mapping.
- *Incomplete, or improper models and theories can have positive, and necessary results*. In other words, a path that today appears to be fruitless based on modern theory might actually be beneficial for ultimately arriving at the correct understanding. These are

common historically, and when examining these instances the future effect of its usage needs to be heavily considered.

- *Concepts should be correlated using spatial models, laboratory findings, and progressive questioning*. There are many tangents, especially in an empirical, lab based discipline like chemistry. Select only topics that correlate and that allow progression forwards, and that helped progression from earlier concepts.

Misconceptions

The misconceptions identified will be from the 8th grade and 9th grade students, followed by the past scientists working with these concepts. As for the students, these misconceptions are apparent to 8th grade teachers, 9th grade teachers, and show up on assessments both formal and informal. As for the scientists, the misconceptions show up in their work, and in the historical roadblocks that science had to overcome. Finally, these will be analyzed for a trend and used to map out the sequence of topics for the curriculum.

Student misconceptions

According to the 8th grade teacher, students struggle with mathematical reasoning related to conservation of mass (C. Johnson, personal communication, October 2, 2020). This appears to be linked to prior math courses, and most likely is skill-based from an algebra class. These students also struggle with identifying types of intermolecular and intramolecular forces, a sign of combination and separation issues linked to bonding.

From my class, and in discussion with my colleague G. Amaral, freshmen struggle with some basic experimental concepts. One of them is between the separation of substances into similar particles and the separation into smaller particles. This, on another level, also sets up the difficulty in distinguishing between the concept of an atom, and the types of atoms observed in the lab. Another is the struggle to distinguish between a compound and a mixture, which is a combination of two separate concepts. There is a struggle in recognizing how atoms are representative of chemicals in the real world, and how basic atomic theory is responsible for changes in reactions. There are also difficulties in recognizing and representing how atoms combine, and in what ratios they combine. Additionally, students mistake changing chemical formulas for molar amounts, which causes problems in both molar concepts and in mass conservation. The problem being that students will conserve molar amounts instead of mass. Lastly, students struggle with thermodynamics by confusing thermal energy changes for temperature changes. Students fail to associate the combination of atoms with the creation of heat.

A review of the student misconceptions in 8th grade shows problems with bonding and mass conservation. The main concepts embedded in the misconceptions in 9th grade are atomic theory, mass conservation, mole concept, bonding, and heat transfer. It is quite possible that, if the 8th grade assessments were expanded, the misconceptions would be identical in each grade. However, both classes showed the ability to use spatial models and to interpret laboratory results. Neither group appeared to struggle with pattern identification or analysis. This shows that there are skills developed at sufficient levels, however, there are misconceptions that halt the learning process.

Research

Atomic theory is a great representative unit for the learning process created by the scientific method. It is presented by simple lab experiments that show seemingly unpredictable separations of substances, and yet requires an abstract model to analyze these particles with. Scientists struggled for centuries with identifying and comparing the basic particles in these interactions. During this struggle, their ideas of how atoms interact, how heat interacts, and how to represent these interactions constantly changed. As experiments revealed new interactions, concepts and models changed accordingly. To pass over this unit and not use it as a building block of the course causes students to lose an understanding of the fundamental concepts in chemistry.

A typical introductory unit transitions quickly from atomic theory to atomic structure. There are several reasons, outlined in the project paper, why this transition should take the entirety of the year, as opposed to a unit. In either case, if atomic theory is to be introduced as the starting point for curriculum, then its development is paramount regardless of the choice of sequence. For this reason, I will focus the initial effort on this topic, its misconceptions, its modeling, and the relevant questioning and experimentation. These efforts will prove that instead of atomic theory being relegated into a subsection topic of a unit on atomic structure, it deserves a larger role in creating an effective model-based chemistry curriculum. In fact, it will be the foundation for the course, as historically it has been the foundation for the discipline as a whole.

Traditional and Atoms First textbooks both begin their initial chapters with Dalton's atomic theory. There is a short description of Dalton's principles from the start of chapter 3 from *A New System of Chemical Philosophy* (Dalton, 1808). What is most interesting, in reading chapter 3, is how integral this theory is in stoichiometry, and how prominent Dalton's use of modeling was when introducing these principals (Dalton, 1808). However, there are some other interesting takeaways. Dalton did not have an idea of heat as abstract energy, but as a tangible liquid attracted to substances. He also did not have accurate measurements for atomic masses, or for molecular formulas. In fact, there is a lot of time spent on identifying methods with which to take temperatures and masses and to observe reactions (Dalton, 1808). Dalton painted the picture of the struggle taking place in the nineteenth century to identify elements, classify elements, and compare them. Intertwined in these concepts was the misconception of heat, called caloric, the misrepresentation of compounds, as well as misleading data. This is such an excellent topic to start with since our students have very similar struggles and misconceptions. Understanding atoms is naturally difficult, and intriguing, and puzzling. To avoid that struggle is to avoid learning atomic theory.

Dalton's struggles appear to mirror the misconceptions that our students have. Also, his usage of data analysis and modeling is also similar to our student strengths. Therefore, it would appear that the progression through Dalton's theories by model usage was not just beneficial historically, but is important for current students to use as well. Mapping out how models were used historically to arrive at, and progress from, Dalton's theory is the next logical step. This takes us back to the forefather of chemistry, Antoine Lavoisier (1789), and his methods as well as model usage.

Lavoisier's book on the treatise of chemistry, considered one of the first textbooks in the discipline, is almost entirely empirical (Lavoisier, 1789). However, there are several theories that have retained prominence. These theories were derived from hours and days and years of experimentation, which he documented. These theories, on heat, the conservation of mass, the importance of pressure on states of matter, as well as the forces between bonded particles, certainly aided Dalton. However, there is no real spatial modeling shown in Lavoisier's work. Instead, his notes are very detailed and experimental. There is very little to aid in the theoretical understanding spatially, and perhaps that is why he lacked descriptions of atomic separation and combination.

Lavoisier did create some explicit and clear support with nomenclature, the naming of chemical compounds. Though Lavoisier struggled with the identification of polyatomic particles, the concept of multiple proportions, and the physical structure of compounds, his ability to relate and identify the correct reactant particles in each product was incredible (Lavoisier, 1789). This went a long way to separate chemistry from the alchemical notion of magic and transmutation. It draws a clear line connecting what occurs before and after a reaction, as well as showing consistency and reliability in reactions and between similar reactions.

Lavoisier also noted, on page 7, that "it is in these things which we neither see nor feel, that it is especially necessary to guard against the extravagancy of our imagination, which forever inclines to step beyond the bounds of truth, and is very difficultly restrained within the narrow line of facts" (LaVoisier, 1789, p. 7). His separation of imagination from analysis is what separated Lavoisier from the magic-seeking alchemists before him. Perhaps, beyond any of his theories, this is the most important aspect of his treatise. He provided a method for identifying, observing, and relating the chemicals involved in a reaction, and that method used sophisticated separation techniques.

The idea of separation and the idea of the smallest inseparable object are related, and that becomes one of the first misconceptions. The separation of a substance into smaller parts is not the same as separation into different parts. This is a rudimentary idea, most likely prehistoric, and yet it is vitally important as it gives rise to the notion of an atom. Also, I believe it is a supporting idea that helps to build the idea of what an element is. This is a cyclical, repetitive function through chemistry's history. Lavoisier was just as dependent upon proper separation of substances as Curie was. In fact, both Lavoisier (1789) and Curie et al. (1898) spent particularly large amounts of time devoted not just to apparatus design, but to analysis of possible impurities and contamination.

Separation also includes various methods that show incrementally small steps in understanding. Decantation and density are documented in ancient, classical scripts, distillation arises during the medieval period, and various methods of filtration are used throughout history. Each of these methods provides indirect measurement, and possible explicit evidence for particle size, particle attraction, and the conflict of forces. Both Dalton(1808) and Lavoisier(1789) mention their interpretations of both the related physical properties and means of separations with the reactions they examined. In both cases, they revealed misconceptions of intramolecular and intermolecular forces. More importantly, they showed correct intuition and deduction that may have led to correcting in subsequent history for their mistakes.

Another prominent misconception is the transformation, or transmutation, of one chemical into another. An old misconception of the alchemists was that chemicals could transmute into any possible product, most notably gold. In a sense, this is more possible if the number of elemental types is smaller, because if you consider all chemicals to be compounds, then it is conceivably possible. However, if you take a large number of elements, there is an impossibility of creating a new one. Freshmen have a similar misconception. They have the assumption that there are almost infinite numbers of viable products, and that to predict a chemical reaction's products requires knowledge of an immense number of reactions. While this is not good for predictive chemistry, it is good for the realization of how elemental puzzles are solved. This becomes an excellent concept, therefore, to emphasize after separation.

The enormous gap between the identification of matter, and workable atomic theory, spans millennia and is only clarified by Lavoisier's nomenclature. However, already by

Lavoisier, there are signs of particulate theory, mass conservation, particle interactions, and other aspects of atomic theory (Lavoisier, 1789). These are rudimentary, and it is entirely possible that these rudimentary ways of viewing the chemical world are necessary in order to create the more sophisticated worldview that exists today.

Table 1 shows a summary of misconceptions from 8th grade, 9th grade, Lavoisier and Dalton:

Table 1

Misconceptions

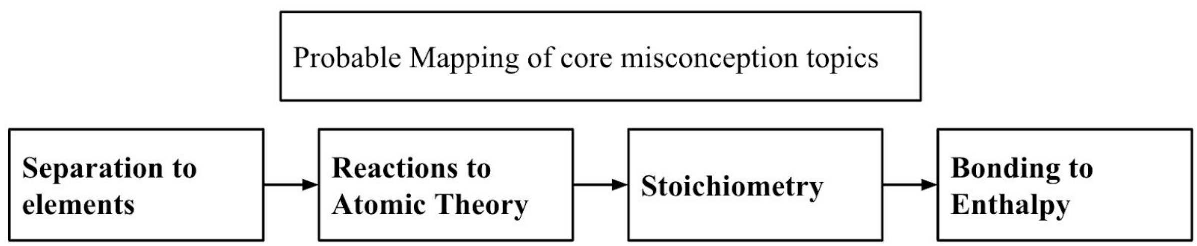
Core Concept Area	8th grade Misconceptions	9th grade Misconceptions	Lavoisier's Misconceptions	Dalton's Misconceptions
Separation	Formula usage for experimentation	Distinguishing between atoms and substances	Lack of representation of reactions spatially	
Atomic Theory	Conservation of Mass *trouble following mass	Conservation of Mass *trouble representing atoms	Rudimental view of atomic theory	Atomic Masses and Formulas misrepresented
Stoichiometry	Forces between atoms	Separation and combination	Lacking any bonding theory	
Enthalpy	Separation and combination due to above problems	Energy vs temperature Bonds Energies being all endothermic	Energy as representing an intangible concept	Energy as representing an intangible concept

Relating misconceptions to curriculum

There are four core areas of misconceptions that appear to be related. In order to map these accordingly, it helps that Lavoisier and Dalton were separated by almost half a century. Additionally, Dalton's misconceptions in Table 1 are fewer and placed into concepts that appeared later historically. For this reason we can be confident that misconceptions for Dalton are a bit more sophisticated than those of Lavoisier. The fact that Atomic Theory is communicated more clearly by, and in fact attributed to, Dalton cements this idea. Therefore the formula representation appears to be important after reactions, which is intuitive. Also, atomic theory appears to require element identification, which is perhaps not intuitive. Elements require basic atomic theory, the representation of some essential indivisible part is communicated by Lavoisier. However, Atomic theory is dependent on the identification of these elements. This theory leads to explicit identification of atomic separation and combination (this is part of Dalton's Atomic Theory). However, even with this theory in pace, Dalton still struggled with the notion of an intangible energy known as heat. The proposed sequence for these related areas of misconception is shown in Figure 1:

Figure 1

Misconception Mapping



Separation to Elements

The concept area that will be examined, therefore, is the transition from separation of substances to the concept of an element and it's identification. The historical process of separation includes the related identification of substances as they are separated. Archimedes' concept of density, the distillation of alcohol, Brand's separation of phosphorus, are all indications of this transition (Principe, 2013). However, to begin the monumental task of identifying elements in these substances required two separate concepts. The first is the identification and representation of chemical reactions. Alchemists, including Brandt, did an excellent job of recording and identifying reactions and related chemicals.

However, in order for these representations to properly identify elements, one needs to get away from Aristotle's concept of atoms. Aristotle's theory described four fundamental elements (Principe, 2013), making all observable substances compounds. This being the case, each combination of substances could lead to an exponential possibility of products formed. In order to discover elements, the idea of four fundamental elements had to go, and a more modern concept of many discoverable elements had to take its place. A summary of the misconceptions in this unit is shown in Table 2.

Table 2

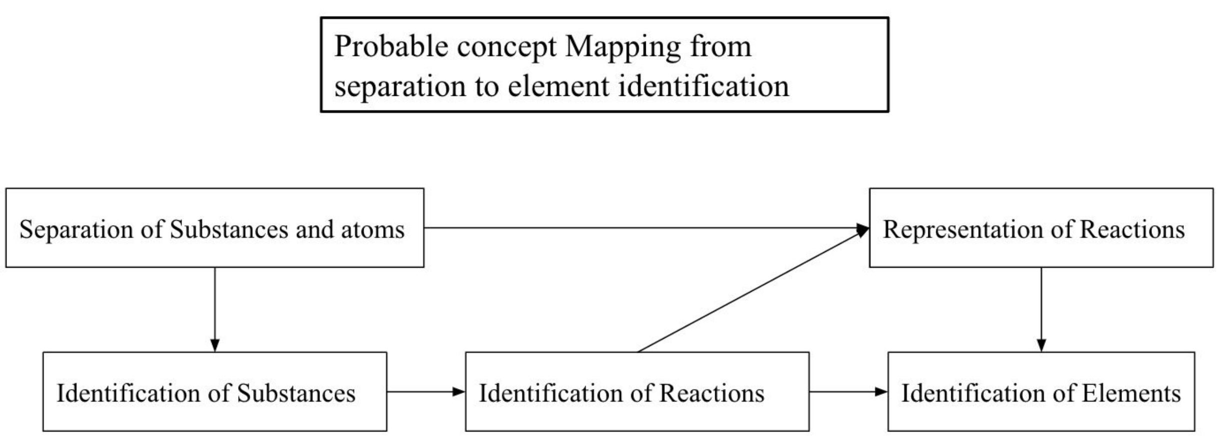
Misconceptions in Separation and Identification

9th grade Misconceptions	Lavoisier's Misconceptions
Distinguishing between atoms and substances	Lack of representation of reactions spatially

The sequence of representation and identification outlined above is summarized in figure 2:

Figure 2

Sequence for Separation and Identification



Here is the unit link: Separation and Identification. This is also found on page 21 of this project

Atomic Theory

Atomic theory, though outlined by Dalton, essentially created the periodic table. The hallmarks of the periodic table are not just the periodicity of chemical properties, but of attributes associated with elemental atoms. The notion of atomic mass, the ability of atoms to combine with other elements, and the variety of combinations that could be made by each element (Mendeleev, 1869). These are all directly related to Dalton's Atomic theory and are referenced by Mendeleev when creating the periodic table.

Though Dalton has several glaring compound misrepresentations, most glaring that for water (Dalton, 1808), almost as glaring as Lavoisier's lack of identifying hydrogen in acids (Lavoisier, 1789), his spatial representations for compounds allowed robust descriptions of combinations in reactions. Lavoisier described these combinations, but without representing them accurately, lacked a more sophisticated view of the separation and combinations of atoms. However, Dalton's concept of multiple combinations culminated in the concept of valency, the possible combinations that an atom can make. A table of the misconceptions related to atomic theory is shown in Table 3.

