Khan Academy

High School Chemistry

Unit 9: Reaction rates and equilibrium

Overview

In this unit, students will explore chemical reaction rates and qualitatively analyze changes in systems at equilibrium.

Lesson 1: Students will investigate factors that affect reaction rates and use collision theory as a **model** to explain these effects.

Lesson 2: Hands-on science activity (see below)

Lesson 3: Students will explore the role of catalysts in increasing chemical reaction rates.

Lesson 4: Students will apply their understanding of reaction rates, solution concentration, gas laws, and exothermic and endothermic reactions to analyze systems at equilibrium. They will use Le Châtelier's principle to predict how and explain why a reaction at equilibrium will shift when the system is disturbed.

Hands-on science activity

Why does food in a refrigerator stay fresh for longer?

Students will **plan and carry out investigations** and **analyze and interpret data** to determine the effects of several factors (temperature, reactant concentration, surface area of a solid reactant, and stirring) on chemical reaction rates. They will then **construct explanations** for their results and for the impact of refrigeration on food freshness using collision theory. [Click here for links to the activity.]

Standards

Performance expectations: **HS-PS1-4 | HS-PS1-5| HS-PS1-6**

Disciplinary core ideas: **HS-PS1.B.1 | HS-PS1.B.2| HS-PS3.B.4**

Science and engineering practices:

- Developing and using models
- Planning and carrying out investigations
- Constructing explanations and designing solutions
- Analyzing and interpreting data

Crosscutting concepts:

- Systems and system models
- Stability and change
- Energy and matter
- Patterns

[Click here to read the full standards.]

Essential questions

- What factors affect the rate of a chemical reaction, and how does collision theory explain these effects?
- What does it mean for a reaction system to be at equilibrium?
- How and why does a reaction system at equilibrium shift when the system is disturbed?

Lesson notes

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Lesson 1: Reaction rates

PEs: HS-PS1-4, HS-PS1-5
DCIs: HS-PS1.B.1, HS-PS3.B.4

Resources
Video 2 · Exercise 3

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<tr><th>Objectives</th><th>Teaching tips</th></tr>
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- Predict how changes in temperature, reactant concentration, surface area of a solid, and/or stirring will affect **reaction rate**.
- Use **collision theory** to explain why changes in temperature, reactant concentration, surface area of a solid, and stirring affect reaction rates.
- Interpret energy diagrams for chemical reactions to identify the **activation energy**, **transition state**, overall change in energy, and whether the reaction is exothermic or endothermic.
- Analyze experimental data to determine how changes in the concentration of a specific reactant affect reaction rate.

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- Guide students to understand how the rate of a chemical reaction is measured. Begin by showing the chemical equation for a simple reaction, like $2H_2O_2\,(aq) \rightarrow O_2\,(g) + 2H_2O\,(l)$. Ask students:
  - *What happens to the amount of H_2O_2 as the reaction proceeds? What happens to the amounts of O_2 and H_2O?*
    Guide students to recognize that reactants will disappear and products will appear over time.
  - *What is a rate? What are some examples of rates?*
    Guide students to define a rate as a change in some variable over time. Accessible examples could include the speed of a car (miles/hour) or heart rate (beats/minute).
  - *If we want to measure the rate of a chemical reaction, what is changing over time?*
    Guide students to understand that reaction rate is measured in terms of change in concentration of reactants (decrease) or products (increase) over time.
- Review how to interpret energy diagrams for exothermic and endothermic reactions (Unit 4). Give students an unlabeled diagram, and ask them to label the axes, the minimum energy required to initiate the reaction, the energy released when the product bonds form, and the overall change in energy. Then, have them classify the reaction as exothermic or endothermic. Introduce and define the terms "activation energy" and "transition state," and show students where these belong in the diagram.
- Review relevant concepts from Unit 7 by having students summarize how *temperature*, *average kinetic energy*, and *particle motion* are related.
- Introduce collision theory using the PhET Reactions and Rates simulation. Project the simulation for the class to observe together or have students work in small groups.
  - In the *Many Collisions* section of the simulation, open the "energy view" to see an energy diagram, and add 4-5 particles of each reactant at a low initial temperature. (The "Total average energy" line should be well below the activation energy peak on the energy diagram.) Ask students:
    - *What do you observe? What are the particles doing?*
    - *Are products forming?*
  - Increase temperature, using the slider under the reaction container, until the "Total average energy" line is at or above the activation energy peak on the energy diagram. Ask students:
    - *What changed about the particles' motion and interactions?*
    - *Do products form every time reactant particles collide?*

