Khan Academy

High School Chemistry

Unit 5: Stoichiometry and the mole

Overview

In this unit, students will explore quantitative relationships between reactants and products in chemical reactions.

Lesson 1: Students will learn about the concept of a mole (Avogadro's number of particles) and the relationship between average atomic mass and molar mass. Students will apply this knowledge to determine the molar masses of elements and compounds using the periodic table.

Lesson 2: Students will **use mathematics and computational thinking** and their understanding of moles and molar mass to convert between mass, moles, and numbers of particles in samples of substances.

Lesson 3: Students will apply their knowledge of chemical reactions and molar relationships to predict theoretical yields and to determine amounts of reactants required to make desired amounts of products.

Lesson 4: Hands-on science activity (see below)

Hands-on science activity

How does the International Space Station produce enough oxygen to keep the astronauts alive?

Students will use stoichiometry to make predictions about a chemical reaction. They will then **carry out an investigation** and **analyze and interpret data** to compare the experimental outcome to their predictions and assess the effectiveness of their procedures. Click here for links to the activity.

Standards

Performance expectations: **HS-PS1-7**

Disciplinary core ideas: **HS-PS1.B.3**

Science and engineering practices:

- Developing and using models
- Planning and carrying out investigations
- Using mathematics and computational thinking
- Analyzing and interpreting data

Crosscutting concepts:

- Energy and matter
- Patterns
- Stability and change
- Scale, proportion, and quantity

Click here to read the full standards.

Essential questions

- What is a mole, and how can the concept of molar mass be used to convert between mass and the number of particles in a sample?
- How can we use stoichiometry to predict the theoretical yield of a chemical reaction or the amount of reactants required to make a desired amount of product?
- How can we analyze data from a chemical reaction to determine percent yield and assess the effectiveness of an experimental procedure?

Lesson notes

Lesson 1: Moles and molar mass

PEs: HS-PS1-7
DCIs: HS-PS1.B.3

Resources

Video	Article	Exercise
2	1	2

Objectives	Teaching tips
• Demonstrate understanding of the **mole** as a fundamental unit in chemistry by using **Avogadro's number** to describe large quantities of particles. • Explain the concept of **molar mass** and apply it to determine the molar mass of an element or a compound using the periodic table.	• Review how to write and interpret very large and small values in scientific notation. Give students opportunities to practice calculating with values in scientific notation before asking them to apply these skills to molar conversions. • Help students to grasp the enormity of a mole with macroscopic examples (e.g., a mole of basketballs would fit into a ball bag the size of the Earth). A number of fun videos can be found online that address this concept. • Use analogies to help students understand the concept of molar mass and how it relates to average atomic mass. For example, compare the mass of a dozen ping pong balls to the mass of a dozen bowling balls. Then, ask students to consider how the mass of one ping pong ball compares to one bowling ball. • Emphasize that molar mass provides a method for "counting" atoms or molecules indirectly by measuring the mass of a sample.

Lesson 2: Mole calculations

PEs: HS-PS1-7
DCIs: HS-PS1.B.3

Resources

Video	Exercise
3	3

Objectives	Teaching tips

• Recognize and interpret **empirical**, **molecular**, and **structural formulas** as different ways to represent compounds.
• Calculate the **percent composition by mass** of each element in a compound.
• Apply the concept of **molar mass** to convert between moles and grams of an element or a compound.
• Calculate the number of atoms, molecules, or formula units in a given sample using **Avogadro's number**.
	• Use model kits to build molecular structures for compounds with the same empirical formula but different molecular formulas, such as ethene (C_2H_4) and butene (C_4H_8). Students can observe that while the *ratio* of C to H atoms is the same, the *number* of C and H atoms in each molecule is different.
	• Have students represent the concept of percent composition by mass using a pie chart to show each element's contribution to total mass. This helps students recognize that one atom of a heavier element can represent a larger percentage than several atoms of a lighter element.
	• Consider introducing two methods for solving molar conversions: by setting up a proportion and by dimensional analysis with a conversion factor. Students benefit from seeing different approaches, and it is useful to reinforce the proportional nature of these relationships.
	    ○ Proportion example:
	    Let *x = the number of moles of Cu in 5.0 g of Cu*
	    $\frac{x}{5.0\ g\ Cu} = \frac{1\ mol\ Cu}{63.55\ g\ Cu} \qquad x = 0.079\ mol\ Cu$

	○ Conversion factor example: $5.0\ g\ Cu \times \frac{1\ mol\ Cu}{63.55\ g\ Cu} = 0.079\ mol\ Cu$ • Emphasize the importance of including units on all values, and demonstrate how to set up molar conversions so that units cancel. • Have students problem solve in small groups on whiteboards to practice showing all their work and so that you can easily see where they need support.