Table 3

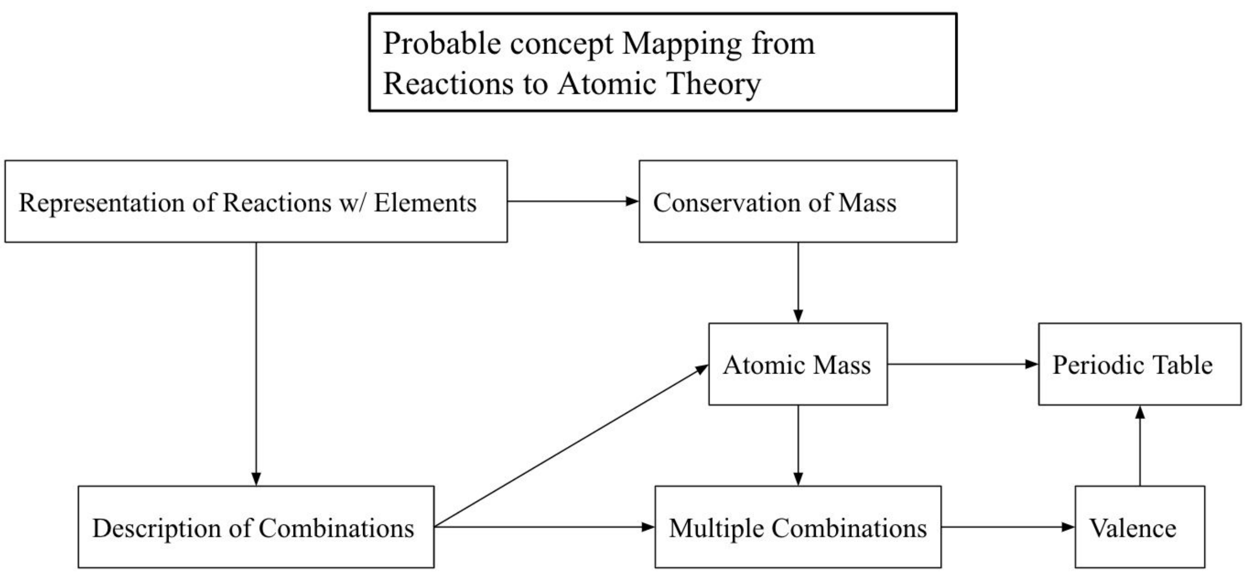
Misconceptions in Atomic Theory

8th grade Misconceptions	Lavoisier's Misconceptions	Dalton's Misconceptions
Formula usage for experimentation	Representations of atoms, very rudimental view of atomic theory	Atomic Masses and Formulas misrepresented

Valency helped to piece together the puzzle of atomic masses, or relative weights. Dalton's masses were improved over Lavoisier, however, they were still too inaccurate for a periodic table to have been made at the time. Repeated guess work, experimentation, and some elimination was needed before Mendeleev had enough reliable data with which to create his table. (This might be an indication of why both Lavoisier and Dalton spend so much of their text describing how they accounted for contamination, error and inaccuracy.) Figure 3 shows the proposed sequence of concepts for atomic theory:

Figure 3

Sequence for Atomic Theory



Here is the link for the Unit Resources: Atomic Theory. This is found on page 41 of this project.

Stoichiometry

The practical tool of Atomic theory is its ability to predict the products of a chemical reaction as well as the mass of the products in the reaction. These predictions can be applied to reactants when product identity and amounts are known as well. The application of atomic theory towards predicting the masses involved in a reaction is the focus of this section.

Historically, Lavoisier was able to complete this with sheer mountains of empirical results (Lavoisier, 1789). However, in order to predict an entirely novel reaction Lavoisier would have been hard-pressed. Dalton would have had better chances, though his lack of accuracy with atomic masses would have caused significant errors. The progression forward took a large amount of trial and error as valances and atomic masses improved. In fact, the path through this process of relating mass amounts in a reaction, known as stoichiometry, was repetitively modified and updated with core concepts of Atomic theory: atomic mass, valence, Conservation of matter. Representing these with symbolic equations helped improve these concepts past the prevalent tables of masses used at the time (Lavoisier, 1789 and Dalton, 1808). Spatial diagrams will help students to double check each of these concepts as well.

Through repeated use, new concepts were not as much conceived as they were perfected. The ideas of molar ratios existed long before they were discussed (Lavoisier, 1789), much like atomic theory. However, increased accuracy led to the increased usage of coefficients in symbolic equations and the description of valence in spatial diagrams. The practice of using coefficients and calculating molar amounts became the capstones for this unit of study. In modern textbooks, however, the use of Avogadro's number is very prevalent. This number, entirely impractical in the lab, and requiring the presentation and usage of scientific notation, is not required for understanding the concept of molar amounts. For this curriculum, the calculation of molar masses will be limited to using actual masses in the lab, or the description of actual masses in the lab. This will help keep the curriculum lab-based, and will decrease the added distraction of an inconceivable number.

The struggles in this section are defined by student misconceptions just as they were by historic inaccuracies. Students struggle with similar calculation mistakes, especially when calculating and comparing molar amounts. Students will confuse the usage of coefficients with the usage of subscripts. Instead of using subscripts for molar mass they include coefficients, which should only be used for molar ratios. These struggles correspond to the misconceptions in Table 4.

Table 4

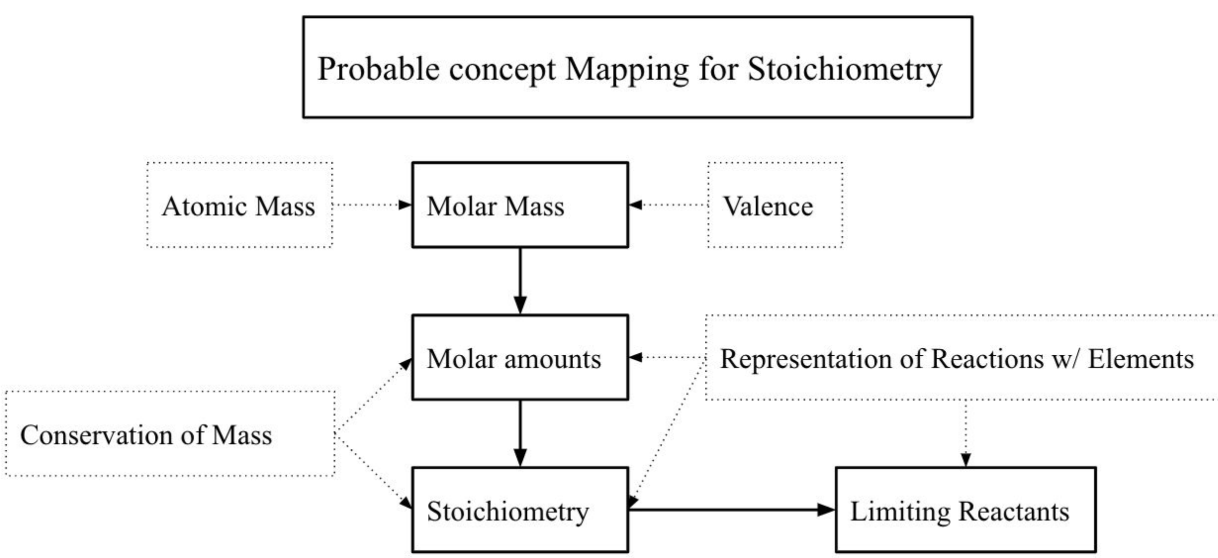
Misconceptions in Stoichiometry

8th grade Misconceptions	9th grade Misconceptions
Conservation of Mass *trouble following mass	Conservation of Mass *trouble representing atoms

In order to combat these misconceptions, an emphasis on modeling and directed questions about the differences between molar mass and molar amounts is used. This is shown in Figure 4.

Figure 4

Sequence for Stoichiometry



Here is a link for the unit resources: Stoichiometry. This is found on page 63 of this project.

Enthalpy

This is the introductory unit for thermodynamics. Enthalpy runs through the ideas that heat can transfer. This starts with the basic notion that heat moves from a warmer object to a cooler one. This concept of motion associated with heat is then defined in a more modern sense with Joule's experiment. This experiment shows that heat is directly related to kinetic motion and that it can be measured (Joule, 1850). This concept is then developed further for objects that transfer heat without changing their temperatures during changes in state. There is an emphasis in this section on the combination and separation of atoms, and how this affects the ability of a substance to absorb or release energy. Finally, the combination of energy changes associated with combination and separation is applied to some basic reactions. This provides a means with which to compare the heat associated with each combination and separation.

The concept of heat transfer is supported by previous units in several ways. The first is the number of prior reactions that have been used in a lab that give off substantial amounts of heat. Those should be referenced. Also, heat can be represented in reactions. The prior repeated use of equation writing supports this inclusion. Even though this usage started during the caloric theory, and was used by Lavoisier (1789) and Dalton (1808) to misrepresent heat as a physical object, it helps support the concept of heat transfer. Spatial diagrama will also help support this idea. Since the important connections in this unit were historically developed in tandem with improvements to measurements for atomic masses and valence, it is important to keep repeating the habits of using symbolic reactions and diagrams.

This unit is rife with misconceptions, both in class and historically. Both Lavoisier (1789) and Dalton (1808) helped to develop and apply a theory known as caloric theory. This theory described heat transfer as the motion of a liquid named caloric which imparted heat to substances. Its presence helped to separate atoms causing substances to melt and evaporate. The important concepts from this include the trends of heat transfer, from warm to cold until equilibrium, the relationship between separation of atoms and heat, and the comparative rates that different chemicals heat up at. However, the idea of a physical object representing heat becomes confusing when heat is lost, when pressure changes, when gasses transfer heat, etc. It was Joule's concept-changing experiment that showed the direct relationship between kinetic motion, energy and temperature (Joule, 1850). This allowed the direct measurement and calculation of heat, opening up the door for the development of the laws of thermodynamics. Table 5 reviews the misconceptions in this unit.

Table 5

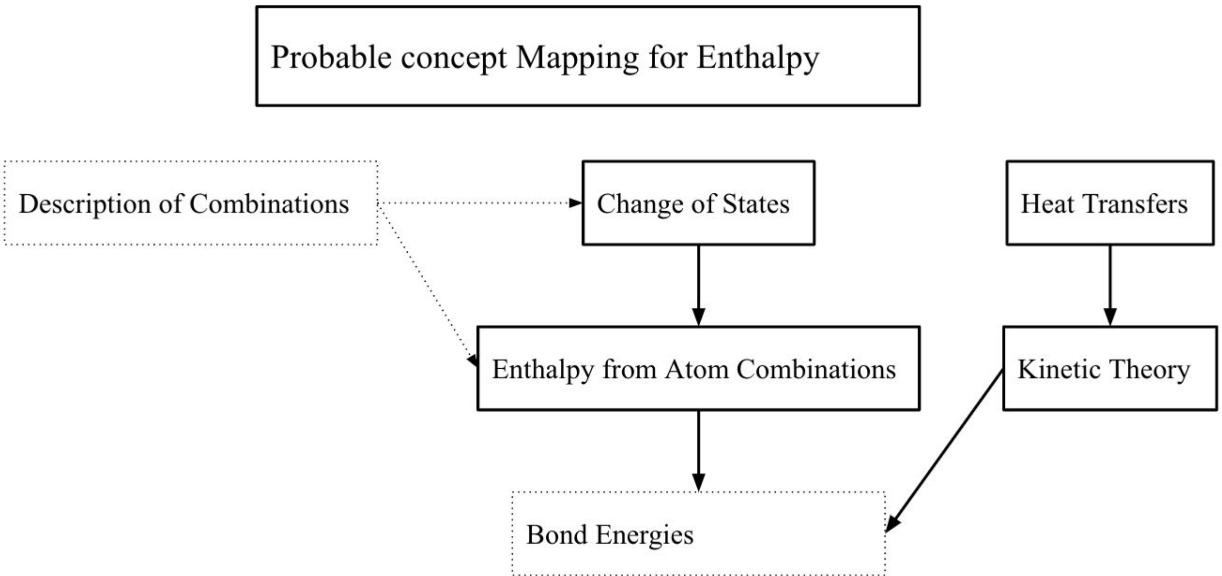
Misconceptions in Enthalpy

9th grade Misconceptions	**Lavoisier's Misconceptions**	**Dalton's Misconceptions**
Concept of Energy vs temperature	Energy as representing an intangible concept	Energy as representing an intangible concept
Bonds Energies being all endothermic		

To help dispel these misconceptions an emphasis should be placed on Joule's experiment. Spatial diagram usage with symbolic equations should also be focused on. The sequence for these concepts is shown in Figure 5.

Figure 5

Sequencing for Enthalpy



Here is the link for the unit resources: Enthalpy. This is shown on page 78 of this project.

This is the end of the project description. What follows next is a collection of unit and subunit resources and descriptions.

Unit Support Resource: Separation and Identification

Summary: This unit covers the progression from the separation of substances, through the identification of these substances using both physical properties and methods of separation, to the identification of and description of chemical reactions using observations and elemental representations.

Misconceptions: The difficulties in this unit revolve around distinguishing between similar concepts. The differences between pure substances and types of atoms is a prominent misconception, more prominent than distinguishing between mixtures and pure substances, or between elements and compounds. Therefore, this problem most likely arises from the difference in separation into similar particles and separation into smaller particles. One separation, the former, leads to the concept of pure substances, while the latter separation leads to the concept of atoms. Another common misconception revolves around the representation of substances and particles. Transitioning from the disappearance and appearance of pure substances to the conservation of their atomic particles is difficult. This transition should be aided through modeling transitions, and heavy use of guided questions aimed at the retention of essential characteristics of chemicals through related reactions.

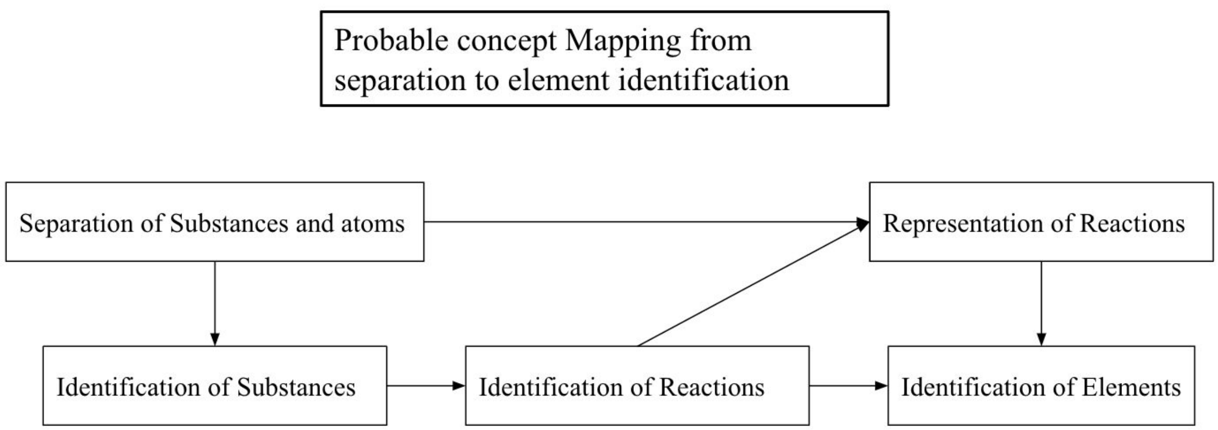
Sequence: Since the most prominent misconception is an immediate roadblock stemming from the first subunit and into each subsequent part of this unit, it must be addressed first. To do this, a basic analysis of separation must be done, showing the difference between separating out types of substances, and separating substances into smaller parts. Each is important, and while one leads to the definition of an atom, the other leads to identification of reactions. Both of these are necessary in order to present and develop the idea of elements and compounds, as well as to promote atomic theory in the next unit.

After the first subunit on separation, the laboratory practice of separating pure substances should be repeated often. Students should be given mixture puzzles, to identify mixtures and pure substances, as well as to promote the type of problem-solving familiar to this curriculum. These should be supported with drawings relating the experiments to substance identification. Once these are routine, two substances are placed together to be separated. The outcome should be predictable, however, for certain combinations they are not. The substances disappear, and new ones appear, and this should be the method of introducing and identifying chemical reactions. Modeling these reactions should start out similar to the experimental diagrams for separation, and slowly be modified to include more simplistic symbolism.

Lastly, related reactions should be used in order to show that there is some relationship between reactant and product in a chemical reaction. Reinforcing this idea with the notion of atoms allows for a change in representing reactions. Reaction chemicals are then examined through multiple sets of reactions to determine which can be confirmed as compounds, and which can be assumed to be elements. Element types are also identified by chemical properties. The suggested progression of this unit through these topics is shown in figure 2.

Figure 2

Sequence for Separation and Identification



The supporting models, experiments and progression questions are shown in table 6:

Table 6

Subunits for Separation and Identification

Sub-Unit	Modeling Supports	Experimental Supports	Progression Questions
Separation of Substances and Atoms	Diagrams of separation techniques	Mixture Puzzles and separation practice	What is an atom? What is the difference between mixtures and pure substances?
Identification of Substances	Modified diagrams of separation	Density Lab, Dissolving Practice	How can pure substances be identified? What happens when a substance dissolves?
Identification of Reactions	Modified diagrams of separation	Mixture and separation reactions	What occurs to the chemicals in a reaction? What is a reactant and a product?
Representation of Reactions	Symbolic equations and modified diagrams	Synthesis and decomposition labs and demonstrations	How can a reaction be represented? How are chemicals in a reaction related?
Identification of Elements	Symbolic equations and spatial drawings	Review of equations as puzzle sets Types of elements lab	How are elements and their type determined in a reaction? What about in the lab?

Sub-Units: The full description of each sub-unit, along with each model description, lab description as well as the full set of progression questions can be found in the attachments below. Remember that these are not lesson plans, but the structure upon which lessons are built.

Separation of Substances and Atoms - this is found on page 24.

Identification of Substances - this is found on page 27

Identification of Reactions - this is found on page 30

Representation of Reactions - this is found on page 34

Identification of Elements - this is found on page 37

Sub-Unit Support Resource: Separation of Substances

Summary: This subunit covers some very basic concepts. However, these are fundamental to the majority of the course concepts. Also in this subunit, students are introduced into the routines of laboratory and model use. Students start the practice of turning the tangible, empirical experience into abstract concepts. This begins with distinguishing between separating pieces of a whole from each other, and separating different types of pieces. Through prompting this should develop a definition of an atom. Then, the methods of separation should be used to create a definition of mixtures and pure substances. The lab techniques of doing so should be recorded and developed into a symbolic model.