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	○ Use student responses to summarize the key points of the model: particles must *collide* in the *correct orientation* and with *sufficient energy* to break bonds in order for a reaction to occur. ● Based on the collision theory model, ask students to work in pairs or small groups on whiteboards to brainstorm factors that could increase the rate of a chemical reaction. Have them use particle diagrams and words to support and explain their reasoning. Then, invite students to share their ideas, and develop a class list of factors. ● Implement the hands-on activity "*Why does food in a refrigerator stay fresh for longer*?" in order for students to collect data, draw their own conclusions, and construct explanations related to factors affecting reaction rates (see Lesson 2). ● Ask students to explore the causes and impacts of acid rain. (*See the "Related phenomena" section below for more information.*)

Lesson 2: Hands-on science activity
Why does food in a refrigerator stay fresh for longer?

PEs: HS-PS1-5
DCIs: HS-PS1.B.1

Resources

Activity
1

Description	Links
Students will **plan and carry out investigations** and **analyze and interpret data** to determine the effects of several factors (temperature, reactant concentration, surface area of a solid reactant, and stirring) on chemical reaction rates. They will then **construct explanations** for their results and for the impact of refrigeration on food freshness using collision theory.	● Full activity overview (**Khan Academy article**) ● Student activity guide (**Doc** | **PDF**) ● Teacher guide (**Doc** | **PDF**)

Lesson 3: Catalysts

PEs: HS-PS1-4, HS-PS1-5, HS-PS1-6
DCIs: HS-PS1.B.1

Resources

Video 1
Exercise 1

Objectives	Teaching tips
● Define a **catalyst**, and explain how catalysts affect chemical reaction rates. ● Describe or illustrate how an energy diagram for a chemical reaction changes when a catalyst is added.	● Introduce catalysts by demonstrating the decomposition of hydrogen peroxide in the presence of a catalyst. (Wear safety goggles and gloves and ensure that students are a safe distance from the demo.) ○ Set up the materials, and explain each component of the demonstration to students: ■ Place 20 mL of 30% hydrogen peroxide solution in each of two 100 mL graduated cylinders, and place the cylinders on a tray or other shallow container. ■ Add 10 mL of dish soap to each cylinder and swirl to mix. ■ Make 5 mL of 2 M potassium iodide solution.

	○ Have students write the balanced chemical equation for the decomposition of aqueous hydrogen peroxide to form oxygen gas and water. Ask them to predict how they will know that the reaction is taking place. ○ Carry out the demonstration, and ask students to record their observations: ■ Add potassium iodide solution to one of the two cylinders. The contents will immediately begin to foam up and out of the cylinder vigorously. ■ To show that thermal energy is being released, place a thermometer in the foam and report the temperature. ■ To show that oxygen is the gas being produced, light a wood splint or match, blow it out, and while it is still glowing, touch it gently to the foam. The splint will relight due to the high concentration of oxygen gas. ○ Ask students to describe what they observed and how the two cylinders differed. Guide students to understand that the decomposition reaction was occurring in both cylinders, but it occurred much faster when the potassium iodide was added. ○ Discuss whether any of the factors affecting reaction rate from Lesson 1 (temperature, reactant concentration, surface area of a solid reactant, and stirring) can explain the difference between the two cylinders. ○ Introduce the concept of a catalyst as a substance that increases the rate of a chemical reaction without undergoing a permanent chemical change. Ask students to hypothesize how/where to represent the potassium iodide catalyst in the chemical equation for the decomposition of hydrogen peroxide. Guide students to understand that a catalyst is not a reactant or product and is not consumed or changed at the end of the reaction, so it is typically written above the arrow. ○ Ask students to draw an energy diagram for the decomposition reaction, based on their observations, and explain their reasoning. They should recognize that the reaction is exothermic from the temperature increase in the surroundings. ○ Explain that a catalyst increases the rate of a reaction by providing an alternative pathway for the reaction that lowers the activation energy. Have students sketch on their energy diagrams to show how the diagrams would differ in the presence and absence of a catalyst. Ask students to describe what changes and what *doesn't* change about an energy diagram in the presence of a catalyst. ○ If time allows, carry out the same demonstration with other catalysts, such as manganese(IV) oxide, sodium iodide, or catalase (an enzyme). If students have taken biology, connect to what they learned about enzymes as biological protein catalysts. Yeast, liver, or potatoes are good sources of catalase. ● Employ an analogy to help students understand what it means for a catalyst to provide an *alternative reaction pathway* that lowers activation energy. ○ Start by drawing a diagram of a scenario where a person on the fifth floor of a building wants to visit a friend on the fourth floor of the building next door. Show the path they would have

