AP CHEMISTRY

# UNIT 5

# Kinetics

**7–9%**
AP EXAM WEIGHTING

**~13–14**
CLASS PERIODS

UNIT 5

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**~13–14** CLASS PERIODS

# Kinetics

**ESSENTIAL QUESTIONS**

- Why are some reactions faster than other reactions?
- Why are some medications taken every 8 hours and others once a day?
- Why is food stored in a refrigerator, but bread dough is kept in a warm place to rise?
- How can the speed of a reaction be controlled by understanding the collisions that occur on the particle level?

## Developing Understanding

Unit 4 focused on chemical changes; in Unit 5 students will develop an understanding of the rates at which chemical changes occur and the factors that influence the rates. Those factors include the concentration of reactants, temperature, catalysts, and other environmental factors. Chemical changes are represented by chemical reactions, and the rates of chemical reactions are determined by the details of the molecular collisions. Rates of change in chemical reactions are observable and measurable. When measuring rates of change, students are measuring the concentration of reactant or product species as a function of time. These chemical processes may be observed in a variety of ways and often involve changes in energy as well. In subsequent units, students will describe the role of energy in changes in matter.

## Building the Science Practices

1.B 5.B 5.C 5.E 6.E

In prior units, students developed their ability to describe symbolic and quantitative information from representations (e.g., Lewis structures, chemical reactions) that illustrate both the particulate and macroscopic level of a chemical phenomenon. In Unit 5, students will build on these explanations and representations by constructing and describing rate laws consistent with experimental evidence. To that end, students will collect data by spectrophotometry and choose an appropriate mathematical routine to determine how concentration varies with time during the course of a reaction. In addition, students will examine proposed reaction mechanisms to determine if there is a match between observed experimental data and constructed rate law expressions. Students will learn to identify any intermediates or catalysts that are included in the reaction mechanism, as well as the rate-determining step, and be able to justify their claims. To do so, students must learn to construct and analyze energy profiles for chemical reactions and identify how such profiles may change with the addition of a catalyst.

## Preparing for the AP Exam

On the AP Exam, students must be able to navigate between experimental data (tabular or graphed), a given or constructed rate law, and a proposed mechanism. Students generally struggle with reading a graph of reactant concentration versus time and drawing appropriate conclusions (i.e., order and rate constant) from the graphed data. Specifically, students confuse the units of the graphs with the units represented in the chemical equation. Teachers can ensure that students have multiple opportunities to graph concentration versus time or concentration versus rate data (using appropriate increments and units for the axes). Once students learn how to graph this data, teachers can help them analyze the graphs to determine the order of a reaction.

SUGGESTED SKILL

*Argumentation*

**6.E**

Provide reasoning to justify a claim using connections between particulate and macroscopic scales or levels.

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 10: How Long Will That Marble Statue Last?**
- The Exam > **2023 Chief Reader Report**

TOPIC 5.1

# Reaction Rates

## Required Course Content

| LEARNING OBJECTIVE | ESSENTIAL KNOWLEDGE |
|---|---|
| **5.1.A** Explain the relationship between the rate of a chemical reaction and experimental parameters. | **5.1.A.1** The kinetics of a chemical reaction is defined as the rate at which an amount of reactants is converted to products per unit of time.<br>**5.1.A.2** The rates of change of reactant and product concentrations are determined by the stoichiometry in the balanced chemical equation.<br>**5.1.A.3** The rate of a reaction is influenced by reactant concentrations, temperature, surface area, catalysts, and other environmental factors. |

TOPIC 5.2

# Introduction to Rate Law

SUGGESTED SKILL

*Mathematical Routines*

5.C

Explain the relationship between variables within an equation when one variable changes.

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 11: What Is the Rate Law of the Fading of Crystal Violet Using Beer's Law?**
- The Exam > **2017 Chief Reader Report**

## Required Course Content

### LEARNING OBJECTIVE

**5.2.A**

Represent experimental data with a consistent rate law expression.

### ESSENTIAL KNOWLEDGE

**5.2.A.1**

Experimental methods can be used to monitor the amounts of reactants and/or products of a reaction over time and to determine the rate of the reaction.

**5.2.A.2**

The rate law expresses the rate of a reaction as proportional to the concentration of each reactant raised to a power.

**5.2.A.3**

The power of each reactant in the rate law is the order of the reaction with respect to that reactant. The sum of the powers of the reactant concentrations in the rate law is the overall order of the reaction.

**5.2.A.4**

The proportionality constant in the rate law is called the rate constant. The value of this constant is temperature dependent and the units reflect the overall reaction order.

**5.2.A.5**

Comparing initial rates of a reaction is a method to determine the order with respect to each reactant.

SUGGESTED SKILL

*Mathematical Routines*

**5.B**

Identify an appropriate theory, definition, or mathematical relationship to solve a problem.