Lesson 3: Stoichiometry

PEs: HS-PS1-7
DCIs: HS-PS1.B.3

Resources

Video	Article	Exercise
2	2	3

Objectives	Teaching tips
• Perform **stoichiometric calculations** to determine mole-to-mole and mass-to-mass relationships in chemical reactions. • Determine the **percent yield** of a chemical reaction to assess its efficiency. • Describe the concept of **limiting reactants** and their role in determining the **theoretical yield** of a chemical reaction. • Identify the limiting reactant in a given reaction scenario using the amounts of reactants available and the balanced chemical equation. • Calculate the theoretical yield of a chemical reaction based on complete consumption of the limiting reactant.	• Review the information represented in a balanced chemical equation. Emphasize that the coefficients represent ratios between all species involved in the reaction in terms of particles or *moles* of particles. Discuss why the coefficients do NOT represent mass ratios. • Use analogies, such as making a sandwich or putting together a bicycle, to help students recognize that there is a set ratio of components, which can be scaled up or down, but which must remain consistent, for a given process/reaction. • Use graphic organizers to help students map out problem solving strategies. Include spaces to write a balanced chemical equation, the mole ratio, relevant molar mass values, and the steps they need to take to solve the problem. • Have students create stoichiometry flow charts showing pathways for problem solving from moles to moles, mass to mass, etc. • Introduce limiting reactants by returning to the earlier analogies of sandwich making or bicycle assembly. Ask students what will happen in different scenarios where the ratios of components available do not match the ratios required. Students should recognize that some components will be used up first, leaving others in excess. • After introducing the concept of limiting reactants, allow students to explore the PhET Reactants, Products, and Leftovers simulation. This will help students connect the macroscopic analogy to the molecular level and visualize what happens when one reactant runs out. • Use BCA (**B**efore, **C**hange, **A**fter) tables to help students identify the limiting reactant, to reinforce the importance of the mole ratio, and to provide an organized method for determining the theoretical yield and the amount of excess reactant remaining. • Implement the hands-on activity "*How does the International Space Station produce enough oxygen to keep the astronauts alive?*" to give students experience using stoichiometry to make predictions, plan an experiment, and analyze the effectiveness of a chemical reaction (see Lesson 4).

Lesson 4: Hands-on science activity

How does the International Space Station produce enough oxygen to keep the astronauts alive?

PEs: HS-PS3-4
DCIs: HS-PS3.A.2, HS-PS3.B.1, HS-PS3.B.2

Resources

Activity

1

Description	Links
Students will use stoichiometry to make predictions about a chemical reaction. They will then **carry out an investigation** and **analyze and interpret data** to compare the experimental outcome to their predictions and assess the effectiveness of their procedures.	• Full activity overview (Khan Academy article) • Student activity guide (Doc | PDF) • Teacher guide (Doc | PDF)

Related phenomena

Example phenomenon

What factors affect the cost of medicines we take?

Medications in bottles

Background information

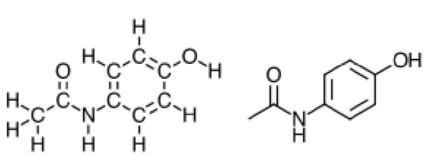
The active ingredients in most pharmaceuticals, from over-the-counter pain medications like ibuprofen to drugs that treat diabetes, are organic molecules that must be produced through a series of chemical reactions. Each reaction requires a certain ratio of reactants and will result in a certain percent yield after the product is isolated. In order to make this process most efficient and cost effective, chemists must determine the optimal conditions and amounts of reactants needed to produce a desired amount of product in the highest yield possible for every reaction step. This becomes more and more important as the number of reaction steps increases, since the final overall percent yield is the product of the percent yields of all the steps. For example, if the percent yields for a three step reaction process are 90%, 75%, and 85%, the overall percent yield for the final product will be only 57%. Many other factors, such as the cost of reactants, catalysts, and solvents, the need for specialized equipment, and energy requirements will also impact the overall cost of production.