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to take: walk down five flights of stairs, cross the street, enter the other building, and walk upstairs to the fourth floor.
Next, draw a bridge connecting the two buildings on the fourth floor. This allows the person to walk down one flight of stairs and then straight across to the other building.
Ask students what is the same in both scenarios (with and without the bridge). Guide them to recognize that the initial and final states are the same (same locations), as is the energy difference between them (fifth and fourth floors).
Ask students to explain what the bridge does, and guide them to understand that it provides an alternative, lower energy pathway. Relate this back to the energy diagrams students drew for reactions in the absence and presence of a catalyst.

Assign small groups of students to research catalysts used in different applications, such as catalytic converters, production of ammonia, hydrocarbon cracking, or production and recycling of plastics. Have students create 2-3 slides to share what they learn with the class.
Ask students to brainstorm the benefits of using catalysts for industrial processes. Prompt student thinking by asking:

How might a company benefit from a faster reaction rate?
How might a catalyst make a reaction safer or more environmentally friendly?

Have students explore the role of a catalyst in depleting the ozone layer. (See the “Related phenomena” section below for more information.)

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Lesson 4: Equilibrium & Le Châtelier’s principle

PEs: HS-PS1–6
DCIs: HS-PS1.B.2

Resources

Video	Exercise
2	2

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Describe what it means for a reaction to be reversible and how this is notated in a chemical equation.
Explain how a chemical reaction system reaches equilibrium and why this state is considered dynamic.
Describe Le Châtelier’s principle, and use it to predict how a reaction at equilibrium will shift when the system is disturbed by changes in temperature, gas pressure, or concentration of reactants or products.
Apply Le Châtelier’s principle and an understanding of exothermic and endothermic reactions to explain the effects of changes in temperature on a reaction system at equilibrium.
Apply Le Châtelier’s principle and gas laws to explain the effects of changes in

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Use analogies to model reversible reactions and systems at equilibrium. Examples might include cars driving in both directions across a bridge or players being substituted in a basketball game. Describe the scenario, including the idea that the rate of change is the same in both directions. (Every time a car crosses east to west, a car crosses west to east; every time a player enters the court from the bench, a player exits the court to the bench.)

Have students draw diagrams representing the movement of cars or players in the scenario. Then ask:

What happens to the number of cars on each side of the bridge or the number of players on the bench and the court?
Do the actual cars or players in each location change?
Does the number of cars on the east side of the bridge have to be equal to the number of cars on the west side of the bridge? Does the number of players on the bench have to equal the number of players on the court?

Build on student answers to establish that:

Most chemical reactions can proceed in both directions,

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gas pressure on a reaction system at equilibrium.

- Apply Le Châtelier's principle and collision theory to explain the effects of changes in reactant or product concentration on a reaction system at equilibrium.

as represented by a double arrow.

- A reaction system reaches equilibrium when the rates of the forward and reverse reactions are the same.
- The forward and reverse reactions continue, so reactants keep changing to products and vice versa (*dynamic*).
- The concentrations of reactants and products remain constant, but *they don't have to be equal to each other*.