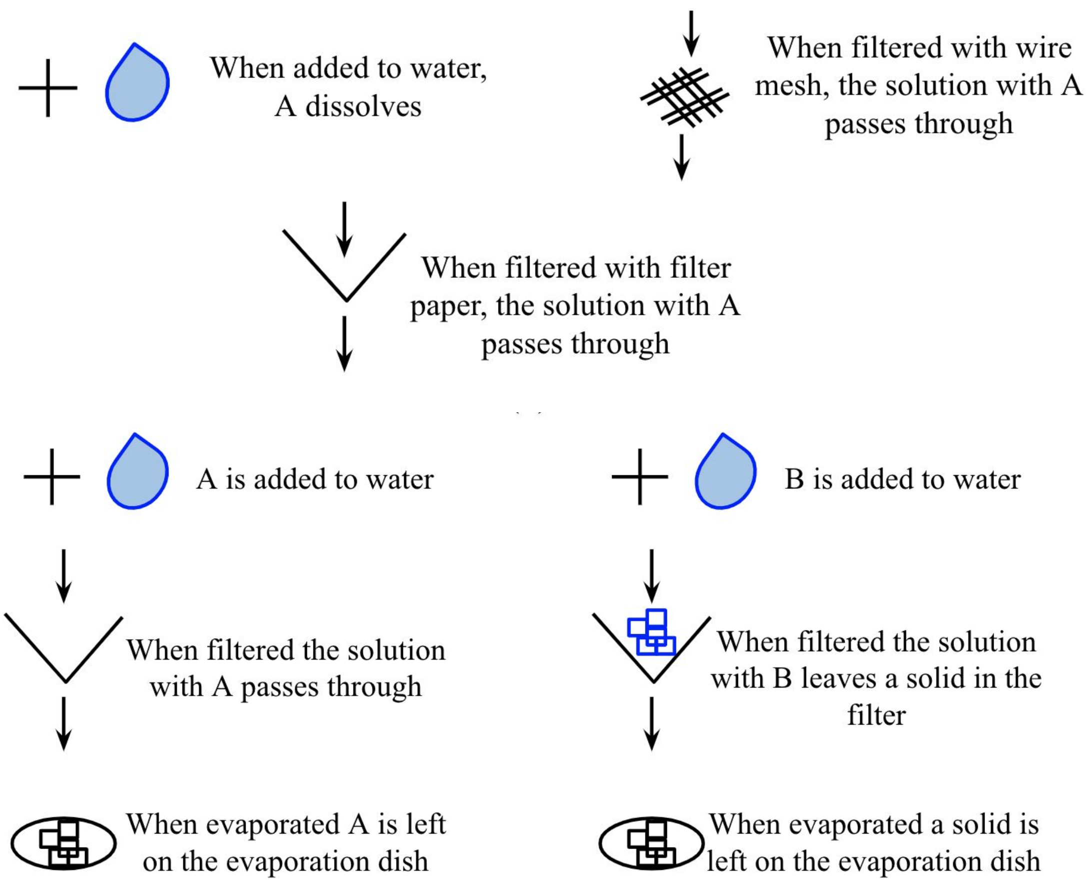
Misconceptions: The two types of physical separation causes some confusion, and the misconceptions from this can be robust, showing up throughout the unit. It is important to address this early, and to clarify the differences between the notion of an atom, and the separation of different substances. Also helping to clarify this is the usage of models.

Modeling: For this introductory subunit on separation techniques it is important to focus on simple, spatial diagrams. Students may want to add details to their diagrams which clutter and distract. The practice of keeping models simple should be reinforced.

Diagrams of separation should be created to show evaporation and filtration. There should be basic symbols for each. Students should be able to relate the diagram to a lab, and be able to identify mixtures and pure substances based solely on the diagram. Examples are on figure 6.

Figure 6

Spatial diagrams for separation



Lab examples: The experiments for this section should include practice separation techniques by both students and demonstrations by the teacher. Separation techniques should include filtration, decantation and evaporation. These should be very repetitive and a habit should be built of recording observations using models. Then students should be given a set of unknown substances. Through independent separation in lab students should be able to identify mixtures and pure substances, relate their findings with models, and be able to identify the composition of their mixtures. The following are good lab examples:

Distillation Demonstration

Mixture Puzzles with metal chlorides and oxides.

Progression Questions: Questions in this section should revolve around the theoretical differences in separations.

What is the smallest divisible part of a substance?

What is a pure substance? (Explain in terms of separation)

Some time should be spent on separating substances allowing these last two questions to be better developed:

How can the components of a mixture be identified?

Is there a way to prove that a substance is pure?

This last one is open ended, in similar fashion to those for proving elements in a future subunit. There really is only separation methods for proving something is a mixture, pure substances are not proven but result from a best guess.

Expectations: Students should be able to explain the difference between the separation of substances and the separation that leads to atoms. They should be able to show separation in the lab as well. Then students should be able to distinguish between mixtures and compounds both in definition and in the laboratory. Finally, students should be able to test and separate mystery substances in the lab to determine which are pure, which are mixtures, and identify the composition of the mixtures.

A sample lesson activity revolves around the use of the mystery mixtures lab. Students are given several substances, as well as filters and evaporation dishes. They separate the substances as best they can and then analyze and identify them. They also should identify the pure substances combined in the mixtures and show this with a diagram. Besides a quick activity to describe mixtures and pure substances, students also need a brief activity for practicing separation techniques initially.

Sub-Unit Support Resource: Identification of Substances

Summary: The identification of substances is an extension of the prior subunit on separation of substances. The important aspects of this subunit are presented when multiple substances show the same outcomes. There are several methods that can be used to distinguish between similar substances. The two new methods to be presented are density and solubility, both requiring laboratory practice for measurements of volume and mass. Students will then use simple equations to solve and compare substances, while noticing that properties like solubility and density are specific to substance types, and not to substance amounts. This will help further develop mental models of substances and atoms.

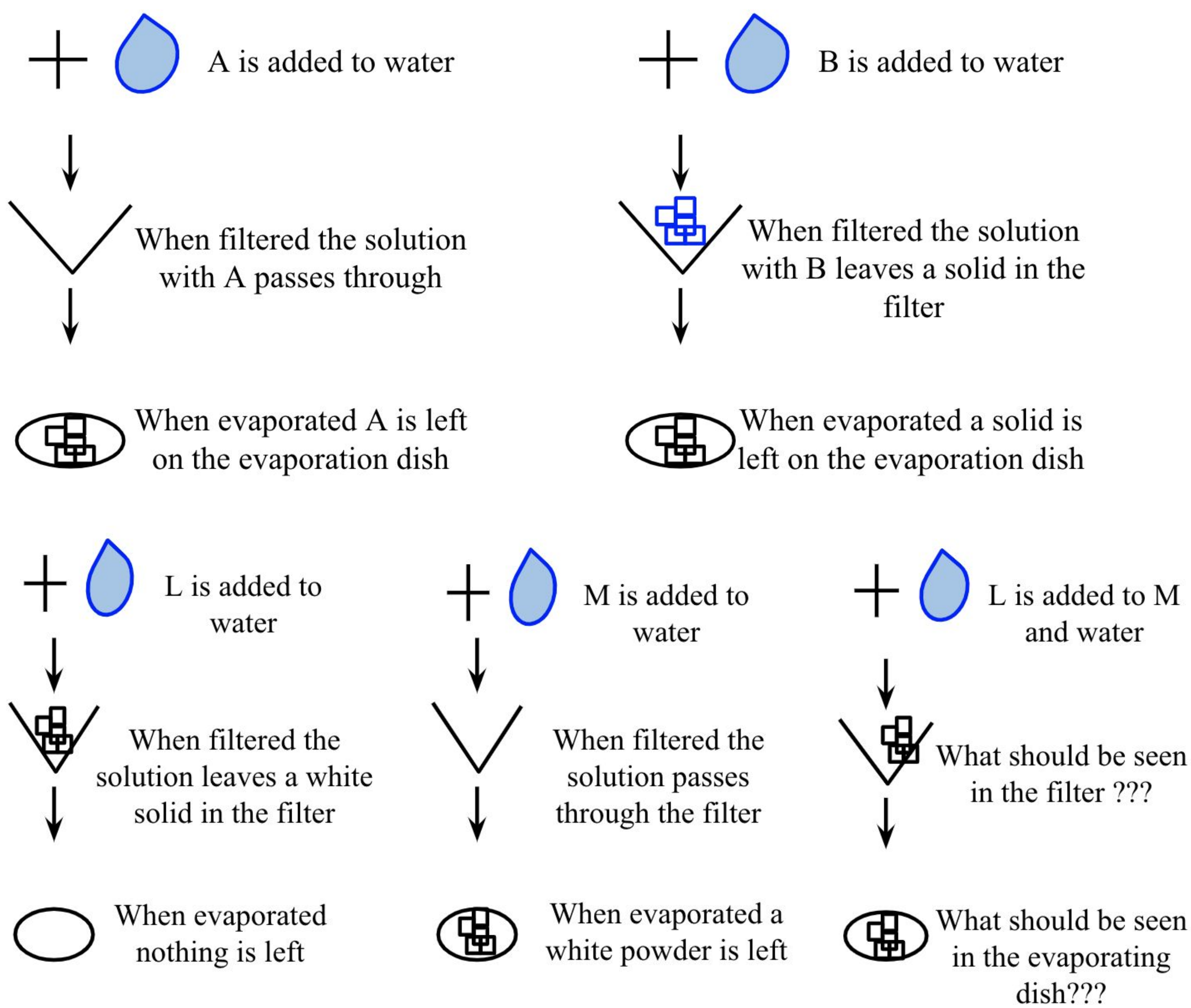
Misconceptions: There are a few misconceptions, some that pertain to vocabulary usage. The first is to distinguish between mass and density. Heavier and more dense at times are used synonymously, and some explicit practice to show that this is not the case for large objects with low density compared to lighter, smaller, more dense objects should be used. Another common misconception is that dissolving chemicals disappear or melt. In this case, a focus on the vocabulary use along with modeling the particle interactions with diagrams during filtration should be used.

Modeling: For this subunit on identification it is important to focus on simple spatial diagrams. Students may want to add details to their diagrams which clutter and distract. The practice of keeping models simple should be reinforced.

Diagrams of separation should be created to show evaporation and filtration. There should be basic symbols for each. Students should be able to relate the diagram to a lab, and be able to identify mixtures and pure substances based solely on the diagram. Examples are on figure 7.

Figure 7

Spatial diagrams for mixture identification



Lab examples The experimentation for this subunit should be geared towards developing measurement skills and increasing lab practice both with separation and measurement. In the solubility lab, further practice with separation and mixture identification occurs, and new particle descriptions arise when using different filter types. Students should practice recording observations as well as drawing basic spatial models of the observations. This will reinforce new ideas about particle size, since larger particles will stay in the filter and smaller particles will move through. Students should also practice measuring volumes with accuracy, as well as use massing repeatedly in the lab. Lastly, students should practice performing the calculations for density, and comparing their answers with the ability of certain substances to float. These two labs are shown below:

Density Lab

Solubility Lab

Progression Questions The questions in this subunit need to develop definitions for both density and solubility. Also, the purpose of using both of these methods should be brought out.

What happens when a substance dissolves?

What is the difference between the particles of substance that filters and the particles of one that does not?

Does the density of a substance change?

How is density measured?

Expectations: Students will be able to distinguish between dissolving and melting, and will identify substances with unchanging densities. Students will be able to accomplish this by taking and comparing accurate measurements in the lab, and be able to calculate density as well. Students will also be able to compare particle sizes by their passage through a filter, and to describe what happens to particles when they dissolve by use of spatial diagrams.

A sample lesson activity: A typical activity would provide students with several different labeled metals. Students would measure their volumes and masses using displacement. Then, students are given unknown metals and must identify them. Another related activity, somewhat shorter, uses a series of different types of filters to determine the order of size of particles for substances that do and do not filter through them.

Sub-Unit Support Resource: Identification of Reactions

Summary: The subunit on the identification of reactions should be a natural progression from the prediction of separation locations for mixtures. The presentation of the concept should come from students mixing known substances and then separating them. There should be some obvious predictions that work, and some obvious predictions that don't. This should be repeated several times, and students should be using the diagrams to identify which substances were there before the mixture was made, and which are made after. Emphasis should be placed on the disappearance and appearance of substances. To represent these situations, students should then start practicing the use of symbolic equations to represent their reactions, slowly modifying these symbols until they are simplistic like letters.

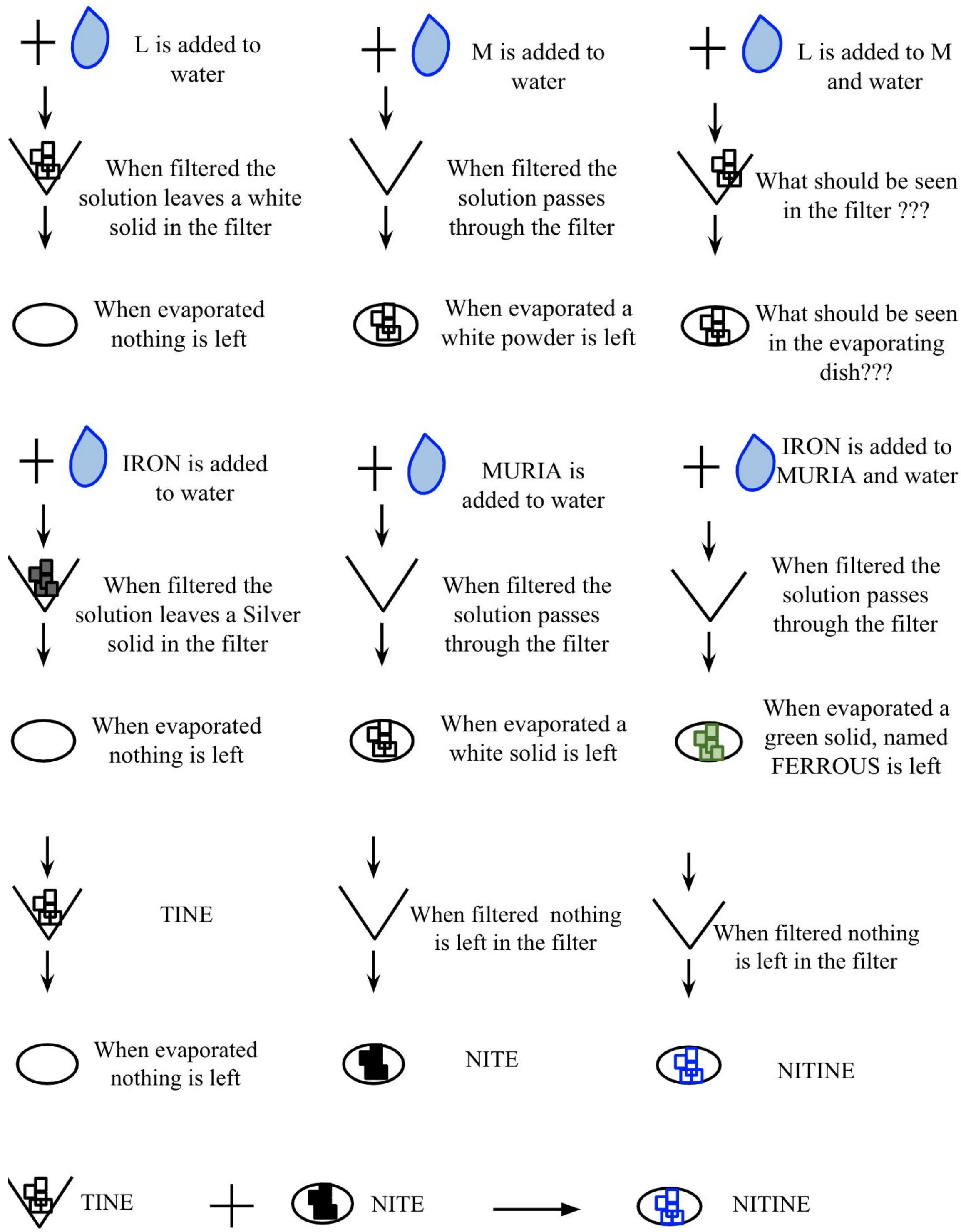
Misconceptions: The misconception of chemicals being retained in a chemical reaction is prominent in this section. Students will confuse the fact that substances disappear but atoms do not. At this point, we want students to understand that substances are created and destroyed though some essence of their form is retained. The concepts of atoms being retained is important in this section and even more important in the next one, so beginning the dialogue in this subunit is important.

Modeling: For this subunit on identification it is important to transition from the spatial diagrams into the use of symbolic equation writing. This is a transition and so the actual starting point most likely is dependent on student comfort. However, the final goal is to use letter symbols so that must be moved toward eventually.