Exploring this phenomenon helps students develop and master the following understandings:

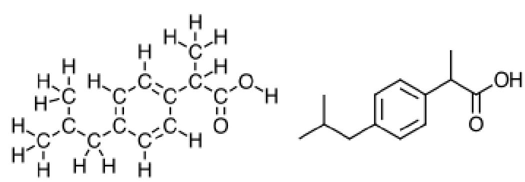
- ☐ Structural formulas are useful for representing organic molecules and provide important information that is not available in empirical or molecular formulas.
- ☐ Stoichiometry can be used to determine the amounts of reactants needed to produce a desired amount of product.
- ☐ Percent yield can be calculated by comparison of the theoretical and actual yields of a chemical reaction and can be used to assess the efficiency of the reaction.

Tips for implementing phenomenon-based learning

- Ideas to encourage student engagement:
  - Ask students to compare the complete and simplified structural formulas for acetaminophen and ibuprofen, the active ingredients in Tylenol and Advil respectively (shown below). Have students record similarities and differences they notice between the complete and structural formulas. Some questions to prompt student thinking: What does each line represent? What is shown in the complete formula that is not shown in the simplified formula? How are these “missing” elements represented in the simplified formula?



acetaminophen



ibuprofen

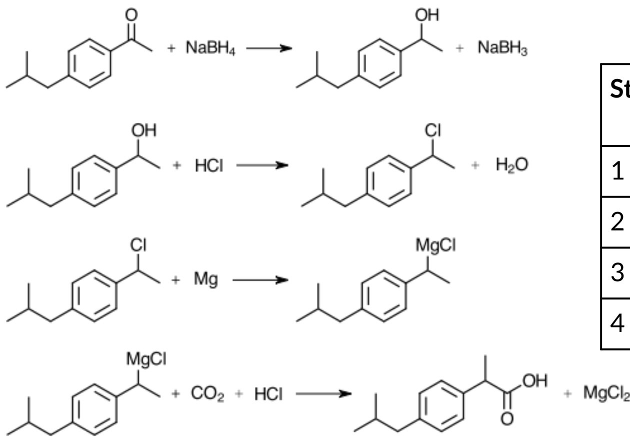
  - Show students the steps in a synthesis of acetaminophen or ibuprofen (such as the one shown below). It is not important for students to understand the chemical reactions involved, but they should be able to recognize how the molecule changes with each step and leads to the final desired product. Provide theoretical and actual yield values in grams or kilograms for each reaction step. Ask students to calculate the percent yield for each step and the overall yield for the entire process.

Step 1:

Step 2:

Step 3:

Step 4:



Example yield values

Step	Theoretical yield (g)	Actual yield (g)
1	25.0	23.2
2	25.5	22.4
3	25.1	24.0
4	23.8	20.5

  - Have students work in groups to brainstorm reasons why the percent yield would be less than 100% for a chemical reaction step. Ask students to consider how the very large scale of the reactions to manufacture pharmaceuticals in factories could have an impact on yield.
- Sample prompts to elicit student ideas and encourage discussion:
  - Why do we often use simplified structural formulas when representing organic molecules?
  - What are some factors that could affect the cost and efficiency of a chemical reaction step in the production of a pharmaceutical?
  - How can stoichiometry be used to maximize yield and minimize waste and cost in pharmaceutical production?
  - Why is it sometimes advantageous to intentionally add excess of one reactant in a chemical reaction?

Example phenomenon

In the fight against climate change, how are cars evaluated for fuel efficiency and greenhouse gas emissions?

Background information

Cars and trucks in traffic

Vehicles that rely on burning gasoline or diesel fuel release carbon dioxide, a greenhouse gas, into the atmosphere. In the U.S., the transportation sector is the largest contributor to greenhouse gas emissions. These gases build up in Earth's atmosphere, causing it to warm and resulting in changes to the climate. As part of efforts to address the growing climate crisis, the Environmental Protection Agency (EPA) has adopted fuel efficiency and emission standards for motor vehicles that manufacturers must meet when designing new vehicles.