- As a follow up, show the TED Ed video "[What is chemical equilibrium?]" Have students [take notes], and then ask them to identify key takeaways about equilibrium reviewed in the video.
- Introduce Le Châtelier's principle with a [live demo] or [video] of this reaction system at equilibrium:

$$Co(H_2O)_6^{2+} + 4Cl^- + heat \rightleftarrows CoCl_4^{2-} + 6H_2O$$

pink *blue*

  - Present the chemical equation, and explain that the reactant cobalt complex is pink and the product is blue. Ask students if the forward reaction is exothermic or endothermic and how they can tell from the chemical equation.
  - Describe Le Châtelier's principle: when a system at equilibrium is disturbed, the reaction shifts in the direction that relieves the disturbance and restores equilibrium.
  - Ask students to predict what will happen if you:
    - Increase the concentration of Cl^- (by adding HCl)
    - Decrease the concentration of Cl^- (by adding $AgNO_3$, which forms a precipitate with Cl^-)
    - Add heat (by placing the reaction in a hot water bath)
    - Remove heat (using a cold water bath)
  - Guide students to understand that the reaction equilibrium will shift in the direction that uses the added reactant/heat or in the direction that replaces the removed reactant/heat.
  - Carry out or watch a video of the demonstration, so students can observe color changes as these shifts occur.
- Use graphic organizers, like the example below, to guide student analysis of reaction systems at equilibrium.

$2SO_2\,(g) + O_2\,(g) \rightleftarrows 2SO_3\,(g) \quad \Delta H < 0$					
Stress	$[SO_2]\uparrow$	$[O_2]\uparrow$	$[SO_3]\uparrow$	Temp ↑	Pressure ↑
Shift (L/R)					

- Connect Le Châtelier's principle to collision theory, energy changes in reactions, and gas laws by having students work in small groups on whiteboards to create annotated diagrams explaining why:
  - Increasing reactant concentration causes the rate of the forward reaction to increase.
  - Increasing temperature increases the rate of the endothermic reaction *more than* the exothermic reaction.
  - Decreasing volume/increasing pressure increases the rate of the reaction that produces fewer moles of gas.
- Have students analyze ozone depletion using Le Châtelier's principle. (*See the "[Related phenomena]" section below for more information.*)

Related phenomena

Example phenomenon

What causes acid rain, and how does it damage stone buildings?

Background information

Gargoyle damaged by acid rain. Image credit: "Gargoyle" by Nino Barbieri, CC BY-SA 3.0.

Acid rain is a global problem that impacts our environment and causes damage to buildings and monuments, particularly those made of limestone, marble, and granite. Rain is naturally slightly acidic, with a pH around 5.6, due to the reaction of water with carbon dioxide in the atmosphere to produce carbonic acid. (This reaction was presented in the context of ocean acidification in Unit 8.)

The increased acidity of "acid rain," with a pH generally below 4.5, is caused by sulfur dioxide and nitrogen oxides that are released into the atmosphere, where they react with oxygen and water to form sulfuric and nitric acids (see below). These acids mix with water in clouds and then fall to the earth as rain and other forms of precipitation.

$$2SO_2\,(g) \ + \ O_2\,(g) \ \rightarrow 2SO_3\,(g) \qquad 2NO\,(g) \ + \ O_2\,(g) \ \rightarrow 2NO_2\,(g)$$

$$SO_3\,(g) \ + \ H_2O\,(l) \ \rightarrow \ H_2SO_4\,(aq) \qquad 2NO_2\,(g) \ + \ H_2O\,(l) \ \rightarrow \ HNO_3\,(aq) \ + \ HNO_2\,(aq)$$

While natural events, such as volcanic eruptions and forest fires, can release sulfur dioxide and nitrogen oxides, combustion of fossil fuels by humans is the main source of increased concentrations of these gases in our atmosphere. In the United States, about two-thirds of sulfur dioxide and one-quarter of nitrogen oxides in the atmosphere comes from burning fossil fuels, like coal, to produce electricity. Combustion of gasoline in car engines is another major contributor.

