AP Chemistry Unit 7, Topic 1

Introduction to Equilibrium

📚 Lesson Date: January 3, 2026

Duration: 60 minutes
Core Concepts: Reversibility, Dynamic Equilibrium & Closed Systems

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CONCEPT 1: Reversibility of Processes

Understanding forward and reverse reactions

What is a Reversible Process?

A **reversible process** is one that can proceed in both the **forward**

direction and the **reverse direction** simultaneously.
Unlike irreversible reactions that go to completion (100% products), reversible reactions reach a state where both reactants and products coexist.

General Form of a Reversible Reaction

$$A + B \rightleftharpoons C + D$$

- **Forward Reaction:** $A + B \rightarrow C + D$
- **Reverse Reaction:** $C + D \rightarrow A + B$

The double arrow ($\rightleftharpoons$) indicates the reaction can proceed in both directions!

🔄 Key Characteristics of Reversible Processes

- ✓ **Bidirectional:** Can proceed forward AND backward
- ✓ **Incomplete:** Do not go 100% to products; reactants remain
- ✓ **Simultaneous:** Both directions occur at the same time
- ✓ **Dynamic:** Continuous molecular activity even when macroscopic properties are constant
- ✓ **Equilibrium State:** Eventually reach a state where forward and reverse rates are equal

Physical Equilibria Examples

Example 1: Liquid-Vapor Equilibrium

System: Water in a sealed container

$$H_2O(l) \rightleftharpoons H_2O(g)$$

Forward Process (Evaporation):

- Liquid water molecules gain energy
- Escape from liquid surface into gas phase
- $H_2O(l) \rightarrow H_2O(g)$

Reverse Process (Condensation):

- Water vapor molecules lose energy
- Return to liquid phase
- $H_2O(g) \rightarrow H_2O(l)$

> **At Equilibrium: Rate of evaporation = Rate of condensation**
> **The amount of liquid and vapor remain constant, but molecules continuously move between phases!**

Example 2: Dissolution Equilibrium

System: Solid salt in saturated solution

$$NaCl(s) \rightleftharpoons Na^+(aq) + Cl^-(aq)$$

Forward Process (Dissolution):

- Solid NaCl crystals break apart
- Na^+ and Cl^- ions enter solution

Reverse Process (Precipitation/Crystallization):

- Aqueous ions collide and form solid

- Ions leave solution and join crystal

> **At Equilibrium: Rate of dissolution = Rate of precipitation**
> **The concentration of ions stays constant, but ions continuously dissolve and crystallize!**

Chemical Equilibria Examples

Example 3: Haber Process (Ammonia Synthesis)

Industrial production of ammonia:

$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$$

Forward Reaction (Synthesis):

- Nitrogen and hydrogen combine
- Ammonia is produced

Reverse Reaction (Decomposition):

- Ammonia breaks down
- Forms nitrogen and hydrogen

> ⚠️ **Important:** Even in industrial reactors, some NH_3 decomposes back to reactants. The reaction never goes 100% to completion. This is why reaction conditions (temperature, pressure, catalysts) must be carefully controlled!

Example 4: Acid-Base Proton Transfer

Weak acid dissociation:

$$CH_3COOH(aq) + H_2O(l) \rightleftharpoons CH_3COO^-(aq) + H_3O^+(aq)$$

Forward Reaction:

- Acetic acid donates proton (H^+) to water
- Forms acetate ion and hydronium ion

Reverse Reaction:

- Hydronium ion donates proton to acetate
- Re-forms acetic acid and water

At Equilibrium: Both molecular acetic acid AND ions coexist in solution. This is why weak acids are only partially dissociated!

CONCEPT 2: Dynamic Nature of Equilibrium

Equal forward and reverse reaction rates

What Does "Dynamic Equilibrium" Mean?

Dynamic equilibrium is a state where:

1. The forward and reverse reactions **continue to occur** (not stopped!)
2. The **rates** of forward and reverse reactions are **equal**
3. The **concentrations** of all species remain **constant** over time

⚖️ The Fundamental Equilibrium Condition

$$\text{Rate}_{\text{forward}} = \text{Rate}_{\text{reverse}}$$

This is THE defining characteristic of equilibrium!

- **✓ When forward rate = reverse rate → concentrations stop changing**
- **✓ When forward rate ≠ reverse rate → NOT at equilibrium (still changing)**

⚠️ Common Misconception

Equilibrium does **NOT** mean the concentrations are equal!
It means the **RATES** are equal.
You can have very different amounts of reactants vs products at equilibrium.