Diagrams of separation should be created to show evaporation and filtration. These should be routine by now, however, they are still needed to identify the disappearance and appearance of pure substances. Examples are on figure 8.

Figure 8

Spatial diagrams for unexpected mixtures: Reactions!



Lab examples: Experiments in this subunit should focus on the mixing and separation of substances. The labs are also important for introducing the usage of symbolic equations. There should be several chemicals that, when mixed, change the solubility between products and reactants. Color change is not required, but definitely helpful, and combining both the solubility change and color change helps to make dynamic and noticeable reactions. Also, it is suggested that these more apparent reactions are used early, along with predictable and separable mixtures that do not react. After several examples, students should also be in the habit of recording the combinations as reactants and products both with diagrams and with rudimentary equations. If students appear proficient, using some labs with gas creation is also helpful here. This experiment is named below:

Intro to reactions from mixtures

Progression Questions: The questions in this subunit should emphasize the changes in substances during reactions. They should also focus on using appearance and disappearance in descriptions of reactants and products.

How are reactions able to be identified in the lab?

What happens to substances involved in a reaction?

Define reactant and product by describing their appearance.

Then the usage of diagrams should be reinforced:

How can we represent the chemicals in a reaction symbolically?

Lastly, transition into the next subunit with the concept of an atom:

How are reactants and products related in a chemical reaction?

Expectations: Students should be able to identify when reactions occur and when they do not occur based upon lab data, especially with information about solubility and separation. Students should also be able to describe reactants as disappearing, and products as appearing, and be able to represent these with symbolic equations. Students should then be refining these equations to simple symbols like letters.

A sample lesson activity: A suggested activity in this subunit would have lab data, preferably collected by students, showing the repeated mixing of various pure substances. Some of the separations after these mixings show a predicted outcome, and some do not. Students would then identify those instances where unpredicted outcomes show signs of a chemical reaction, and represent the substances involved in a symbolic reaction. This would be repeated until students are familiar with the process, and perhaps extra reaction types can be used, for example, where gasses are involved.

Sub-Unit Support Resource: Representation of Substances

Summary: The emphasis in this subunit is on the repeated usage of symbolic representation. The presentation of related reactions should help introduce the idea that there are atomic particles that are retained in compound products. These particles are capable of revealing their identities in other related reactions as the compounds separate chemically. Students should start to follow the motion of the particles as they combine in some products, and then separate as reactants, and vice versa.

Misconceptions: The underlying misconception in this unit has been addressed in small part by the previous subunit, however, it needs to be confronted. That misconception is that any product is capable of forming in a reaction. Some related misconceptions, that there are unlimited numbers of elemental particles, or that there are only four elemental particles(Aristotle), allow for this possibility. However, when analyzing substances for their constituent parts this misconception gives way to the fact that only products with represented reactant particles are possible.

Modeling: For this subunit on representation it is important to use symbolic equation writing repeatedly. This is necessary for the eventual identification of compound and elemental substances. Also, diagrams to represent substances and their representative particles in an abstract matter should be introduced.
Diagrams of particles should be created to represent certain parts of the reactant particles that are retained. These can be transitioned from the alchemical symbols, shown in figure 9, to simple circular usage similar to Dalton, shown in figure 10.

Figure 9

Symbolic alchemical-like equations

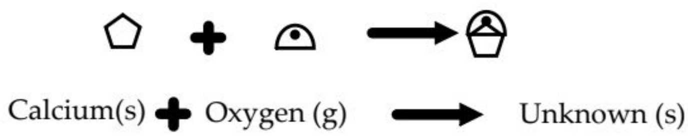
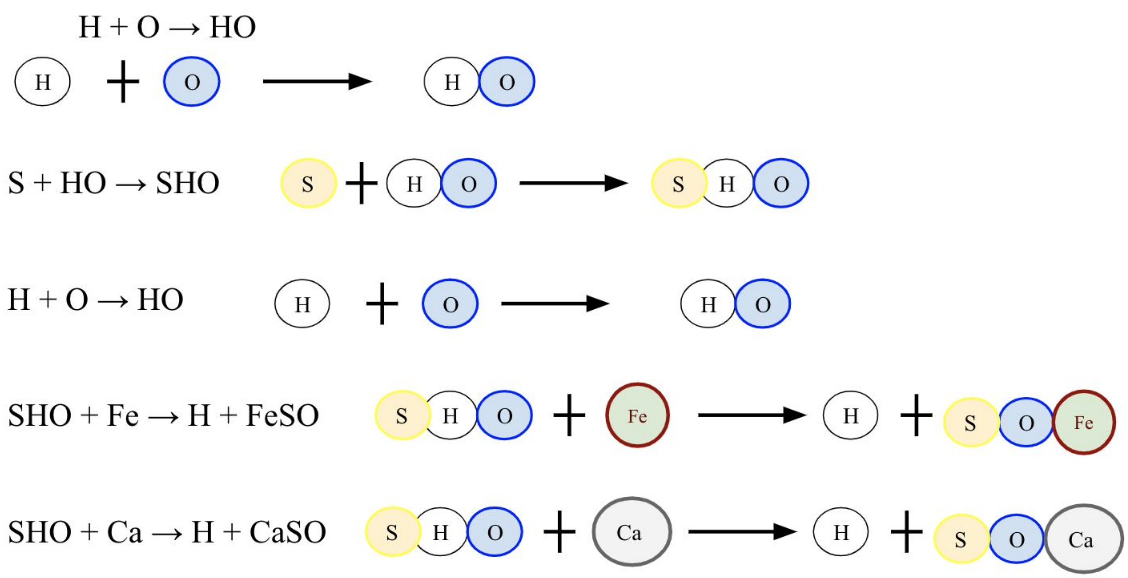


Figure 10

Symbolic equations approaching Dalton's style



Note that each element is only represented once, Dalton's were more complex

Lab examples The experimentation in this subunit can include similar experiences to the last subunit. In-lab experiences are not required as much as the review of a large number of lab results. Students should be spending time looking over lab sets and outlining the possible motion of particles as they are combined in certain products, and then separated in others.

Progression Questions The questions in this subunit should focus on the relationship between reactant and product particles. Students should be noticing that products in a reaction are not random, but specific.

How are reactants and products related in a chemical reaction?

This is from the last subunit and should be built on. When showing familiar substances that react and disappear, and then reappear from reactions involving the same product a further question is:

(For related reactions) Where did these product substances come from?

What happened to the particles in the reactants, did they disappear?

Finally, the idea of complex substances vs simple should be introduced

Which of these substances is more complex, and which is more simple?

What particles seem to be related in the more complex substance?

Expectations: Students should be able to relate reactant particles with product particles. Students should be able to identify some more complex product substances by the reactant particles that combined in them. Students should use lab data represented with symbolic equations and decide the source of product particles from reactants in other related reactions. This relationship should be shown symbolically as well

A sample lesson activity: A suggested activity is the comparison of various lab sets to determine which substances are created from combinations of other substances, and which appear to be simple and not composed of other substances. Students are guided through the initial set of reactions to discover that there are in fact related particles. Subsequently, they should be reviewing enough related reactions to predict the identity of unknown substances.

Sub-Unit Support Resource: Identification of Elements

Summary: The identification of elements should be straightforward once students recognize that certain representative particles are retained, and certain substances are made of combinations of these particles. This was started in the prior subunit. However, the identification of elements can take several avenues in the lab. Besides the analysis of related reactions, there are also different element types, namely metals and non-metals, that can be shown in contrast. This unit should culminate in the identification of elemental substances, as well as their classification as a metal or a nonmetal.

Misconceptions: The most common misconception is the confusion between elements and pure substances. The second most common misconception is the confusion between an element and an atom. In order to distinguish between elements and substances, the foundation has been laid with concepts of separation and chemical reactions. In this subunit, the separation of element types in chemical reactions should be stressed and clarified that this is very different from separating substances physically. In order to distinguish between elements and atoms, it is suggested to use the simple circular spatial diagrams and reinforce the idea that these representations are for the unseen atoms. Elements, on the other hand, are very visible and tangible.

Modeling: For this subunit on representation it is important to use symbolic equation writing repeatedly, as shown in figure 11. This is necessary for the eventual identification of compound and elemental substances. In this subunit, an added focus should be placed on the rewriting of compounds with their elemental components. This allows students to follow the combination and separation of elemental particles as well as predicting outcome products formed in reactions with these compounds. Also, there should be the usage of diagrams to represent substances and their representative particles in an abstract matter to better visualize the process, as shown in figure 10.

Figure 11

Symbolic equations for rewriting

RXN #1: **A + E --> B**

RXN #2: **E + I --> C**

RXN #3: **B + I --> D + E**

RXN #4: **A + C --> B + I**

Rewriting RXN #1 : A + E → AE   this shows that B = AE

Rewriting RXN #4: A + EI → AE + I

Figure 10

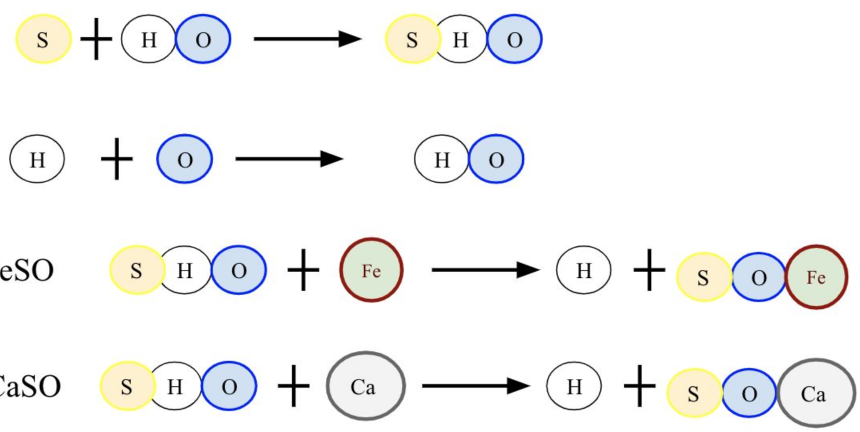
Symbolic equations approaching Dalton's style

S + HO → SHO

H + O → HO

SHO + Fe → H + FeSO

SHO + Ca → H + CaSO



Lab examples The experiments for this subunit are in two types, one for the identification of elements and the other for their classification using density. The first experiment set does not necessarily need to be in the lab by students, since some of the most helpful experiments are likely to be the most dangerous as well. These should be demonstrations of synthesis and decomposition reactions, followed by single replacement reactions using repeated compounds. These should be presented in a series of sets, with each set providing a means of solving the elemental 'puzzles' similar in fashion to figure 11. The last lab should focus on the difference between the malleability and reactivity with acids between metals and non-metals. This lab should include students using appropriate acids for testing as well as hammering them in order to test their malleability.

Elemental Puzzles

Metal and Non-metal lab

Progression Questions: The questioning for this subunit should focus on the transition from the prior subunit into the concept of an element.

What is the difference between an element and a pure substance?

How can the elemental components of a compound be identified?

How can elements be determined in a lab?

Once the repeated search for elements has become routine, students can then start to identify them based on their malleability and reactivity with acids.

What is the difference, in the lab, between a metal and a nonmetal?

Expectations: Students should be able to identify compounds from synthesis and decomposition reactions, and use these compounds in related replacement reactions to identify other compounds as well. Students should also identify substances that do not appear to have multiple components as elements. However, they should also realize that it is possible to discover reactions that show substances previously thought to be elements which are actually compounds. Students should recognize that the process of discovering elements is a lengthy analysis of reactions. Finally, students should be able to distinguish between the element types of metals and non-metals based on malleability and reactivity with acids.

A sample lesson activity: A suggested activity would include the presentation of several reaction sets. Each set should start with basic synthesis and decomposition reactions, allowing for the determination of related components placed together in compounds. Then the sets should include some replacement reactions that allow for the determination of other compounds, and predictions of unidentified substances.

Unit Support Resource: Atomic Theory

Summary: This unit covers the progression from the representation of reactions with elements through the hallmarks of Dalton's Atomic theory. The culmination of atomic theory results in a collection of identified elements with their valences and masses. These are placed into a powerful reference tool in Mendeleev's Periodic Table.

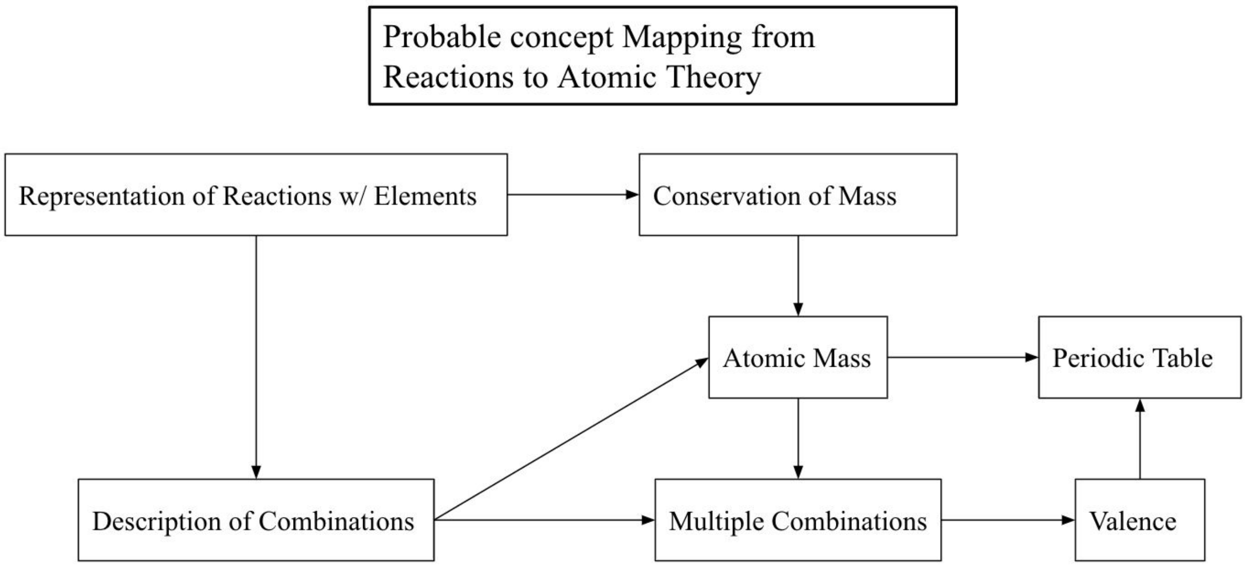
Misconceptions: The difficulties in this unit revolve around the representation of chemicals with the appropriate symbols. Students see the chemicals physically in the lab, and need to associate their physical properties through mass analysis. These are then shared through usage of spatial drawings and symbolic chemical equations.

Sequence: Review of writing reactions with elements is a necessary starting point. This is because the goal for this unit is to improve the representations of the compounds involved. Even though this unit is geared toward the Periodic Table of Elements, the attributes of these elements can not be deduced *without* an analysis of the types of compounds they make. This is twofold: the first is the identification of mass associated with each atom type; the second is an examination of the multiple combinations possible between two atom types. Without observing the mass changes between two atom combinations using identical atom types, a reliable analysis of the compound formula can not be made. The observation of mass changes between two atom types also allows for a calculation of their mass ratios, which creates the basis of the definition for atomic mass. Likewise, the multiple combinations of atoms, when drawn in an appropriate diagram, creates the basis for the definition of valence. In this way, it is important for mass analysis to use symbolic equations, and it is important for valence analysis to use spatial drawings. Lastly, both of these concepts, atomic mass and valence, allow for the creation of the Periodic Table.

The suggested progression of this unit through these topics is shown in figure 3.

Figure 3

Sequence for Atomic Theory



The supporting models, experiments and progression questions are summarized in table 7:

Table 7

Subunits for Atomic Theory

Sub-Unit	Modeling Supports	Experimental Supports	Progression Questions
Description of Combination	Use of symbolic Equations & spatial drawings	Replacement and/or Synthesis Labs	How do atoms combine and separate in a chemical reaction?
Conservation of Mass	Use of symbolic equations	Massing using prior Labs	How is the mass of products related to reactants in a reaction?
Atomic Mass	Use of symbolic equations	Metal Oxide Labs	How are the masses of different elements related in a chemical reaction?
Multiple Combinations	Use of symbolic Equations & spatial drawings	Change of Valence Labs (W/O & Cl)	Why are there multiple combinations?
Valence	Spatial Drawings	*Drawing Based*	How many other atoms can an atom combine with?
Periodic Table	Spatial Drawings & Cards	(Cards w/ elements)	Which trend is periodic and which is linear?

Sub-Units: The full description of each sub-unit, along with each model description, lab description as well as the full set of progression questions can be found in the attachments below. Remember that these are not lesson plans, but the structure upon which lessons are built.

Description of Combination - this is found on page 44.

Conservation of Mass - this is found on page 48.

Atomic Mass - this is found on page 51.

Multiple Combinations - this is found on page 54.

Valence - this is found on page 57.

Periodic Table - this is found on page 60.