AVAILABLE RESOURCES

- AP Chemistry Lab Manual > **Investigation 11: What Is the Rate Law of the Fading of Crystal Violet Using Beer's Law?**
- The Exam > **2022 Chief Reader Report**

TOPIC 5.3

# Concentration Changes Over Time

## Required Course Content

### LEARNING OBJECTIVE

**5.3.A**

Identify the rate law expression of a chemical reaction using data that show how the concentrations of reaction species change over time.

### ESSENTIAL KNOWLEDGE

**5.3.A.1**

The order of a reaction can be inferred from a graph of concentration of reactant versus time.

**5.3.A.2**

If a reaction is first order with respect to a reactant being monitored, a plot of the natural log (ln) of the reactant concentration as a function of time will be linear.

**5.3.A.3**

If a reaction is second order with respect to a reactant being monitored, a plot of the reciprocal of the concentration of that reactant versus time will be linear.

**5.3.A.4**

The slopes of the concentration versus time data for zeroth, first, and second order reactions can be used to determine the rate constant for the reaction.

Zeroth order:

EQN: $[A]_t - [A]_0 = -kt$

First order:

EQN: $\ln[A]_t - \ln[A]_0 = -kt$

Second order:

EQN: $1/[A]_t - 1/[A]_0 = kt$

*continued on next page*

## LEARNING OBJECTIVE

**5.3.A**

Identify the rate law expression of a chemical reaction using data that show how the concentrations of reaction species change over time.

## ESSENTIAL KNOWLEDGE

**5.3.A.5**

Half-life is a critical parameter for first order reactions because the half-life is constant and related to the rate constant for the reaction by the equation:

EQN: $t_{1/2} = 0.693/k$.

**5.3.A.6**

Radioactive decay processes provide an important illustration of first order kinetics.

SUGGESTED SKILL

*Mathematical Routines*

**5.E**

Determine a balanced chemical equation for a given chemical phenomena.

## TOPIC 5.4

# Elementary Reactions

## Required Course Content

| LEARNING OBJECTIVE | ESSENTIAL KNOWLEDGE |
|---|---|
| **5.4.A**<br>Represent an elementary reaction as a rate law expression using stoichiometry. | **5.4.A.1**<br>The rate law of an elementary reaction can be inferred from the stoichiometry of the particles participating in a collision.<br>**5.4.A.2**<br>Elementary reactions involving the simultaneous collision of three or more particles are rare. |

TOPIC 5.5
# Collision Model

SUGGESTED SKILL

*Argumentation*

6.E

Provide reasoning to justify a claim using connections between particulate and macroscopic scales or levels.

## Required Course Content

### LEARNING OBJECTIVE

**5.5.A**

Explain the relationship between the rate of an elementary reaction and the frequency, energy, and orientation of particle collisions.

### ESSENTIAL KNOWLEDGE

**5.5.A.1**

For an elementary reaction to successfully produce products, reactants must successfully collide to initiate bond-breaking and bond-making events.

**5.5.A.2**

In most reactions, only a small fraction of the collisions leads to a reaction. Successful collisions have both sufficient energy to overcome the activation energy requirements and orientations that allow the bonds to rearrange in the required manner.

**5.5.A.3**

The Maxwell-Boltzmann distribution curve describes the distribution of particle energies; this distribution can be used to gain a qualitative estimate of the fraction of collisions with sufficient energy to lead to a reaction, and also how that fraction depends on temperature.

SUGGESTED SKILL

*Representing Data and Phenomena*

3.B

Represent chemical substances or phenomena with appropriate diagrams or models (e.g., electron configuration).

AVAILABLE RESOURCES

- The Exam > **2017 Chief Reader Report**

# TOPIC 5.6
# Reaction Energy Profile

## Required Course Content

### LEARNING OBJECTIVE

**5.6.A**

Represent the activation energy and overall energy change in an elementary reaction using a reaction energy profile.

### ESSENTIAL KNOWLEDGE

**5.6.A.1**

Elementary reactions typically involve the breaking of some bonds and the forming of new ones.

**5.6.A.2**

The reaction coordinate is the axis along which the complex set of motions involved in rearranging reactants to form products can be plotted.

**5.6.A.3**

The energy profile gives the energy along the reaction coordinate, which typically proceeds from reactants, through a transition state, to products. The energy difference between the reactants and the transition state is the activation energy for the forward reaction.

**5.6.A.4**

The rate of an elementary reaction is temperature dependent because the proportion of particle collisions that are energetic enough to reach the transition state varies with temperature. The Arrhenius equation relates the temperature dependence of the rate of an elementary reaction to the activation energy needed by molecular collisions to reach the transition state.