Analogy: The Crowded Subway Platform

Imagine a subway platform at rush hour:
People entering platform: (Forward "reaction")

- Constant stream of people arriving from street

People boarding trains: (Reverse "reaction")

- Constant stream of people leaving on trains

Dynamic Equilibrium Achieved When:

- Rate of people arriving = Rate of people leaving
- The number of people on platform stays constant

- BUT people are continuously arriving AND leaving!
- The platform is NOT static - there's constant motion

> **This is exactly like chemical equilibrium:**
> **Reactions continue, but concentrations stay constant because the rates are balanced!**

Why Both Rates Must Be Non-Zero

🔬 Molecular-Level Activity at Equilibrium

Consider the equilibrium:

$$\mathbf{A + B \rightleftharpoons C + D}$$

At Equilibrium (Molecular View):

- ✓ A and B molecules are continuously colliding and forming C and D
- ✓ C and D molecules are continuously colliding and forming A and B
- ✓ Both reactions happen at the same rate
- ✓ Net result: No change in amounts of any species

❌ WRONG Idea	✅ CORRECT Idea
"At equilibrium, all reactions stop." This is completely false! Reactions never stop - they	"At equilibrium, forward and reverse reactions continue at equal rates." This is dynamic equilibrium! Molecular activity continues forever.

continue at equal rates.	

Example: Reaching Equilibrium Over Time

Scenario: Start with only reactants A and B

$$\mathbf{A + B \rightleftharpoons C + D}$$

Time = 0 (Initial):

- [A] and [B] are high, [C] and [D] = 0
- Forward rate is high (lots of A and B colliding)
- Reverse rate = 0 (no C or D to react)
- Net direction: Forward (products forming)

Time = t (During approach to equilibrium):

- [A] and [B] decrease, [C] and [D] increase
- Forward rate decreases (less A and B available)
- Reverse rate increases (more C and D available)
- Net direction: Still forward, but slowing down

Time = t_{eq} (At Equilibrium):

- [A], [B], [C], and [D] all constant (not changing)
- Forward rate = Reverse rate (equal!)
- Both rates are non-zero
- Net change: Zero (no net change, but reactions continue!)

CONCEPT 3: Macroscopic vs.

Microscopic Properties

Observable properties vs. molecular-level activity

Two Different Perspectives on Equilibrium

When we study equilibrium, we can view it from two different scales:

1. **Macroscopic (Observable):** What we can see and measure in the lab
2. **Microscopic (Molecular):** What's happening at the atomic/molecular level

👁️ MACROSCOPIC VIEW

Definition: Observable, measurable properties that we can detect with our senses or instruments

At Equilibrium, These Are CONSTANT:

- ✓ Concentrations of all species
- ✓ Partial pressures of gases
- ✓ Color of the solution
- ✓ pH of the system
- ✓ Temperature (if no heat exchange)
- ✓ Total pressure (in closed system)

Key Point: To an observer, the system appears static and unchanging!

🔬 MICROSCOPIC VIEW

Definition: Molecular-level processes that we cannot directly observe but know are occurring

At Equilibrium, These CONTINUE:

- ✓ Molecular collisions between reactant particles
- ✓ Formation of products from reactants
- ✓ Decomposition of products back to reactants
- ✓ Bond breaking and bond forming
- ✓ Energy transfer between molecules
- ✓ Movement of all particles

Key Point: At the molecular level, there is constant activity and motion!

🎯 Connecting the Two Views

The Big Picture:

Constant Macroscopic Properties ≠ No Molecular Activity

Even though we observe no change in concentration, color, pressure, etc., at the molecular level there is continuous reaction.

Why don't we see changes?

Because the forward and reverse reactions occur at equal rates:

- For every molecule of product formed (forward), another molecule of product decomposes (reverse)
- For every reactant molecule consumed (forward), another reactant molecule

is re-formed (reverse)

- Net result: No observable change, but constant molecular activity

Example: NO_2/N_2O_4 Equilibrium

Reversible Reaction:

$$2NO_2(g) \rightleftharpoons N_2O_4(g)$$
$$\text{(brown)} \qquad \text{(colorless)}$$

🔵 **Macroscopic Observation:**

- At equilibrium, the color of the gas mixture stays constant
- The mixture appears as a steady brown color - not getting darker or lighter
- $[NO_2]$ and $[N_2O_4]$ remain constant over time

🔴 **Microscopic Reality:**

At the molecular level:

- NO_2 molecules are continuously colliding and forming N_2O_4
- N_2O_4 molecules are continuously decomposing back to NO_2
- Both processes happen at the same rate

Conclusion: The unchanging brown color (macroscopic) masks the continuous interconversion of NO_2 and N_2O_4 (microscopic).