Sub-Unit Support Resource: Description of Combination

Summary: This sub-unit covers the combination and separation of atoms as they change during a chemical reaction. Students must first be able to identify an element or compound based on the reaction. The most important part of this is the realization that some essence of the reactant chemical, described by an atom, is retained in a compound. Then this elemental atom can re-appear in subsequent reactions involving the compound. After that concept is developed, the identification of which atoms are separating and which atoms are combining in a reaction is straightforward. Students should notice that metals do not combine with each other. The next step is to follow the mass as it moves in a reaction, as well as to identify the multiple combinations of atoms when they combine together. Additionally, the position of atoms needs to be seen spatially, when separating or combining, not just for accuracy in this sub-unit, but for accuracy in valence as well.

Misconceptions: The difficulties in this sub-unit revolve around the confusion between atoms separating and chemicals separating. This is essentially a failure to analyze spatial representations of the atoms in the reaction. Instead, students tend to rely on reactants as separating and products as combining. This causes, typically, students to confuse the entire reactant compounds as separating from each other, and the entire product compounds as combining. These compounds do not combine or separate though, their specific atoms do and this needs to be reinforced.

Modeling: Both the use of symbolic equations and spatial diagrams are needed. The symbolic equations are needed both as practice for future use, reference for description of combination and separation as well as descriptions of mass in the next sub-unit.

The symbolic equations should by now have moved past the use of alchemical or generic symbols. In other words, no more azote + hydrogen → ammonia. The modern element symbols should be in use. However, they are still void of both coefficients and subscripts at this point. Here are some examples:

Water: **H + O → OH** obviously this is not right, but at this point it is appropriate.

Rust: **Fe + O → FeO** again, a little less obvious, but just fine at this point.

Acid and Oxide: **HCl + CuO → CuCl + OH**

Spatial diagrams are specifically atomic representations at this point. Keep them simple, keep their attachments obvious, and keep their placement order identical to that of the reaction. Also, do not use more than one atom for each atom type at this moment. That will come in the next steps. Examples are shown in figure 10.

Figure 10

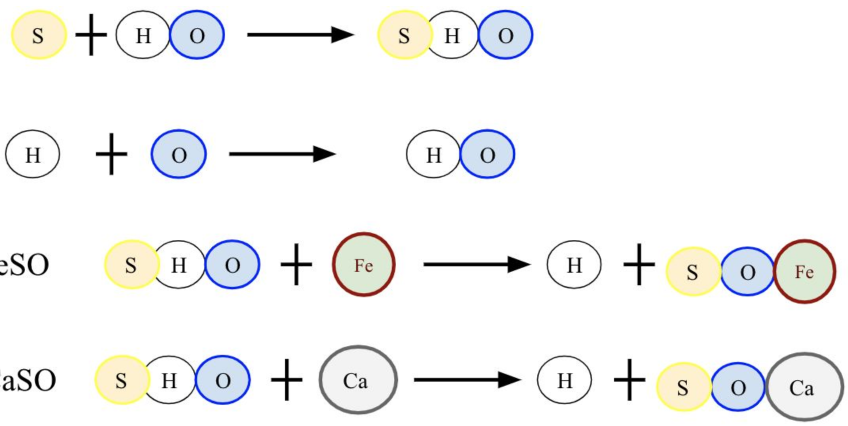
Symbolic equations approaching Dalton's style

S + HO → SHO

H + O → HO

SHO + Fe → H + FeSO

SHO + Ca → H + CaSO



Lab examples: The experimentation in this subunit should include labs that are visually obvious and dynamic. Focus on changes in state, changes in color, or any other obvious changes in appearance. Students should be able to identify chemicals from descriptions of their appearances alone. Also, if possible, use past experiments as examples on the board, and use new experiments for student labs. Some good laboratory combinations are shown below:

HCl + CuO

Zn + S

Fe + S

Mg + HCl

Fe + HCl

Progression Questions: The questions for this sub unit should be used over and over. The real question is:

> Which atoms separate and which atoms combine in the following reaction?

> Which types of atoms tend to combine, and which do not tend to combine?

The last question helps to reinforce differences between metals and non-metals. Another way to phrase this question:

> What happens to each atom in the following reaction?

A review question is also important here:

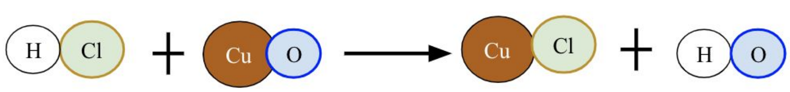
> What happens to the particles of a reactant substance in a reaction, do they disappear?

Expectations: When provided a reaction equation, students should describe the atoms that are separated and the atoms that have combined, being able to name the atoms and not the compounds. Figure 12 shows an example.

Figure 12

Symbolic equations for describing combinations

HCl + CuO → CuCl + OH
diagram :



In the reaction above, students should describe the reaction this way: H separated from Cl, Cu separated from O, and Cu combined with Cl while O combined with H. Students should also notice that metals do not combine with each other. In the reaction above, copper is a metal and chlorine is a non-metal so this follows the rule.

A sample lesson activity: A suggested activity involves the students completing a reaction set between between the hydrochloric acid and copper (II) oxide, the magnesium and hydrochloric acid, as well as the iron with the hydrochloric acid (set up in the fume hood). The teacher completes a demonstration of the zinc and sulfur or the iron and sulfur. Some lab sets use mass measurements for the next sub-unit as well. Students should then write out the reactions and draw a diagram representing the reaction. With the diagram, students should describe the atoms that separate and the atoms that combine.

An extension to this could be added in the homework, students must show the motion of the atoms separating and combining through either animation, video, or other visual means.

Sub-Unit Support Resource: Conservation of Mass

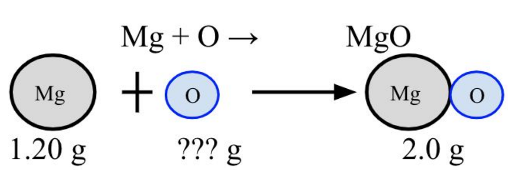
Summary: This sub-unit covers the conservation of mass in a reaction, and uses this law to predict masses of unmeasured chemicals. Students must first be able to identify the elements and compounds present in reactions, as well as mass chemicals physically in the lab. Repeated practice will show students a definite trend: the mass is conserved in a reaction. Students will then predict masses of unmeasured chemicals when given masses of all other related chemicals. This unit will be used to compare atomic masses in the next sub-unit.

Misconceptions: The difficulties in this sub-unit revolve around identifying where the mass is located, as well as in associating mass with a gas. Some students will associate all mass in a reaction, the reactants and products, as belonging to the reaction. This obviously misses the trend of conservation, and does not allow for making predictions. The other misconception is that gasses have no mass. While most students will realign their thinking after the realization that mass is conserved, some still might not. For those students, literally trapping carbon dioxide in a balloon and weighing it to compare with hydrogen trapped in a balloon will help. This is not just to correct the misconception, but can be a dynamic demonstration when brought safely to a flame.

Modeling: The use of symbolic equations is required. Spatial diagrams are encouraged as well, however, there is no change in their usage from the last sub-unit. The symbolic equations are needed both as practice for future use and as a reference to describe the location and motion of mass in a reaction. An example of this is shown in figure 13.

Figure 13

Symbolic equations with spatial diagram for mass conservation



The symbolic equations should be similar in usage to the last sub-topic. Remember to connect the symbolic chemical equation to an algebraic equation using mass. Here are some examples:

Water: **H + O → OH**

and using mass: 2.0 + 16.0 = 18.0

Acid and Oxide: **HCl + CuO → CuCl + OH**

and using mass: 37.0 + ??? = 68.0 + 9.0

Solving the last equation, CuO can be represented by x in an algebraic equation:

$$37.0 + x = 68.0 + 9.0 \therefore 37 + x = 77 \therefore X = 77\text{-}37 = 40$$

Lab examples: The experimentation for this subunit should include the labs from the prior section with mass measurements. This subunit is an analysis of the prior subunit's laboratory results. This might require some extra massing, and some repetition of prior lab experiments. The last subunit had many options, and if some were not covered there should be time to try them in this subunit.

Progression Questions: THe questions for this subunit revolve around the location and motion of mass in the reaction. Initial questioning should repeatedly revolve around:

> What is the mass of each chemical in the following reaction?

As students progress through various examples a definite trend should emerge, and the following question becomes important:

> How does the mass of products relate to the mass of reactants in a reaction?

This provides an additional extension. With algebraic analysis, an unknown chemical amount can be determined. This extends to gas amounts as well as other states of matter:

> How can the mass of an unmeasured chemical be determined?

Expectations: Students should be able to accurately measure the mass of chemicals in a reaction, including gases. Students should recognize that the mass of products is equal to the mass of reactants in a reaction. This is known as the conservation of mass, and students should apply this concept to examples with unmeasured chemicals in order to predict the unknown amount using algebra.

A sample lesson activity: A suggested activity involves mass measurements taken in the lab. These measurements are then recorded along with the symbolic equation and diagram. After this practice is repeated several times, students are asked how the mass of products and reactants are related. This introduces the idea of mass conservation, which is then used to solve algebraic equations to predict the masses of unmeasured chemicals involved in reactions where all the other chemicals have been massed.

Sub-Unit Support Resource: Atomic Mass

Summary: This subunit focuses on the mass comparisons between atoms. Students should be comparing differing amounts of the same two atoms in order to notice a constant ratio. They should also be comparing multiple combinations of different pairs of atom types. This way, students can determine the relative atomic masses of multiple atom types and arrange them by weight. This will allow for comparison with the smallest possible atom, hydrogen. These atomic masses, when combined with valence, will then be arranged into the periodic table in a subsequent subunit. Also, in the next unit, this will allow for the prediction of any unmeasured chemical mass through stoichiometry.

Misconceptions: The difficulties in this subunit revolve around the algebraic calculations from compound mass to atomic mass. The other difficulty arises from the correct set-up and calculation of mass ratios. In order to support these mathematical applications, it is important to use models to reinforce the combined compound masses as well as to show the arrangement of atoms.

Modeling: The use of symbolic equations is required to transition students from the lab into the symbolic representation and then into the algebraic equation. Spatial diagrams are encouraged as well to aid in this transition, however, there is no change in their usage from the last two sub-units.

The symbolic equations should be similar in usage to the last two sub-units. Here is an example:

Single Replacement: $Mg + HCl \rightarrow MgCl + H$

$6.0 + 9.1 = 14.6 + 0.5$

In this case, the mass of Cl needs to be calculated, so assigning the Mg as 6 or the H as 0.5 helps. Solving this through an algebraic equation requires Cl to be represented by x:

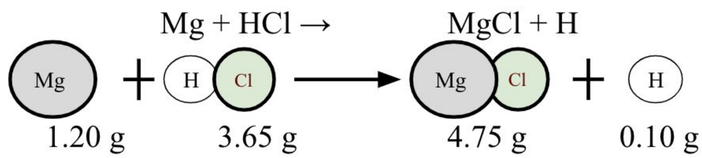
$$HCl = 9.1 \text{ and } H + Cl = HCl \therefore 0.5 + x = 9.1 \therefore x = 9.1 - 0.5 = 8.6 \text{ or}$$

$$MgCl = 14.6 \text{ and } Mg + Cl = MgCl \therefore 6 + x = 14.6 \therefore x = 14.6 - 6 = 8.6$$

A spatial diagram that incorporates the symbolic equation, the mass measurements and the atomic arrangement is included in figure 14.

Figure 14

Symbolic equations with spatial diagram for atomic mass



Lab examples: The experimentation in this subunit should include metals reacting with oxygen. These give various comparisons with the same chemical, oxygen, and there are a variety of metals that react with dynamic changes, typically by igniting on fire. Lab examples include:

Mg + O * careful as the magnesium ribbon is very bright and can crack ceramics.

Ca + O

Fe + O * difficult to mass when using steel wool.

Al + O *careful as the aluminium powder can burn through glass.

Progression Questions: The questioning for this subunit revolves around the trends students see in massing. The initial questioning should follow from the identification and calculation of masses of the elements in a reaction. This should elicit some algebra, and the following question:

How can you calculate the mass of an element in a compound in the lab?

Students should then be given data from several different masses for identical atom combinations. This should allow them to internalize the constant ratio trend. To follow the sequence, start with:

Can you predict the amount of product when given the amount of reactant?

The repeated use of this question should open up the students' ability to apply this concept to all combinations in general:

Even though the mass of each element is changing, what remains constant?

What is an atomic mass, and how can it be measured?

Students should finally define what atomic mass is, and explain why these ratios are compared to hydrogen:

Why is atomic mass the mass ratio with hydrogen? Why not with oxygen, water, etc?

Expectations: Students should be able to identify and compare atomic amounts. They should apply algebra in order to discern the masses of each element in a reaction. Then they should notice the trend of constant ratios between atoms. In light of that trend, students should calculate those ratios. Finally, students should also note that hydrogen's mass is the smallest, and allows for the most whole number ratio comparisons. Here are some examples:

Mg	+	HCl →		MgCl	+	H
6.0	+	9.1	=	14.6	+	0.5

Students would use either MgCl(14.6 - 6.0 = 8.6) or HCl(9.1 - 0.5 = 8.6) to determine the mass of chlorine to be 8.6. Then students would rank the atoms: H is 0.5, Mg is 6.0 and Cl is 8.6. This would mean that H is 0.5/0.5 = 1 times H, Mg is 6.0/0.5 = 12 times H, and Cl is 8.6/0.5 = 17.2 times H. These are not equal to the values on the periodic table, however, the process is the important part. A discussion about why these are not equal can help transition into the next sub-unit as well: multiple combinations. (In this case H was actually H_2)

A sample lesson activity: A suggested activity involves two parts. The first is providing students with chemical masses from a lab that they have done. Then students draw the reaction, calculate the mass of each element, and order the elements according to their masses. The second is for students to calculate the ratios of masses in the reaction, and ultimately compare each chemical to hydrogen. This can be done directly like the example above, or indirectly for those students capable of solving more sophisticated algebraic puzzles.

Sub-Unit Support Resource: Multiple Combinations

Summary: This subunit is very similar in style to the last one in that it has two steps. The first step is identical to the preceding subunit's: mass from lab experiments must be used to determine the mass of each element involved in the reaction. However, instead of proceeding to compare mass ratios, students will repeat the first process for the exact same combination of chemicals placed under different temperatures and pressures. This will reveal the second step: at certain conditions the amounts of one of the chemicals will change in a whole number ratio. Students will then identify the chemical that has changed its mass, and revise their atomic models to account for this by adding extra atoms into the drawings for those compounds.

Misconceptions: The difficulties in this subunit typically arise from referencing lab data to build appropriate models. At a certain point, students become overwhelmed with data, especially numerical data. It helps to keep a repetitive usage of the models in prior concepts, and doing so usually brings this concept to the forefront well before these results are shared. Also, reducing the stress of analyzing numerical data by providing simple, basic steps to make the analysis more procedural helps as well. Those are both supported by the guiding questions and the modeling used, and both become extremely important.

Modeling: Both the use of symbolic equations and spatial diagrams are needed. The symbolic equations are needed to recognize the disparity in masses caused by multiple combinations which Dalton (1808) called multiple proportions. The spatial drawings help students to relate the particle model to what is observed from the multiple combinations. These drawings also become important for the next subunit as well, since valence is the real outcome of this subunit.

The symbolic equations are the same as they have been in the three prior subunits. However, after step two the usage of subscripts needs to be explicitly introduced. Here are some examples:

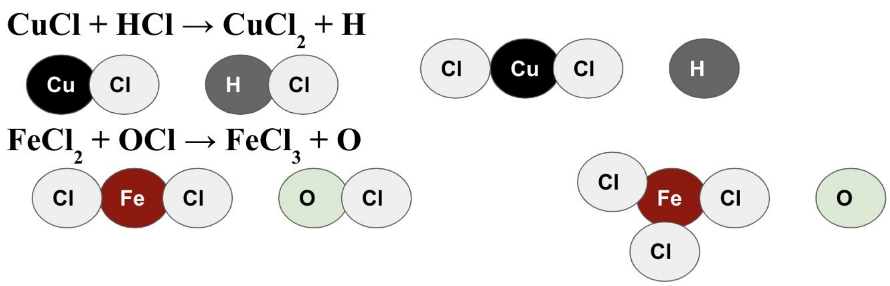
$Pb + O \rightarrow PbO$ However, step two will become: $Pb + O \rightarrow PbO_2$

$Cu + Cl \rightarrow CuCl$ However, step two will become: $Cu + Cl \rightarrow CuCl_2$

Spatial diagrams are still atomic representations at this point. Keep them simple, keep their attachments obvious. Transition from single to multiple combinations. An example is shown in figure 15.

Figure 15

Symbolic equations with spatial diagram for changing combinations



Note that masses should be added to the equations and diagrams when measured

Lab examples: The experimentation should include the use of valence-changing, dynamic demonstrations. Another suggestion is to refrain from massing on these examples if the difficulties associated with separating out each type of chemical causes too large of an impact to time and accuracy, which is likely. Instead, have the students perform the experiments to notice and identify color changes due to the new combinations. Suggested labs include:

$CuCl + (H)Cl$

$FeCl_2 + (O)Cl$

$CoCl + (H)Cl$

The elements in the parenthesis will not affect the combination, the chlorine will.