***Exclusion Statement:*** *Calculations involving the Arrhenius equation will not be assessed on the AP Exam.*

TOPIC 5.7

# Introduction to Reaction Mechanisms

**SUGGESTED SKILL**

*Models and Representations*

**1.B**

Describe the components of and quantitative information from models and representations that illustrate both particulate-level and macroscopic-level properties.

## Required Course Content

### LEARNING OBJECTIVE

**5.7.A**

Identify the components of a reaction mechanism.

### ESSENTIAL KNOWLEDGE

**5.7.A.1**

A reaction mechanism consists of a series of elementary reactions, or steps, that occur in sequence. The components may include reactants, intermediates, products, and catalysts.

**5.7.A.2**

The elementary steps when combined should align with the overall balanced equation of a chemical reaction.

**5.7.A.3**

A reaction intermediate is produced by some elementary steps and consumed by others, such that it is present only while a reaction is occurring.

**5.7.A.4**

Experimental detection of a reaction intermediate is a common way to build evidence in support of one reaction mechanism over an alternative mechanism.

***Exclusion Statement:*** *Collection of data pertaining to detection of a reaction intermediate will not be assessed on the AP Exam.*

SUGGESTED SKILL

*Mathematical Routines*

**5.B**

Identify an appropriate theory, definition, or mathematical relationship to solve a problem.

AVAILABLE RESOURCES

- The Exam > **2022 Chief Reader Report**

# TOPIC 5.8
# Reaction Mechanism and Rate Law

## Required Course Content

### LEARNING OBJECTIVE

**5.8.A**

Identify the rate law for a reaction from a mechanism in which the first step is rate limiting.

### ESSENTIAL KNOWLEDGE

**5.8.A.1**

For reaction mechanisms in which each elementary step is irreversible, or in which the first step is rate limiting, the rate law of the reaction is set by the molecularity of the slowest elementary step (i.e., the rate-limiting step).

***Exclusion Statement:*** *Collection of data pertaining to detection of a reaction intermediate will not be assessed on the AP Exam.*

TOPIC 5.9
# Pre-Equilibrium Approximation

SUGGESTED SKILL

*Mathematical Routines*

5.B

Identify an appropriate theory, definition, or mathematical relationship to solve a problem.

AVAILABLE RESOURCES

- The Exam > **2019 Chief Reader Report**

## Required Course Content

| LEARNING OBJECTIVE | ESSENTIAL KNOWLEDGE |
|---|---|
| **5.9.A** Identify the rate law for a reaction from a mechanism in which the first step is not rate limiting. | **5.9.A.1** If the first elementary reaction is not rate limiting, approximations (such as pre-equilibrium) must be made to determine a rate law expression. |

SUGGESTED SKILL

*Representing Data and Phenomena*

3.B

Represent chemical substances or phenomena with appropriate diagrams or models (e.g., electron configuration).

TOPIC 5.10
# Multistep Reaction Energy Profile

## Required Course Content

| LEARNING OBJECTIVE | ESSENTIAL KNOWLEDGE |
| --- | --- |
| 5.10.A<br>Represent the activation energy and overall energy change in a multistep reaction with a reaction energy profile. | 5.10.A.1<br>Knowledge of the energetics of each elementary reaction in a mechanism allows for the construction of an energy profile for a multistep reaction. |

## TOPIC 5.11
# Catalysis

**SUGGESTED SKILL**

*Argumentation*

**6.E**

Provide reasoning to justify a claim using connections between particulate and macroscopic scales or levels.

**AVAILABLE RESOURCES**

- The Exam > **2021 Chief Reader Report**

## Required Course Content

### LEARNING OBJECTIVE

**5.11.A**

Explain the relationship between the effect of a catalyst on a reaction and changes in the reaction mechanism.

### ESSENTIAL KNOWLEDGE

**5.11.A.1**

In order for a catalyst to increase the rate of a reaction, the addition of the catalyst must increase the number of effective collisions and/or provide a reaction path with a lower activation energy relative to the original reaction coordinate.

**5.11.A.2**

In a reaction mechanism containing a catalyst, the net concentration of the catalyst is constant. However, the catalyst will frequently be consumed in the rate-determining step of the reaction, only to be regenerated in a subsequent step in the mechanism.

**5.11.A.3**

Some catalysts accelerate a reaction by binding to the reactant(s). The reactants are either oriented more favorably or react with lower activation energy. There is often a new reaction intermediate in which the catalyst is bound to the reactant(s). Many enzymes function in this manner.

**5.11.A.4**

Some catalysts involve covalent bonding between the catalyst and the reactant(s). An example is acid-base catalysis, in which a reactant or intermediate either gains or loses a proton. This introduces a new reaction intermediate and new elementary reactions involving that intermediate.

**5.11.A.5**

In surface catalysis, a reactant or intermediate binds to, or forms a covalent bond with, the surface. This introduces elementary reactions involving these new bound reaction intermediate(s).