Every new car being sold in the U.S. must display a [Fuel Economy and Environment sticker] that lists the car's miles per gallon of fuel consumption for city and highway driving and the grams of carbon dioxide emitted per mile. To determine these values, a car is placed on a machine called a dynamometer that allows the wheels to turn while the car remains stationary. A driver runs the car through a standard set of driving routines that simulate trips around a city or on the highway. A hose connected to the tailpipe collects the engine exhaust, and the exhaust is analyzed to determine the amount of carbon dioxide emitted during each set of testing conditions. Using stoichiometry, the amount of carbon dioxide produced by the engine can then be used to calculate the amount of fuel that burned. This is how the miles per gallon fuel economy values are determined.

Exploring this phenomenon helps students develop and master the following understandings:

- [ ] The coefficients of a balanced chemical equation relate moles of reactants consumed to moles of product produced in a chemical reaction.
- [ ] The molar mass of a compound can be determined using the periodic table and can be used to convert between moles and grams of the compound.
- [ ] Stoichiometry can be used to predict the theoretical yield of a chemical reaction or the amount of reactants required to make a certain amount of product.

Tips for implementing phenomenon-based learning

- Ideas to encourage student engagement:
    - Have students plan car trips of different distances around where they live, to another town or city, or across the country. For each trip, ask them to:
        - Map out the complete route, determine which parts would be considered "city" or "highway" driving, and calculate the total miles of each kind of driving.
        - Look up the city and highway fuel economy values for a car of their choice, and use them to calculate the total gallons of gasoline consumed during the trip.
        - Use the density of octane, the major component of gasoline, to determine the total grams of octane consumed during the trip.
        - Write a balanced chemical equation for the combustion of octane (C_8H_{18}) and apply stoichiometry to predict the grams of CO_2 produced during the trip.
    - After students determine the CO_2 emissions for their trips, ask them to share their results with each other. Discuss what they notice about the impact of different types of cars and different kinds of driving (city vs highway).
    - Challenge students to come up with ways to reduce the CO_2 emissions for one of their trips. They might consider more fuel efficient gasoline or hybrid cars, other forms of transportation (e.g., train, bus, motorcycle), or different types of fuel (e.g., diesel, natural gas, electricity). Ask students to support their proposals with evidence using stoichiometric calculations.
- Sample prompts to elicit student ideas and encourage discussion:
    - What are we assuming to be the limiting reactant in a combustion reaction that powers a car, and what reactant is in excess?
    - How do hybrid and electric cars reduce carbon dioxide emissions?
    - What kinds of vehicles have diesel engines, and why does burning diesel fuel produce more carbon dioxide per gallon than gasoline?
    - How do the processes involved in extracting, refining, and transporting fuel and in producing electricity also contribute to carbon dioxide emissions?

Common student misconceptions

Possible misconception: *Coefficients of balanced chemical equations relate reactants and products in terms of grams.*

Students generally have experience using a balance to measure the mass of a sample, and the amounts of reactants or products in stoichiometry problems are typically given in grams. As a result, students may assume that the coefficients in a balanced chemical equation relate reactants and products in terms of grams, rather than moles. This may lead students to use the ratio of coefficients to convert directly from grams of one substance to grams of another without taking into account molar mass.

Critical concepts

- The coefficients of a balanced chemical equation indicate the relative number of particles (or moles of particles) of each reactant and product involved in the reaction.
- Every element has a unique molar mass that can be found in the periodic table. While a mole of any element or compound has the same number of particles, it does not have the same mass.
- Molar mass is used to relate the mass of a sample to the number of particles in that sample and is given in units of grams/mole.

How to address this misconception

Macroscopic examples can help students to distinguish a ratio based on the numbers of components from a ratio based on the masses of the components. For example, revisit the comparison of a dozen ping pong balls and a dozen bowling balls. Although there is a 1:1 ratio in terms of numbers, there is a much different ratio in terms of mass, as each bowling ball has a much larger mass than each ping pong ball. Similarly, you can ask students to consider putting together a bicycle. The ratio in terms of numbers of components is 2 wheels to 1 frame, but since the frame weighs more than the wheels, this ratio will not be equivalent in terms of grams.