When acid rain strikes a limestone or marble structure, a reaction occurs between the acid and calcium carbonate in the stone:

$$CaCO_3\,(s) \ + H_2SO_4\,(aq) \ \rightarrow \ CaSO_4\,(s) \ + \ H_2O\,(l) \ + \ CO_2\,(g)$$

Since the calcium sulfate product is slightly soluble in water, it will be washed away on exposed surfaces, leading to deterioration of the structure. As human activities increase concentrations of sulfur dioxide and nitrogen oxides in the atmosphere, the rate at which these gases react with oxygen and water to form sulfuric and nitric acids increases. As the concentration of acid in rainwater increases, the rate of reaction with calcium carbonate in stone structures increases, endangering important infrastructure and historic monuments.

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

- ☐ Particles must *collide* in the *correct orientation* and with *sufficient energy* to break bonds in order for a reaction to occur.
- ☐ Factors that increase the *frequency* and/or *average energy* of collisions between reacting particles increase reaction rates.
- ☐ Increasing the concentration of a reactant increases reaction rate, because more particles in the same volume leads to an increased frequency of collisions between reacting particles.
- ☐ Increasing the concentration of H^+ ions in solution leads to a decrease in pH and a more acidic solution (review from Unit 8).

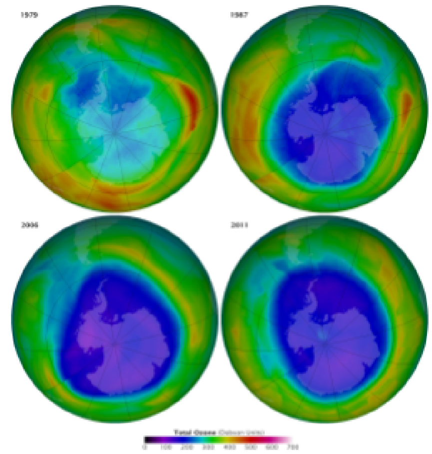
Tips for implementing phenomenon-based learning

- Ideas to encourage student engagement:
  - Introduce the problem of acid rain by showing students a few images of decorative stonework, gravestones, statues, or historic and culturally important structures, such as the Taj Mahal in India or the Acropolis in Greece, that have been damaged by acid rain. Ask students to explore and take photos in their own neighborhoods or find examples online of other stone structures that appear to have suffered similar deterioration.
  - Leverage student learning from Unit 8 by asking them to work in pairs or small groups to address the following prompts:
    - *What does it mean for rainwater to be "acidic?"*
    - Rainwater naturally has a pH around 5.6 due to the reaction of water with carbon dioxide in the atmosphere. *What is the chemical equation for this reaction?*
    - "Acid rain" has a pH below 4.5. *About how many times more acidic is this compared to natural rainwater?*
    - *How does the concentration of hydrogen ions in acid rain compare to natural rainwater?*
  - Show this video, then discuss what students learned about the causes of acid rain. Write out the chemical equations for the production of sulfuric acid from sulfur dioxide gas in the atmosphere, then ask students to write the equation for the reaction of calcium carbonate with sulfuric acid to produce calcium sulfate, carbon dioxide, and water. Have them use a solubility chart to determine if calcium sulfate is soluble in water. Ask students to recall when they have studied calcium sulfate in an earlier unit (the giant Naica Cave crystals in Unit 3). For more practice, have students write the chemical equation for the reaction of calcium carbonate with nitric acid.
  - Assign students to create a flow chart or infographic with words, chemical equations, and diagrams explaining how increased combustion of fossil fuels leads to an increased rate of deterioration of stone structures by acid rain. Students should include the roles that collision theory, reactant concentration, and reaction rate play in the overall process.
  - Have students research methods for addressing the causes of acid rain, such as installing "scrubbers" in power plants to remove sulfur dioxide from gases being emitted, switching to renewable energy sources, like wind and solar, and manufacturing low or zero-emissions vehicles. Invite them to write a letter to their local representative or create a PSA explaining why acid rain is a problem and what continued actions are needed to reduce its impact.
- Sample prompts to elicit student ideas and encourage discussion:
  - What are the most important sources of sulfur dioxide and nitrogen oxides in our atmosphere?
  - What is the chemical reaction that occurs between sulfuric acid and calcium carbonate, and how does it lead to deterioration of limestone and marble structures?
  - How is the rate of deterioration of buildings and monuments from acid rain related to reactant concentration and collision theory?
  - What are people doing to address the causes of acid rain and reduce its harmful effects?