Progression questions: The questions for this subunit revolve around the identification of multiple outcomes from the lab, and how to modify spatial models accordingly. The first question is another repetitive question similar to the prior subunit:

What is the mass of each element in the reaction?

The prior subunit of atomic mass should have built the idea that atom combinations are consistent. When presented with multiple lab results to the contrary, students should notice that a different trend is occurring:

> Which element amount appears to change? In what ways do you notice this change?

The labs are important for this because it is not just the mass amount that changes, but the color and character of the products as well. The last question alludes to the changes in spatial models and the idea behind multiple combinations.

> How are these compounds that are created different from each other?

> How can you draw these changes to the compounds in their diagrams?

These last two questions should be paired together. The final question is about representing this in the symbolic formula for the compound.

> How can the amount of an element in a compound be represented in the formula?

Expectations: Students should be able to identify the changes in compounds created based on the mass amounts of the elements involved as well as in the changes in product color. Students should then be able to redraw a modified diagram showing compounds with multiple atoms of the same element. Here is an example: CuCl is blue, however, as more Cl is added the compound changes to become green. In each case, there is twice as much Cl present in the green compound as the blue. The chemical formula is therefore written as $CuCl_2$.

A sample lesson activity: A suggested activity involves using a lab where a metal changes its valence and the compound involved changes its color. Then, students are presented with multiple examples of how the masses involved in creating these compounds change. Students are then prompted to modify their diagrams and formulas to account for this change.

Sub-Unit Support Resource: Valence

Summary: This subunit on valence is a review unit on the prior multiple combinations subunit. The real progression occurs when predicting possible compound combinations. Students should be presented with a wide range of compound diagrams for atoms that do not change their valence, but are known to have multiple combinations due to their mass comparisons. Showing these multiple combinations could be an optional extension activity included in the atomic mass subunit, but is not essential. Students should be predicting what new combinations look like based on the presented diagrams. To accurately predict these compounds, students need to recognize that valence is not the amount of an element's atoms, but the amount of other atoms that an element combines with. Students should then relate subscript usage with valence.

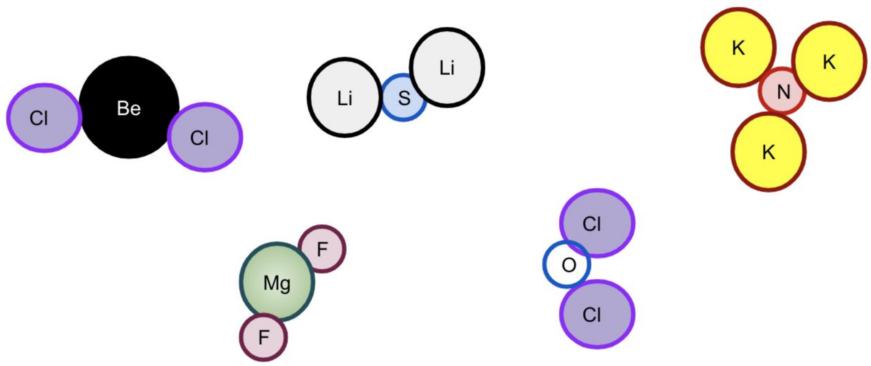
Misconceptions: The major misconception is to assume that an element's subscript is constant throughout the compounds it combines in. This misconception tends to be rooted further when the periodic table is introduced, as it reinforces the idea of consistent atomic trends. Therefore, this subunit must come before the periodic table is introduced. Also, a consistent and repetitive usage of compound diagrams helps to show the spatial relationship between amounts and valence. Due to the abstract nature of this topic, its importance in every subsequent unit, and the prevalence of student difficulty in this topic, it is also suggested that this is presented without additional content. (No electrons, obviously, but also no extra analysis of lab, masses or equations)

Modeling: Spatial diagrams are the single most important aspect when examining valence, and they should remain the focus. Equations are not needed. However, equations can be presented, without massing, to keep the repetition of their use up as they will be needed later. The symbolic formulas are needed to reinforce the usage and meaning of subscripts.

Spatial diagrams should be kept simple and labeled with the appropriate symbols. Initial combinations should always have a central atom surrounded by one(binary), two or three other atoms. This is exactly how Dalton used them, and should be modeled like those in figure 16.

Figure 16

Spatial, Dalton-like diagrams showing valence



Lab examples: Experiments are not suggested for this unit. A review demonstration of multiple combinations or combinations would support the relationship between the lab and the spatial diagrams. However, the most important activity is the repetitive use of the diagrams and the related atomic formulas.

Progression questions: The questioning for this subunit should revolve around the review of subscripts and the transition to valence.

How can you represent the number of atoms in a drawing with the chemical formula?

Through repeated usage of diagrams and formulas students should be ready for the next question:

What is always consistent for each atom type in each drawing / formula?

Really the prior question follows a sequence of smaller question steps, and it is important to map this out since the development of the concept of valence relies on the prior question being answered accurately.

(Is the subscript for an element always the same?)

(Is there always the same number of atoms for each element in every compound?)

(What does the number of atoms in a chemical compound depend on?)

Finally, students need to define valence and relate it to subscripts:

What is valence? Describe this in the context of a compound's diagram.

How does valence relate to the subscript in a chemical formula?

Expectations: Students should identify that valence is constant but an atom's subscript, the number of that element, in a compound is not. Students should then be able to use the valence of atoms combined in a compound to draw and write the chemical formula for that compound. Conversely, students should be able to see a drawing or a chemical formula and identify the valences of each element in the compound.

A sample lesson activity: A suggested activity includes repeated usage of spatial diagrams with their associated formulas to reinforce the idea that subscripts are not consistent. Then guided questions would bring up the idea of valence. Then students would practice with both creating diagrams from valence and identifying valence from diagrams. These are more compatible with set work than laboratory work, which is suggested.

Sub-Unit Support Resource: Periodic Table

Summary: This subunit on the periodic table is a synthesis of the valence and atomic mass units. The chemical properties of elements, from the last unit, is also supportive and should be reinforced as well. The suggested progression is a presentation of elemental properties of mass, valence, and reactivity with water and acids. Students should arrange the elements based on their mass, and then regroup them based on their valence. For a majority of the groups, the chemical properties can be used to check for accuracy. This is a re-enactment of Mendeleev's creation of the periodic table, which should be given to them when they are complete. Students should then be able to identify the atomic mass, valence and chemical properties of elements based on their positions on the periodic table.

Misconceptions: The most common errors students make in this section is to confuse rows and columns. This doesn't seem like a significant error, but it renders the periodic table useless for the rest of the course. Students will also tend to mistake mass order for atomic mass. In some cases, background knowledge about electrons will cause confusion between valence and outer shell, or valence, electrons. This is another reason to keep the discussion of electrons out of the curriculum at this point.

Modeling: Spatial diagrams can be used for support, similar to those in figure 17. Their repetition is encouraged. However, elemental symbols are more important in this sub unit. Equation writing is really not needed. Though it is nice to keep those repeated in the course, it is a distraction here.

Figure 17

Spatial, Dalton-like diagrams showing elemental valences

Elemental symbols should be kept simple and labeled with the appropriate symbols. Start placing the atomic number and atomic mass on them similar in fashion to the periodic table that they will be using throughout the year. (Suggested to place mass first and then rank them)

Ex: $Ca^{20}{}_{40}$ $Be^{4}{}_{9}$ $O^{8}{}_{16}$

Lab examples: Similar to the prior subunit, experiments are not suggested for this unit. However, this subunit revolves around an in class activity that can be enhanced using manipulatives like cards. This will help students to spatially organize the elements, and helps to create the structure of the table mentally as well.

Progression questions: The questions for this subunit should center on the order and organization of elements

.

What is the atomic number of an element and how is it related to the atomic mass?

What trends in valence do you notice when ordering elements by their atomic mass?

After students have reorganized their tables with valence they should relate the position on the table to mass, valence and chemical properties.

How can the mass, valence and chemical property of an element be identified using the periodic table?

Expectations: Students should relate their experience to Mendeleev's creation of the periodic table and be able to predict information of an undiscovered element based on the position it occupies on the periodic table. They should be able to identify the mass, valence and chemical property of an element due to its position on the periodic table. Subsequently, they should be able to use this as a review of the last subunit on valence. When given a compound name, students should be able to look up the related valences and both draw the compound diagram as well as write the compound formula. As an extension, molar mass can be introduced.

A sample lesson activity: A suggested activity includes the presentation of cards, each with the mass, valence and chemical properties of an element. Students, preferably in groups, would be guided through the organization process of placing these into mass order, groups of valences, and subsequently into the periodic table. Students should then practice using the periodic table as a tool when referencing valence to write and draw formulas and diagrams of named compounds. As an extension the periodic table can also be used to reference atomic masses to calculate molar masses.

Unit Support Resource: Stoichiometry

Summary: Stoichiometry, the comparison of the masses of substances in a chemical reaction, is reliant on the concept of a mole. This concept builds on the ideas of molar mass, molar amounts, and molar ratios. These concepts are each heavily infused with atomic theory, and so the concepts of atomic mass, valence, and the conservation of mass are used repeatedly. In order to keep each of these concepts clear, spatial diagrams are helpful to reference for each. As an extension, the idea of limiting reactants is also related to the overall use of stoichiometry as a process for predicting amounts.

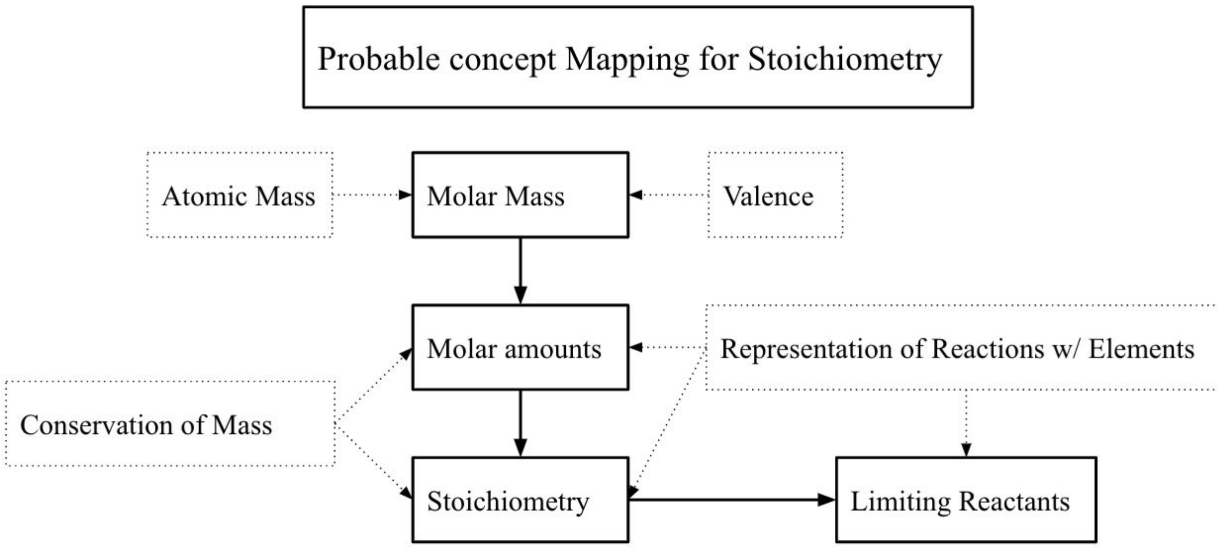
Misconceptions: The concept of a mole is difficult to grasp, and it creates confusion in the subsequent subunits. When molar masses are calculated a common mistake is the use of coefficients, and when molar ratios are made there is a common mistake in the order that coefficients are placed in. To reduce these misconceptions and mistakes, care should be taken to habitually use drawings with equations, to use obvious lab results, and to remove the introduction of Avogadro's number.

Sequence: Historically these concepts were all developed together and shared common fates based upon the accuracy of results. However, in order to apply a molar ratio students need to compare molar amounts. In order to determine molar amounts students need to calculate using the actual, physical mass as well as the molar mass. This means the sequence is pretty basic, from molar mass to amounts to ratios. Each of these requires repetitive input from the prior unit concepts. Atomic mass and valence are necessary for molar masses. This concept is intertwined with molar amounts, which includes the usage of the conservation of mass and the representation of equations. Really this is the basis for the concept of a mole as well as the description and calculation of molar amounts. Finally, molar ratios and limiting reactants are both extensions of the use of molar amounts in reactions with unequal molar amounts. This leads to the usage of coefficients, which allows students to complete problems related to stoichiometry.

The suggested progression of this unit through these topics is shown in figure 4.

Figure 4

Sequence for Stoichiometry



The supporting models, experiments, and progression questions are summarized in table 8.

Table 8

Subunits for Stoichiometry

Sub-Unit	Modeling Supports	Experimental Supports	Progression Questions
Molar Mass	Use of spatial drawings	Calcium Lab, metal oxide labs	How are atomic masses related to the mass of a compound?
Molar Amounts	Use of symbolic Equations & spatial drawings	Mg + O lab Same valence replacement labs	How is the mass of each substance in a reaction related, or predicted?
Stoichiometry	Use of symbolic Equations & spatial drawings	Metals and acid Epsom Salts (is more complex)	Why do some reactions have unequal molar amounts?
Limiting Reactants	Use of symbolic Equations & spatial drawings	Cabbage juice neutralization Metal replacements	Is it possible to add a reactant without creating more product mass?

Sub-Units: The full description of each sub-unit, along with each model description, lab description as well as the full set of progression questions can be found in the attachments below. Remember that these are not lesson plans, but the structure upon which lessons are built.

Molar Mass - this is shown on page 66.

Molar Amounts - this is shown on page 69.

Stoichiometry - this is shown on page 72.

Limiting Reactants - this is shown on page 75.

Sub-Unit Support Resource: Molar Mass

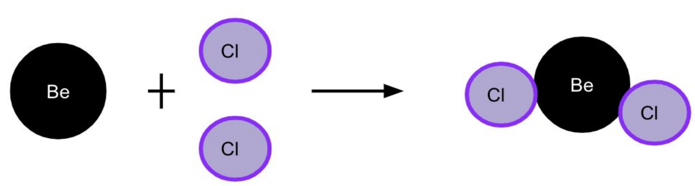
Summary: The molar mass of a substance is determined by the addition of each atomic mass present. This means that in monoatomic elements, molar mass is synonymous with atomic mass. However, for compounds and diatomic elements, this is not the case. Students usually arrive at the process intuitively, though some laboratory evidence is necessary to confirm this. Also included in this subunit is the memorization of diatomic elements. Polyatomic particles should be reviewed as well.

Misconceptions: Students will confuse the terms molar mass and atomic mass, they are similar after all. So distinctions should be made explicit. Also, without writing out proper chemical formulas mistakes will be unavoidable. For this reason, students need to keep repeating the practice of using valence and nomenclature to write chemical formulas as well as calculating the molar masses for those compounds.

Modeling: Molar Mass does not require as much equation writing, however, it always helps to practice. More importantly, the basic spatial diagrams support checking both correct formulas and reinforcing the mental models required to add the atomic masses together. An example of this is shown in figure 18.

Figure 18

Symbolic equation and spatial diagrams showing molar mass



$$Be \quad + Cl * 2 \quad \rightarrow \quad BeCl_2$$

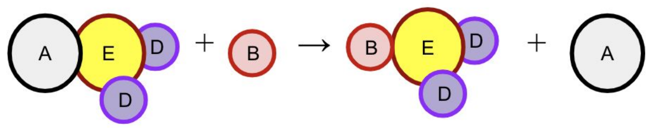
$$9 \quad + 35.5*2 \quad = \quad 80$$

A polyatomic extension is included in figure 19.

Figure 19

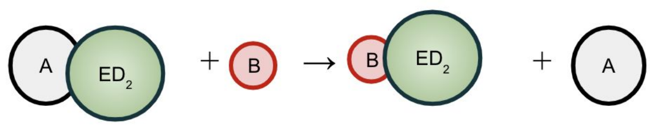
Symbolic equation and spatial diagrams showing polyatomic particles

$AED_2 + B \rightarrow BED_2 + A$



Becomes

$A\underline{ED}_2 + B \rightarrow B\underline{ED}_2 + A$



This is for polyatomic review and can be linked with mass as well

Lab examples: Molar Mass should initially require practice using chemical formulas. These do not necessarily require lab experiments, however, there are several activities that help from the lab. One is simply checking chemicals from the stockroom. Teachers can bring out a cart full of chemicals and read off the names. Students can then write out the formulas and calculate the molar masses. Then they can check their work on the containers. There is also another sequence that does a nice job of presenting a polyatomic, hydroxide, and how to calculate its molar mass using the subscripts. First off, it is suggested to use magnesium and oxygen in a crucible. Ignite and mass before and after. This gives a basic understanding of the addition of atomic masses in compounds. Then place calcium in a beaker with a low water amount and repeat the process. Students will notice that the product is not oxide, but hydroxide based on the mass ratios. This also alludes to more sophistication, however, and should be seen as an extension. The experiment names are below.