Possible misconception: *The reactant present in the least amount is always the limiting reactant.*

Students often neglect to take into account the mole ratio when determining which reactant is limiting. They may believe that whichever reactant is present in the least amount will always be consumed first.

Critical concepts

- The coefficients in front of reactants in a balanced chemical equation indicate the relative number of units (atoms, molecules, formula units) of each reactant needed to form products.
- The limiting reactant is the one that will run out first when the reaction proceeds according to the mole ratio indicated by the coefficients of the balanced chemical equation.

How to address this misconception

Emphasize from the outset the mole ratio's importance in determining how reactants are consumed and products are made. Have students use BCA (**B**efore, **C**hange, **A**fter) tables to organize their mole values for the entire reaction in one place. This framework supports proportional reasoning and provides an effective way to visualize the theoretical outcome of a reaction if one reactant or the other is considered limiting. Ensure that practice problems offer many examples that contradict the misconception.

Unit resources

Student resources

- PhET Reactants, Products, and Leftovers: Use this simulation for a virtual investigation of stoichiometric relationships, including limiting reactants.
- www.fueleconomy.gov: Visit this website for more information about fuel economy and greenhouse gas emission standards and testing.
- Scientific notation examples: Review scientific notation with this Khan Academy video.
- Article and video note taking template (Doc | PDF): Use this printable template for structured note taking on the articles and videos in this unit.

Classroom implementation resources

- PubChem Periodic Table of Elements and Printable Periodic Tables: Download various versions of the periodic table, including a blank template.
- Weekly Khan Academy quick planning guide (Doc | PDF): Use this template to easily plan your week.
- Using Khan Academy in the classroom (Doc | PDF): Learn about teaching strategies and structures to support your students in their learning with Khan Academy.
- Differentiation strategies for the classroom (Doc | PDF): Read about strategies to support the learning of all students.
- Using phenomena with the NGSS: Learn more about how to incorporate phenomena into NGSS-aligned lessons.
- Hands-on science activities from Khan Academy: Choose from Khan Academy's collection of high-quality, ready-to-use, and free hands-on science activities. Each one is engaging, three-dimensional, phenomenon-based, and simple to implement.

NGSS standards reference guide

Performance expectations

- **HS-PS1-7:** Use mathematical representations to support the claim that atoms, and therefore mass, are conserved during a chemical reaction.

Disciplinary core ideas

- **HS-PS1.B.3:** The fact that atoms are conserved, together with knowledge of the chemical properties of the elements involved, can be used to describe and predict chemical reactions.

Science and engineering practices (SEPs)

- **Developing and using models**: Students progress to using, synthesizing, and developing models to predict and show relationships among variables between systems and their components in the natural and designed worlds.
- **Using mathematics and computational thinking:** Students progress to using algebraic thinking and analysis, a range of linear and nonlinear functions including trigonometric functions, exponentials and logarithms, and computational tools for statistical analysis to analyze, represent, and model data. Simple computational simulations are created and used based on mathematical models of basic assumptions.
- **Planning and carrying out investigations:** Students progress to include investigations that provide evidence for and test conceptual, mathematical, physical, and empirical models.
- **Analyzing and interpreting data:** Students progress to introducing more detailed statistical analysis, the comparison of data sets for consistency, and the use of models to generate and analyze data.

Crosscutting concepts (CCCs) and their implementation

Crosscutting concept	Unit implementation
Energy and matter: Flows, cycles, and conservation. Tracking fluxes of energy and matter into, out of, and within systems helps one understand the systems' possibilities and limitations.	Students apply conservation of mass to predict theoretical yields and to determine amounts of reactants required to make desired amounts of products.
Patterns: Observed patterns of forms and events guide organization and classification, and they prompt questions about relationships and the factors that influence them.	Students use patterns in reactivity to predict the outcomes of chemical reactions.
Stability and change: For natural and built systems alike, conditions of stability and determinants of rates of change or evolution of a system are critical elements of study.	Students observe changes from reactants to products and represent them with balanced chemical equations.
Scale, proportion, and quantity: In considering phenomena, it is critical to recognize what is relevant at different measures of size, time, and energy and to recognize how changes in scale, proportion, or quantity affect a system's structure or performance.	Students recognize that the incredibly small size of atoms means only incredibly large numbers of them are easily measured, which requires the application of Avogadro's number and molar mass.