Example phenomenon

How did human activities lead to the ozone layer's depletion, and what global actions have helped restore it?

Background information



Ozone hole over Antarctica 1979 to 2011. Image credit: NASA.

The ozone layer in our stratosphere serves as a protective shield for life on Earth. Ozone molecules, made up of three oxygen atoms bonded together (O_3), are able to absorb harmful ultraviolet B (UV-B) radiation from the Sun before it reaches the planet's surface. Exposure to UV-B rays can cause skin cancer and cataracts in humans, negatively affect plant growth, disrupt marine ecosystems, and upset biogeochemical cycles.

In the 1970s, scientists discovered that chlorofluorocarbons (CFCs), small molecules commonly used in refrigerants and aerosol sprays, were depleting the ozone layer and potentially leading to dangerous climate and health effects.

Under normal atmospheric conditions, an equilibrium exists between ozone decomposition and formation:

$$2O_3(g) \rightleftarrows 3O_2(g)$$

Chlorine atoms from CFCs disrupt this equilibrium by catalyzing the forward reaction and increasing the rate at which ozone breaks down to oxygen gas. Chlorine does not catalyze the reverse reaction, so equilibrium shifts toward the products, and O_2 concentration goes up, while O_3 concentration goes down. Since chlorine acts as a catalyst, it is not consumed in the reaction, which means that one chlorine atom can catalyze the destruction of thousands of ozone molecules.

In 1985, scientists reported a "hole" in the ozone layer over Antarctica that has since been linked to CFCs. The hole appears annually in August to October as a result of [specific local atmospheric conditions] that create higher concentrations of available chlorine atoms to catalyze ozone decomposition.

In response to mounting scientific evidence and advocacy, the international community came together in 1987 to draft the Montreal Protocol on Substances that Deplete the Ozone Layer, which aimed to ban the global production and use of ozone-damaging chemicals, including CFCs. Signed by 197 countries, it is considered one of the most successful global environmental actions. The treaty has led to substantial and continued decline in atmospheric CFC levels, which has allowed equilibrium to shift back toward higher concentrations of ozone. If the current trend continues, the ozone layer is expected to recover to its pre-1980 condition by the middle of the 21st century.

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

- ☐ Most chemical reactions can proceed in both directions, as represented by a double arrow.
- ☐ A reaction system reaches equilibrium when the rates of the forward and reverse reactions are equal.
- ☐ A catalyst increases the rate of a reaction, without itself undergoing a permanent chemical change, by providing an alternative pathway that lowers activation energy.
- ☐ When a system at equilibrium is disturbed, the reaction shifts in the direction that relieves the disturbance and restores equilibrium.