Mg and O

Calcium and water

Progression questions: The questions in this subunit should bring out the summative nature of compound masses:

How do atomic masses relate to the masses of compounds?

There is another question when looking at specific element types as well:

What is a diatomic element?

Expectations: Students should be able to calculate the atomic mass of compounds when given their names or formulas. Students should be able to write a chemical formula based on the name, and then use that formula to calculate the molar mass. Students should also know how to use subscripts appropriately in these calculations, as well as polyatomic particles and diatomic elements.

A sample lesson activity A suggested approach would be to provide a brief example of a lab where the mass of two reacting elements are added together to equal the mass of a single product compound. Then repetitive practice with names, formula writing, diagram drawing, and then calculations of molar mass should be used. Students should then be provided with more difficult problems with both polyatomic particles and diatomics.

Sub-Unit Support Resource: Molar Amount

Summary: Molar amount takes the concept of molar mass and compares it with actual masses from the lab. Ideally, students should notice a trend between the actual amount and the molar mass and this trend should be consistent across each substance in the reaction. This trend, the ratio between the actual amount and the molar mass, should also be different between different reactions. In other words, each reaction should have its own molar amount. This is easier for reactions that have no coefficients and so only those types of reactions should be used. Also aiding in this discovery is the ability to compare the actual and molar masses side by side. For this reason, it is suggested to provide tables, since this is a purely mathematical relationship.

Misconceptions: The largest roadblock for most students is to confuse actual and molar masses. Time should be spent on distinguishing between the two and showing the sources of each. One is from the physical scale in the lab, the other is from centuries of modifications on the periodic table. Using tables to display these two should help the clarification somewhat. Another source of confusion is between chemicals, so providing a means to check their differences, perhaps spatially with diagrams, is beneficial. Adding in Avogadro's number will further the confusion and the difficulties with the mathematical presentation of amounts. Additionally, it is impossible to show someone counting a hundred billion billion atoms or to wrap one's mind around it. Therefore it is highly recommended not to include Avogadro's number.

Modeling: The modeling should be focused on the use of spatial diagrams for clarity, and symbolic equations for comparison. Beneath these should be a table for each reaction as well, to record and compare the actual and molar masses. An example is shown in figure 20.

Figure 20

Symbolic equation and spatial diagrams with molar amount table

$$Zn + CuCl_2 \rightarrow Cu + ZnCl_2$$

MM:	65	135	64	136
Mass	6.5 g	13.5 g	6.4 g	13.6 g

Lab examples: Lab examples for this unit should be focused on same-valence chemicals in either synthesis or replacement reactions. These tend to help build amounts forward and have a little more natural addition built into them. Starting with basic synthesis reactions, like measuring the mass of magnesium before and after it's combustion in air, is helpful. The bright light in this reaction is also dynamic, memorable, and will help associate the concepts. Then move students into the replacement reactions. For example, copper (II) chloride and aluminum is a simple reaction, however, it progresses quickly, and has very dynamic color changes. The heat released in the reaction is also memorable and will be good to reference in the next unit on enthalpy. These reactions also provide decent accuracy for their masses, though it might be best for the teacher to measure the masses of each substance to use for accuracy. The experiments are:

Magnesium and Oxygen in a crucible

Metal replacements reactions

Progression questions: The questions in this subunit should focus on the ratios between the actual and molar masses. Make sure to pair these questions with the data, and this practice should be routine:

What do you notice about the ratios between the actual mass and the molar mass?

What is a molar amount? (Called a mol)

How do molar amounts change between chemicals in a reaction?

This last question should help students to start predicting amounts of products in reactions. Then, when this is also getting routine:

How can you predict the amount of, or mass of, products in a reaction?

How do molar amounts change between reactions?

Expectations: Students should understand that the ratio of actual mass to molar mass in a reaction is constant for each chemical in the reaction. This ratio is known as a mol, and students should be able to use it to describe reactions and predict products formed in various reactions when given or measuring reactant masses. Ideally, this last ability should be shown in the lab. Students should be doing calculations with both variations of the associated equation:

Mol = actual mass / molar mass, and Mass = mol * molar mass

A sample lesson activity: A suggested activity uses various metal replacement reactions to progress students through their understanding of and calculation of the molar amounts in a reaction. This should be represented with a symbolic equation and spatial diagram created by the students. Then they should measure out the amount of reactant metal they use in the reaction, and predict the mass of products in that reaction using the molar amounts. Finally, students should complete the reaction and measure the amounts to check their predictions.

Sub-Unit Support Resource: Stoichiometry

Summary: Molar comparisons are similar to molar amounts, however, this includes the specific instances when the molar amounts in a reaction change. These changes, the ratios of the molar amounts between chemicals in a reaction, are known as the stoichiometric ratios. Therefore, this is the second pivotal piece of this unit, to recognize that molar amounts change. In order to predict these ratios, students need to conserve the amount of atoms represented in a chemical reaction. This is aided by both the use of spatial diagrams as well as symbolic equations. The use of coefficients is added in this subunit to represent the comparative whole number amount of each chemical in a reaction. There are really three steps in total: usage of a coefficient, balancing of an equation, and the prediction of an amount.

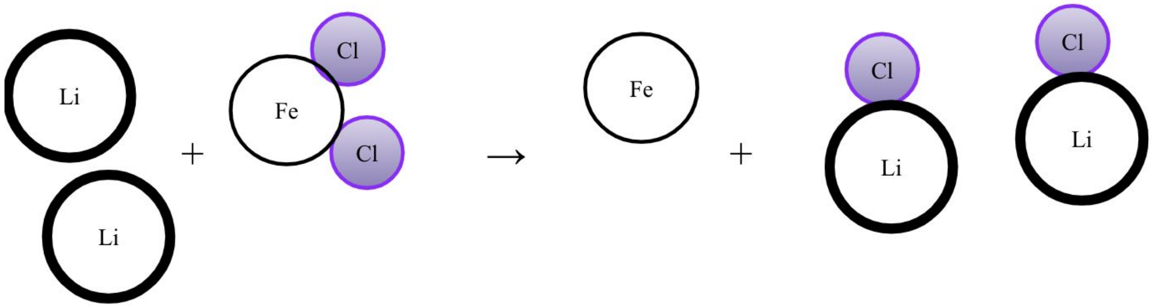
Misconceptions: Students struggle with ordering molar amounts, as well as coefficients. Some students tend to place the coefficients in the opposite order on their ratio. Also, at this point, there are subscripts, valence, coefficients, molar mass and actual masses to confuse with each other. Routine practice with each of these before this subunit helps to clarify the differences between these. Also, the usage of diagrams helps to recheck proper molar masses, as well as the appropriate ratios.

Modeling: Modeling should focus on the use of spatial diagrams and symbolic equations for comparison and clarity. A focus should be placed on counting the number of atoms for each element. A table beneath for helping students to double check their coefficients is helpful as well. This is shown in figure 21.

Figure 21

Symbolic equation and spatial diagrams with balancing equation table

$$2\ Li + FeCl_2 \rightarrow Fe + ??\ LiCl$$



Chemical	Reactant Amount	Product Amount
Li	**2**	**??**
Fe	**1**	**1**
Cl	**2**	**??**

Lab examples: Metals with acids can be similar, repeatable reactions that also allow for accurate mass measurements. Zinc, magnesium and aluminium all make for timely reactions with hydrochloric acid, while copper and iron work well with nitric and sulfuric acids, respectfully. In these reactions there is a small amount, by mass, of hydrogen gas released, but the other amounts can be measured and compared. There are also ratios of 2:1 and 3:2 to work with in these reactions. So, having students write out the reactions, measuring their masses and determining the molar amounts is both possible while students are discovering the ratios, and while they are moving on to predicting the ratios. A further extension is the evaporation of the water hydrates from epsom salts. This results in a fractional coefficient, however, and the presence of water in a compound formula is usually not a familiar occurrence. This means that students will need more practice with these concepts before they are prepared for this lab. These experiments are named below:

Metal and acids lab

Epsom salt lab

Progression questions: The questions in this subunit should focus on the initial difference between the molar amounts:

Do all reaction chemicals have identical molar amounts? Why or why not?

How can you represent different molar amounts in a drawing, or in an equation?

How can you predict the coefficients that should be used in a balanced reaction?

After these representations have been used routinely, students are ready for predictions:

Which product is produced in a greater amount, one with a larger or small coefficient?

How can you predict the amount of product formed from known reactant amounts?

Expectations: Students should be able to calculate molar amounts, and determine which chemicals are in greater abundance. Students should then be able to represent these amounts using coefficients in a chemical equation, as well as in spatial diagrams of the reaction. Once students are able to identify and use coefficients, students should be able to re-write reactions using coefficients without mass information, just based on balancing the equation for the element atoms involved. Finally, students should be able to predict product amounts when given reactant amounts based on the coefficients involved in the reaction.

A sample lesson activity: A recommended activity uses lab data to calculate the unequal molar amounts in a reaction. Then students are required to draw a representation of the reaction. Students then must modify their drawings to ensure that there are equal amounts of each element in the products and reactants. Students then account for the differences in amounts based on the modifications to their drawings. Students then use coefficients to show these amount differences. Once this is practiced enough, and becomes routine, students begin to predict product amounts when given reactant amounts using the balanced symbolic equations with these coefficients.

Sub-Unit Support Resource: Limiting Reactants

Summary: Limiting reactants, though it is a unique subunit, is almost more important as a review of stoichiometry. Of the three steps in stoichiometry, this subunit should really focus on a review of the last two: balancing reactions and predicting amounts. This subunit adds an extension to the prediction of when there are two different amounts for reactants that result in two different product amounts. The smaller amount is always the actual outcome. This can be explained by spatial diagrams as well as using reactant amounts to predict other reactant amounts. The diagrams are more simple, but the calculations are more practical. For this reason, they should both be used.

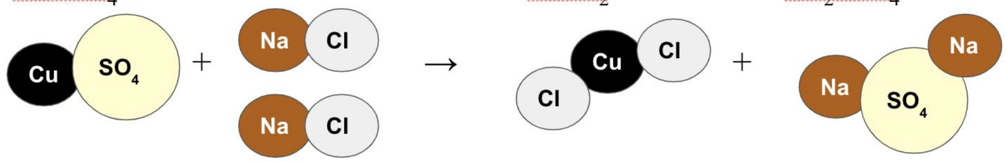
Misconceptions: Students will take a shortcut to the predictions using mass instead of molar amounts. This shows the numerous processes that students must perform. In order to reduce these shortcuts from occurring, reinforce the meaning of coefficients, and focus on the fact that these coefficients are compared. Diagram usage can help solidify the fact that it is molar amounts that get compared, not masses. There are two ways of predicting amounts as well. One is to use both reactant amounts to predict the product amounts for comparison, and the other is to divide molar amounts by coefficients for the comparison. Distinguishing which method works for each student is important since they do not need to do both.

Modeling: Both spatial diagrams and symbolic equations are necessary for limiting reactants. The spatial diagrams are to help conceptualize the lack of amounts of one reactant compared to another. The symbolic equations help to streamline the process, and should be used after the diagrams. The equations should also be supported with diagrams to show the predicted masses, and so including a table or a location to place these values for comparison is also helpful. An example is shown on figure 22.

Figure 22

Symbolic equation and spatial diagrams with a limiting reactant

$Cu(SO_4)$ + $2NaCl$ → $CuCl_2$ + $Na_2(SO_4)$



Amounts

2 moles 3 moles ???

Lab examples: Labs that show the swing in amounts from products to reactants can help. For example, neutralization reactions that show color changes with universal indicator or cabbage juice really help to show the dynamic shift from having too much of one reactant and then too much of the other as it is added. The color change labs are beneficial for the conceptual part and should be used when this subunit is introduced. This is not useful for showing the mathematical representation or the predicted amounts. For this extension, using a metal replacement lab should be beneficial again. These labs were used in the prior subunit, and are accurate for massing. Also, metals tend to add some color to the lab, and besides the accurate measurements they also add support conceptually. Adding the modeling to the labs will also help make the concept routine.

Progression questions Should focus on the prediction of the other substances in a reaction.

Why would adding more of one reactant not increase the products formed?

What is the difference between a limiting reactant and an excess reactant?

Then a focus should be placed on the actual outcomes.

Which reactant will determine the product amounts, the limiting or the excess reactant?

How can the limiting reactant be determined?

Expectations: Students should be able to routinely balance equations using progressively less support. They should also be able to predict product amounts when given reactant amounts and this should also be routine. In this sense, this subunit is a review of the prior subunit and crucial for practice. The new skill should be to identify limiting reactants when given two or more reactant amounts, calculating the molar amounts and dividing by the coefficients. Accurate prediction of product amounts based on the limiting reactant should be expected as well.

A sample lesson activity: A suggested activity for conceptualizing this subunit uses a simple acid and base reaction with a colorful indicator like universal or cabbage juice. The demonstrator adds specified amounts of both reactants, while the students calculate the molar amounts. The color is noted, signaling the excess reactant. Students decide on the reactant that needs to be added, and then the demonstrator adds a specified amount, molar amounts are recalculated, and the outcome is analyzed similarly. In this way, students should be able to relate molar amounts and coefficients to determine the limiting reactant. Practice with predicting the product amounts should help to make the process routine.

Unit Support Resource: Enthalpy

Summary: Enthalpy focuses on two major pathways that lead to the concept of bond energies. The first pathway starts with changes of states, and incorporates the ideas of endo and exothermic into the separation and combination of atoms as they change states. The second pathway focuses on the basics of heat transfer from warm to cool bodies, and uses Joule's experiment to provide a definition of heat and temperature using the particle motion in a substance. These two pathways are both needed as they combine to create the concept of bond energies, which will become the focus of the next unit. The definition of temperature as particle motion due to Joule's experiment is the largest concept-changing activity in this unit, and it lays the basis for kinetic theory in general.

Misconceptions: Perhaps the most prominent source of common misconceptions between students and past scientists comes from this unit. The idea of heat as being a tangible object is very common, almost as if the visual appearance of fire has been cemented as the manifestation of heat. Students and past scientists have explained it's transfer like the motion of fire between objects. Taking students away from this notion, and placing the concept of particle motion into their heads is one of the most difficult, and important, challenges in this unit. The second robust misconception is that creating a bond takes energy. Review of exothermic changes in state should help to change students' minds on this concept. These two misconceptions each drive the separate pathways in this unit.

Sequence: There are two subunits that can be used to start this unit, one is with changes of state, and the other is with heat transfer. Both of these should be fresh in students minds. Heat transfer has been indirectly shown in a number of prior laboratory experiments, and the description of combinations and separations has been used in the past two units which aids with changes of state. However, since the culminating subunit of kinetic theory should be saved for the end, it appears at first that the change of state pathway should be started with. It is difficult to bring out the necessary heat changes in state changes, however, without at first describing generic changes in heat. This is because there is no change in temperature during a state change, and it is usually easier to comprehend heat changes with change in temperature. Therefore, it is suggested to start with heat transfer, then move to changes of state and enthalpy changes with combinations before finally moving to kinetic theory.

Heat transfer should be kept basic since there are some robust misconceptions associated with it. Heavy usage of terminology and simple spatial diagrams helps. To start, have some heat transfers between warm and cold objects. Identify the warm objects and cold objects by temperature beforehand, and then place together. Create a simple diagram of the event, indicating the direction of temperature change for both objects, and have students describe the motion of heat. Define and use terms like endothermic, exothermic and equilibrium. Students should perform many examples, and analyze them to notice that heat flows from warm objects to cooler ones until their temperatures are equal.

The subunit on changes of state should focus on writing subscripts for states of matter, and in identifying changes in those states of matter. These should include melting, freezing, boiling, condensation, decomposition and sublimation. There should be several hands-on demonstrations, like cooling wax on the hands, acetone evaporating, and ice melting. With these changes should be included the changes of state equations, and diagrams showing the change of heat. A focus should be placed on which object is taking heat, and which object is giving heat. This should be reinforced because only one object is changing temperature, typically the hand. To reinforce the heat flow the use of simple diagrams showing the motion should be used. Finally, students should analyze which states of matter are endothermic and which are exothermic.