Tips for implementing phenomenon-based learning

- Ideas to encourage student engagement:
    - Introduce the topic of ozone depletion with this short National Geographic video. Provide students with a template to take notes on the following questions:
        - Where is the ozone layer found?
        - How does the ozone layer protect life on Earth?
        - What is the chemical structure of ozone?
        - What has caused the ozone layer to become thinner?
        - Where are the thinnest areas of the ozone layer, and why do ozone "holes" occur there?
        - How did the Montreal Protocol address the problem of ozone depletion?
        - What is the predicted outlook for the future of the ozone layer?
    - Discuss what students learned, and record a list of questions they have, based on the video. Post the questions for easy reference throughout the unit, and use them as jumping off points for exploring aspects of the phenomenon or for assigning mini research projects.
    - Have students work in pairs or small groups to analyze the equilibrium system involving ozone decomposition and formation. Ask students to:
        - Write a balanced chemical equation for the reversible exothermic decomposition of ozone gas to oxygen gas.
        - List the stresses on the reaction system that would cause a shift toward products.
        - Use an energy diagram and words to explain how a chlorine atom (from a CFC molecule) acting as a catalyst would cause a shift toward products.
        - Explain why a decrease in the concentration of CFCs in the stratosphere would cause the equilibrium system to shift toward reactants.
        - Hypothesize why, when the Montreal Protocol banned the production and use of ozone-depeleting chemicals, CFCs didn't quickly go back to their natural levels.
    - Invite students to explore data available on the NASA Ozone Watch website, including maps, animations, graphs, and charts tracking changes in the ozone layer since 1979. Assign them to use this and other resources (e.g., EPA, UNEP, National Geographic, and The Conversation) to answer some of the questions they generated from the introductory video or class discussion.
    - For more advanced learners, have them read and summarize the key points from Mario Molina and Sherry Rowland's 1974 paper in the Journal *Nature*, in which they first described a link between CFCs and destruction of the ozone layer.
- Sample prompts to elicit student ideas and encourage discussion:
    - How does the ozone layer protect life on Earth, and what caused it to become depleted?
    - How was an ozone "hole" detected, and why is it over Antarctica?
    - How can we use Le Châtelier's principle to predict and explain shifts in the ozone equilibrium system caused by changes in CFC concentrations in the stratosphere?
    - What did the Montreal Protocol accomplish, and how do we know that our efforts to ban CFCs are having a positive effect on the ozone layer?

Common student misconceptions

Possible misconception: *All collisions between reacting particles result in reactions, and more total collisions mean a faster reaction rate.* Students may not realize that only a small fraction of the total collisions between reacting particles result in bond-breaking and rearrangement of atoms, because most collisions do not have the correct orientation *and* sufficient energy. In addition, they may not take into account that rate is a measure of change *over time*. This may lead them to think that simply increasing the total number of collisions increases reaction rate, when really an increase in *frequency* of successful collisions is required to increase reaction rate.
Critical concepts • Particles must *collide* in the *correct orientation* and with *sufficient energy* to break bonds in order for a reaction to occur. • Factors that increase the *frequency* and/or *average energy* of collisions between reacting particles increase reaction rates.
How to address this misconception Help students to visualize particle collisions using the PhET Reactions and Rates simulation. Encourage them to notice that most of the collisions, especially at low temperatures, do not result in formation of products. Demonstrate that adding more particles increases the frequency of collisions but has only a small impact on reaction rate if most collisions lack sufficient energy to reach the activation energy peak in the energy diagram.

Possible misconception: *When a reaction system reaches equilibrium, the forward and reverse reactions stop, and no new reactants or products are formed.* Students may think of equilibrium as an end state where forces are balanced, and no more change occurs.
Critical concepts • A reaction system reaches equilibrium when the rates of the forward and reverse reactions are equal. • Chemical equilibrium is a *dynamic* state where reactants continue to form products and vice versa.
How to address this misconception Use analogies and physical models to help students understand the dynamic nature of chemical equilibrium. Have students draw diagrams to analyze scenarios, like cars driving in both directions across a bridge or players being substituted in a basketball game, which are described in the teaching tips in Lesson 4. Students can physically model dynamic equilibrium by transferring water between two large containers simultaneously, as in this video. They can see that the amount of water in each large container remains constant once the system reaches equilibrium, even though liquid continues to be transferred from one to the other in both directions.

Possible misconception: *A reaction reaches equilibrium when the concentrations of reactants and products are equal.*

Students may think of the "equality" in equilibrium as being between the concentrations of reactants and products, rather than between the rates of the forward and reverse reactions.

Critical concepts

- A reaction system reaches equilibrium when the *rates* of the forward and reverse reactions are equal.
- The concentrations of reactants and products remain constant at equilibrium, because they are being consumed and produced at the same rate, but *they don't have to be equal to each other*.
- The ratio of reactant to product concentrations will shift if a stress is applied to a system at equilibrium.

How to address this misconception

As with the previous misconception, analogies and physical models can help students visualize equilibrium systems where the rates of the forward and reverse reactions are equal, but the concentrations of reactants and products are not equal. This video simulation shows very clearly that the amounts of water in the large beakers are constant, but not the same, when the system reaches equilibrium. Similarly, students can observe shifts to higher concentrations of reactants (pink) or products (blue) in the Cobalt Complex Ion Equilibrium video when the system restores equilibrium in response to a disturbance. Point out to students that we would expect the color to be a mixture of these two (purple) if the concentrations were always equal at equilibrium.

Unit resources

Student resources

- Endothermic and exothermic reactions: Use this Khan Academy video from Unit 4 (Chemical reactions) to review energy diagrams for exothermic and endothermic reactions.
- Thermal energy, temperature, and heat: Use this Khan Academy video from Unit 7 (Thermochemistry) to review the relationships between temperature, average kinetic energy, and particle motion.
- PhET Reactions and Rates: Use this simulation to explore collision theory.
- Enzymes: Use this Khan Academy video to learn more about enzymes as biological protein catalysts.
- What is chemical equilibrium?: Watch this TED Ed video to review key takeaways about equilibrium.
- Cobalt Complex Ion Equilibrium: Observe how changes in reactant concentration and temperature cause shifts in a reaction at equilibrium.
- Modeling Equilibrium Reactions and Simulation of dynamic equilibrium: Watch simulations using water to understand systems in a state of dynamic equilibrium.
- Acid Rain and Acid rain (Khan Academy): Watch these videos for an introduction to acid rain.
- Climate 101: Ozone Depletion: Watch this video for an introduction to ozone depletion.
- 2020 Weather Patterns Push Antarctic Ozone Hole to 12th-Largest on Record: Learn about the specific local atmospheric conditions that cause a hole to form in the ozone layer over Antarctica each year.
- NASA Ozone Watch, EPA, UNEP, National Geographic, and The Conversation: Use these resources to explore data and learn more about topics related to ozone depletion.
- 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

- Elephant Toothpaste Chemistry Demonstration and Elephant's Toothpaste Demonstration: Learn more about demonstrating the decomposition of hydrogen peroxide in the presence of a catalyst.
- Pink and Blue - A Colorful Chemical Balancing Act: Use this Flinn resource for details on setting up an equilibrium demonstration with cobalt(II) chloride.
- 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-PS1-4:** Develop a model to illustrate that the release or absorption of energy from a chemical reaction system depends upon the changes in total bond energy.
- **HS-PS1-5:** Apply scientific principles and evidence to provide an explanation about the effects of changing the temperature or concentration of the reacting particles on the rate at which a reaction occurs.
- **HS-PS1-6:** Refine the design of a chemical system by specifying a change in conditions that would produce increased amounts of products at equilibrium.

Disciplinary core ideas

- **HS-PS1.B.1:** Chemical processes, their rates, and whether or not energy is stored or released can be understood in terms of the collisions of molecules and the rearrangements of atoms into new molecules, with consequent changes in the sum of all bond energies in the set of molecules that are matched by changes in kinetic energy.
- **HS-PS1.B.2:** In many situations, a dynamic and condition-dependent balance between a reaction and the reverse reaction determines the numbers of all types of molecules present.
- **HS-PS3.B.4:** The availability of energy limits what can occur in any system.

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.
- **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.
- **Constructing explanations and designing solutions:** Students progress to explanations and designs that are supported by multiple and independent student-generated sources of evidence consistent with scientific ideas, principles, and theories.

Crosscutting concepts (CCCs) and their implementation

Crosscutting concept	Unit implementation
Systems and system models: Defining the system under study—specifying its boundaries and making explicitly a model of that system—provides tools for understanding and testing ideas that are applicable throughout science and engineering.	Students describe and apply a collision model to explain changes in reaction systems.
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 predict how changes in different factors affect chemical reaction rates and systems at equilibrium.

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 predict, observe, and quantify the flow of thermal energy and/or matter into, out of, and within systems as matter undergoes chemical reactions.
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.