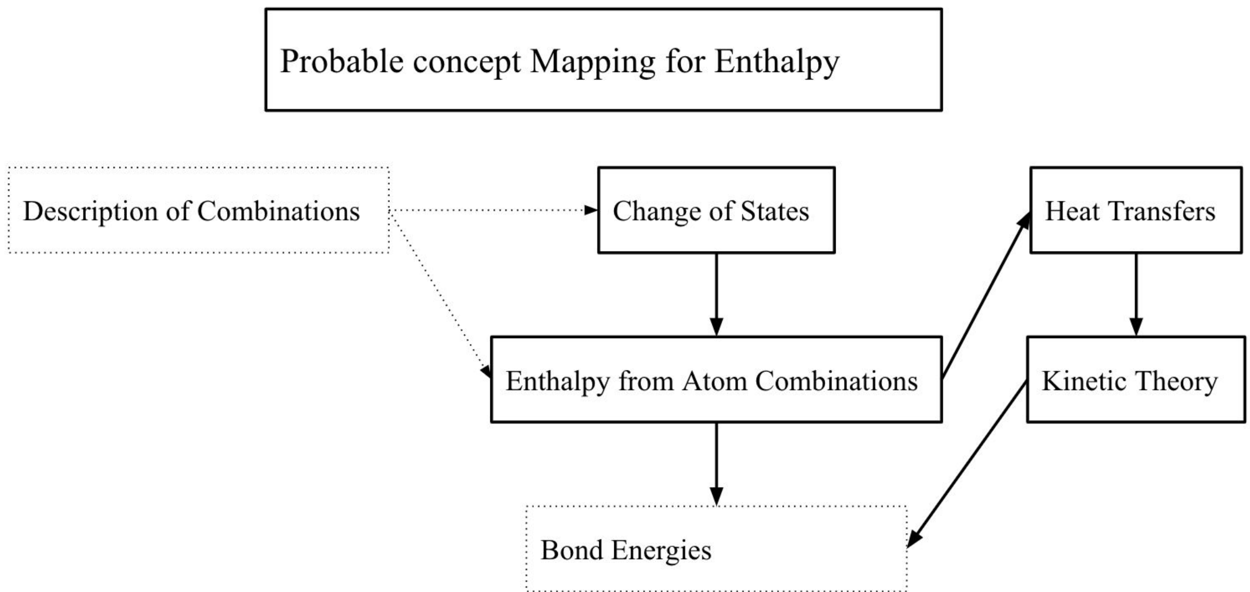
The subunit on enthalpy changes requires students to describe atoms as combining or separating during changes of state. In order to do this, students should describe each state as having atoms combined tightly, lightly, or not at all. Students should then review their changes of state to see which energy change is associated with combination, and which with separation. This is an important step because students often have the notion that it requires energy to build something, and therefore requires energy to combine. It is important to review this misconception in several obvious instances, using simple diagrams when needed, to change students' ideas of exothermic combinations.

The culminating unit on kinetic theory should incorporate Joule's experiment in some way for students to analyze. Students should associate an increase in particle motion with an increase in temperature. This is the basis for kinetic theory. Students should then use specific heats to determine the amount of energy associated with reactions. This will require performing several experiments with temperature changes and measurements to calculate both specific heats and energies. This ability will be used in the subsequent unit on bond energy. An emphasis needs to be placed on energy being an intangible property associated with particle motion.

The suggested progression of this unit through these topics is shown in figure 5.

Figure 5

Sequencing for Enthalpy



The supporting models, experiments and progression questions are summarized in table 9:

Table 9

Subunits for Enthalpy

Sub-Unit	Modeling Supports	Experimental Supports	Progression Questions
Heat Transfers	2-part Spatial Models	Two object transfers with hot and cold objects	What happens when hot and cold objects touch? How does heat transfer?
Change of States	2-part Spatial Models	Change of state demonstrations (hands-on)	Which changes of state are exothermic?
Enthalpy from Combinations	2-part Spatial Models	Review of change of state labs	Which states of matter are combined tightly? Do combining atoms release or absorb energy?
Kinetic Theory	2-part Spatial Models	Joules Lab, specific heat lab	What is temperature? Why do some materials heat up faster than others?

Sub-Units: The full description of each sub-unit, along with each model description, lab description as well as the full set of progression questions can be found in the attachments below. Remember that these are not lesson plans, but the structure upon which lessons are built.

Heat Transfers - this is shown on page 82.

Change of States - this is shown on page 84.

Enthalpy from Combinations - this is shown on page 87.

Kinetic Theory - this is shown on page 89.

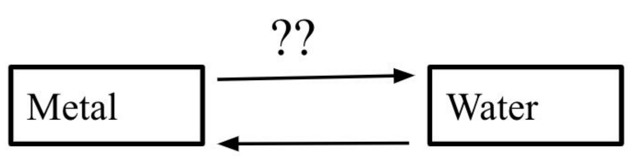
Sub-Unit Support Resource: Heat Transfer

Summary: This subunit covers the concept of the transfer of heat from warmer objects to cooler ones. Students should practice and use temperature measurements, as well as terminology for exothermic and endothermic objects. Students should then be able to draw basic diagrams showing heat transfer from a warmer to a cooler object and to check their work with a table. Finally, students should notice and communicate that heat transfers cause cool objects to warm and warm objects to cool until both objects are the same temperature.

Misconceptions: The most common misconception is that heat is a tangible object. While this subunit does not confront that notion head on, it lays the foundation for later concepts by using simple spatial diagrams. The use of endothermic and exothermic terms will also help to clarify future concepts. This subunit should be kept straightforward and explicit through both diagrams and terminology for this reason.

Modeling: The modeling in this unit should focus on spatial diagrams showing the transfer of heat from one object to another. These objects should be reduced to the most basic forms, and any detail given should focus on temperature. These should be repeated several times, and the goal is to get students recognizing and showing motion, as well as a relationship between one object that gives and another that takes. An example is shown in figure 23

Figure 23



Lab examples: The lab examples should be easily measured, easily observed and described. There should also be two objects that come into contact with each other. Metals placed into water work well, oil and water works well, and in both cases the water can be warmer or cooler than the other object. Save state change demonstrations for the next section.

Progression Questions: The questions should be structured around observation, and end up with some analysis:

What happens to the temperature of the warmer objects, what about the cooler ones?

These questions should then go towards describing the changes in heat. The idea that heat is a tangible substance that moves will actually help in this part.

How does the heat flow or move in the example?

How can you show this motion with a diagram?

Define exothermic and endothermic.

Finally, use repeated observations to build up to the overall trend:

What occurs when two objects of different temperatures are in contact?

Expectations: Students should be able to describe temperature as flowing from warmer to cooler objects until temperatures are equal. They should also be able to draw a diagram using temperature measurements that they have taken to show the predicted movement of heat.

A sample lesson activity: A basic activity is to measure temperatures of metals in a hot water bath, and have students place the metals into cool water whose temperature was measured in an insulated container. Then take temperatures at specific intervals, maybe every 30 second or minute until the temperature stops changing. Graph the result, and have students draw a diagram of the change in heat. Repeat this process with several combinations and then have students describe the overall trend in heat transfer that occurs when warm and cool objects come into contact.

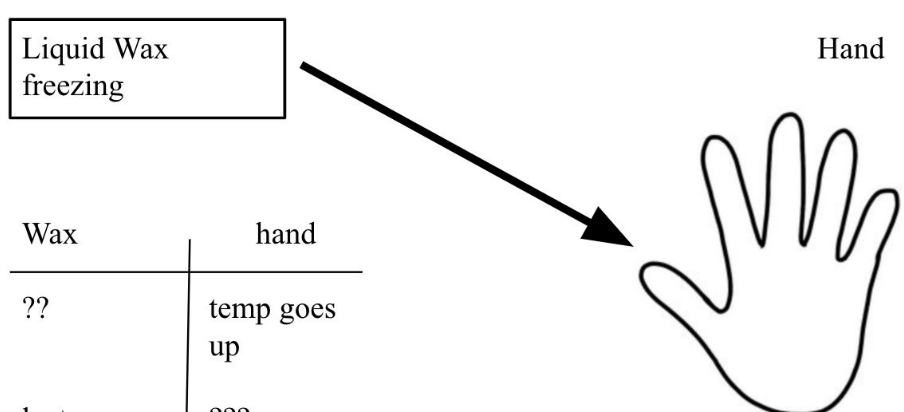
Sub-Unit Support Resource: Change of State

Summary: This subunit should focus on heat changes that occur without changes in temperature. In these cases, a change in state takes or gives energy to another substance. Remembering from the prior subtopic that one substance will give while another gains heat, students should be able to identify the state changes that take, and those that give heat by observing the energy changes in the other substances. Using spatial diagrams to reinforce their predictions should help. Finally, students should be able to write the change of state equations using subscripts for states. Changes of states that should be used include melting, freezing, evaporating, condensing, sublimation and decomposition. The more hands-on students can experience these state changes the better.

Misconceptions: The most common misconception is that your hand will feel warm if an object is taking in energy and vice versa. Students associated how they feel with how the object they are touching feels as well, though it is the opposite. Using terminology for endothermic and exothermic and diagrams showing one way heat transfer should help to clarify the differences between the two objects.

Modeling: The modeling in this subunit, similar to the modeling for the unit, focuses on simple spatial diagrams. Include the two substances involved in the heat transfer as simply as possible, including an arrow for the transfer. An example is shown in figure 24.

Figure 24



Wax	hand
??	temp goes up
lost energy	??? energy
???thermic	???thermic

Students should also be able to show the transfer using equations with subscripts for states as well like the following:

$H_2O_{l} \rightarrow H_2O_{s}$ this is for water freezing

Lab examples: The lab examples should be hands-on, obvious, and show state changes. Some examples include freezing wax on hand, evaporating acetone on hand, melting ice on hand (or gallium), condensing steam on hand. Be careful with the last one. Treat these as short demonstrations with students describing the temperature change of their hand, and drawing a diagram to show the heat transfer.

Progression Questions: Should start reviewing the prior subunit and progress into this one

If one object heats up, did heat enter or leave the other object?

How can you determine the heat change of an object that was not measured?

Is it possible to transfer heat without changing temperature?

The following questions should be asked after some of the demonstrations:

What happens when a substance changes is state?

Which changes of state are endothermic, which are exothermic?

Expectations: Students should be able to feel a change in temperature from a state change, and infer whether the substance gained or lost heat when changing state. Students should be able to articulate the transfer using the words endothermic and exothermic, and to communicate the transfer with spatial diagrams as well. Students should identify changes of state with heat transfers based on observational data, and write equations for the change with subscripts for the states of matter.

A sample lesson activity: A typical lesson would review the prior cases of heat transfer, reiterating that one substance gains and another loses heat. However, what happens when the temperature of both objects can not be measured? Students then are given several hands-on substances that change their states in a safe manner. Students record their observations of temperature change of their hand and change of state in the substance. Students then draw diagrams and determine if the state changes are exothermic or endothermic. Then as these are reviewed students write equations for these state changes using subscripts. Finally, students observe several demonstrations to predict either temperature changes or state changes. Throwing hot water into sub-freezing air is a good example: does it evaporate or freeze?

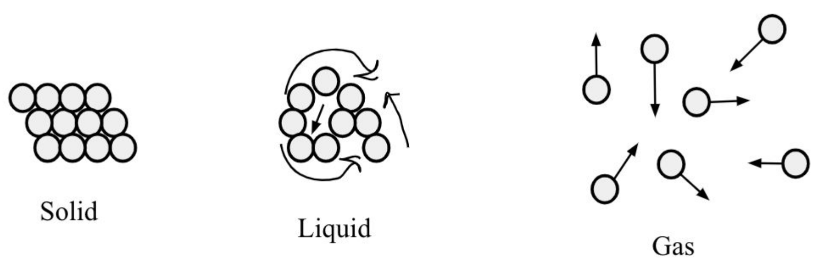
Sub-Unit Support Resource: Enthalpy from Combinations

Summary: This subunit has a focus on a review from the changes in state subunit, and then adds some description of each state of matter in terms of their combinations. Solids are held together the most tightly, liquids loosely, and gas particles are not held together. Students then examine the changes in state for changes in combinations to determine if atoms are combining together or separating. Finally students analyze the changes of combination and separation to determine if the combinations are endothermic or exothermic as well as the separations.

Misconceptions: The most common misconception in this subunit revolves around the assumption that creating a substance by combining particles requires energy. This is similar in understanding for separating particles, and is true in that aspect. It is important to review that there are two different options when heat is transferred, and that both of these do not require energy. Showing that changes of states which combine particles release heat is important as well.

Modeling: The modeling in this subunit should focus on how particles are represented in states of matter. Comparing the previous results with heat transfer helps as well. In both cases, it is important to keep the diagrams simple and spatially related. Included are arrows showing motion, which will also help in the next subunit. An example is shown in figure 25.

Figure 25



Lab examples The lab examples should be reviewed from the last subunit. The emphasis should be on applying the diagrams for the particle combinations to the results of the changes of state. This should allow students to see that combinations release heat. There is no real lab needed, but perhaps a demonstration showing that freezing releases energy (think of the back of a refrigerator or freezer) would help as well.

Progression Questions: The questioning should progress from descriptions of states of matter to identification of state changes with both their heat transfer and their combination or separation. It is suggested to start with states of matter:

Which states of matter have their particles held together tightly, loosely or not at all?

Which changes of state cause particles to combine, and which to separate?

Then students should review and analyze the heat transfers with their particle definitions of states of matter that they just made.

Does the combination of particles cause endothermic or exothermic heat transfer?

Expectations: Students should be able to identify states of matter using descriptions of how tightly or loosely particles are held together. Gases are not, liquids are loosely held together and solids are tightly held together. Then students should use these descriptions to create diagrams that show these relationships. Liquid is difficult to model in this way, however the diagrams help to get an idea of what students are thinking. Students should then describe changes of state as combining particles or separating particles. Melting, evaporation and sublimation are separating particles, while deposition, condensation and freezing(or fusion) are combining them. Students should then be able to use these descriptions with last subunits' heat transfers to describe combinations as exothermic and separations of particles as endothermic.

A sample lesson activity: A suggested activity has students in small groups or completing set work individually. Students are tasked with defining and drawing pictures for states of matter in terms of how tightly their particles are held together. Then students should define the changes of state as either combining or separating particles. Finally, students should combine the results from the last subunit with their change of state definitions to determine that combinations are exothermic. Showing sample demonstrations and having students predict if heat transfers are endothermic or exothermic will help reinforce the new concept.

Sub-Unit Support Resource: Enthalpy from Combinations

Summary: This subunit should focus on the description of temperature in terms of particle motion. An increase in motion results in an increase in temperature. This idea is not really an obvious outcome from the prior section. However, with the understanding that heat helps to separate particles, it is not an enormous step to assume that more heat added, when particles have already been separated, will result in an increased motion. Gas expansion due to temperature increases help reinforce this somewhat. However, Joule's lab does an excellent job of showing this trend as explicitly as possible. This also helps students to change their understanding of heat from a tangible object that substances have to the ability to separate particles or make them move faster. As an extension, if there is time, the concept of specific heat can be introduced as well in order to calculate the actual values of heat.

Misconceptions: The most common misconception in this section is that heat is a tangible object. The notion that heat increases particle motion, or particle speed, is usually relatable. However, to relate temperature wholly to particle motion is difficult due to the prior misconception. Therefore, Joule's experiment does help to show the explicit relationship. This idea should be reinforced with several examples, like gas expansion, diffusion in liquids or gases, and perhaps even brownian motion.

Modeling: The modeling in this subunit is similar to the previous. Particle diagrams should be incorporated using arrows to depict particle speed. This can be extended to show that not all particles move at the same speed as well. However, as an introduction to kinetic theory this subunit is only intended to show the relationship between temperature and motion. An example is shown in figure 26.

Figure 26

Lab examples: Though not impossible, it is difficult to set up Joule's experiment. If this can not be done, there is a re-enactments of this experiment that was done using the same types of instruments in the same room Joule used that has been posted online. (Histodid, 2013) Including some demonstrations of gases expanding when heated, diffusion in a liquid or gas as temperature changes, or using hot scents vs cold scents spreading in a room can also help. As an extension, students can calculate the specific heats of metals, and use them to predict the final temperatures of metal and water mixtures in a specific heat lab.

Progression Questions: These questions should step from reviewing the effect of heat on object separation to predicting what heat will do to individual particle motion.

Does the absorption of heat cause particles to combine or to separate?

What would happen to individual particle motions when they are heated?

At this point Joule's experiment should be shown (Histodid, 2013), and then the following questions presented:

How is temperature related to particle motion?

How can a value of 'heat' be measured?

This last question can be answered in the extension lab on specific heat as well. Included in that specific heat lab can be:

Why do some objects heat up more than others?

Expectations: Students should be able to apply the concept from the prior subunit of endothermic reactions to that of heat causing particle separation. Students should be able to associate increased motion to higher temperature from Joule's lab. Students should be able to model this with pictures by showing particles with more motion as having longer arrows, and be able to interpret these types of drawings made by others. Students should associate heat as the energy involved when increasing the speed of particles in a substance. This is in addition to heat as being the energy that separates particles. As an extension, students should also associate specific heat as being the amount of heat required to change the temperature of a substance, and be able to measure this in the lab.

A sample lesson activity: A sample lesson will start with a review of the last subunit results and the separation caused by endothermic changes of state. Then students are posed the question about how heat affects particle motion. Then Joule's lab is presented with attention paid to the change in temperature as the paddle wheel moves more and more. Students then create drawings to show the changes in particle motion with arrow lengths. Finally, students analyze other drawings to identify warmer and cooler particle representations.

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