Example: Saturated Solution

System: Solid sugar in saturated sugar solution

$$C_{12}H_{22}O_{11}(s) \rightleftharpoons C_{12}H_{22}O_{11}(aq)$$

👁️ **Macroscopic Observation:**

- The amount of solid sugar at the bottom stays constant
- The concentration of dissolved sugar stays constant
- The solution appears unchanging

🔬 **Microscopic Reality:**

- Sugar molecules at the crystal surface are continuously dissolving into solution
- Dissolved sugar molecules are continuously crystallizing back onto the solid
- Rate of dissolution = Rate of crystallization

> **If you could track individual molecules with radioactive tracers, you'd see them constantly moving between solid and solution!**

📊 Summary Table

Property	Macroscopic (Observable)	Microscopic (Molecular)
Change Over Time	❌ No change (constant)	✓ Continuous change
Concentrations	Constant	Individual molecules changing
Reactions	Appear stopped	Both directions ongoing

Rate	Net rate = 0	Both rates > 0 and equal
Energy	No net energy change	Energy constantly exchanged

CONCEPT 4: Closed Systems & Graphical Analysis

Requirements for equilibrium and interpreting graphs

Why Closed Systems?

> **Equilibrium can ONLY be established in a closed system.**

🔒 Closed System Definition

Closed System: A system where no matter can enter or leave, but energy can be exchanged with surroundings.

✅ Closed System Examples	❌ Open System Examples
• Sealed flask with stopper • Closed container with tight lid • Sealed gas cylinder • Closed reaction vessel → **CAN establish equilibrium**	• Open beaker (gases can escape) • Flowing river • Open flame • Test tube without stopper → **CANNOT establish equilibrium**

Why is this important?
If reactants or products can escape, concentrations cannot remain constant. The system will never reach a state where forward rate = reverse rate because the amounts of substances keep changing due to loss to surroundings.

Example: Water Evaporation

$$H_2O(l) \rightleftharpoons H_2O(g)$$

❌ Open Container	✅ Sealed Container
Water in an open beaker: • Water evaporates (forward) • Water vapor escapes to atmosphere • Very little condensation (reverse) • Eventually, all water evaporates **NO equilibrium established!** The system goes to completion (all liquid → gas).	Water in a sealed bottle: • Water evaporates (forward) • Water vapor cannot escape • Vapor condenses back (reverse) • Equilibrium established **Equilibrium achieved!** Both liquid and vapor coexist with constant amounts.

Graphical Analysis: Concentration vs. Time

Graphs of concentration vs. time are powerful tools for identifying when a system reaches equilibrium.

Concentration vs. Time Graph

[Imagine a graph with Time on x-axis and Concentration on y-axis]
- Reactants line starts high and decreases, then levels off
- Products line starts at zero and increases, then levels off
- Both lines become horizontal at equilibrium
- Vertical line marked "EQUILIBRIUM" where lines flatten
- Labels: "[Reactants] constant" and "[Products] constant"

Key Features to Identify Equilibrium:

- ✓ Lines level off (become horizontal)
- ✓ Concentrations remain constant over time
- ✓ Both reactants AND products present (not zero)
- ✓ No further change in amounts after equilibrium reached

Graphical Analysis: Reaction Rate vs. Time

Another way to identify equilibrium is by graphing the rates of forward and reverse reactions over time.

Reaction Rate vs. Time Graph

[Imagine a graph with Time on x-axis and Reaction Rate on y-axis]
- $\text{Rate}_{\text{forward}}$ line starts high and decreases
- $\text{Rate}_{\text{reverse}}$ line starts at zero and increases
- Both lines converge to same value at equilibrium
- Vertical line marked "EQUILIBRIUM" where rates equal
- Label: "Rates Equal"

Key Features to Identify Equilibrium:

- ✓ Lines converge to the same value
- ✓ $\text{Rate}_{\text{forward}} = \text{Rate}_{\text{reverse}}$ (lines meet)

- ✓ Both rates remain constant after convergence
- ✓ Both rates are non-zero at equilibrium

📊 Interpreting Equilibrium Graphs

Graph Type	Before Equilibrium	At Equilibrium
[Concentration] vs. Time	• Lines are curved/changing • Concentrations increasing or decreasing	• Lines are horizontal/flat • Concentrations constant
Rate vs. Time	• Forward and reverse rates different • Lines not equal	• Forward and reverse rates equal • Lines converge to same value
Net Direction	• Net reaction toward products OR reactants • System changing	• No net reaction • System appears static

📚 Key Takeaways - Unit 7.1

1. Reversible processes proceed in both forward and reverse directions simultaneously (⇌)
2. Dynamic equilibrium: $\text{Rate}_{\text{forward}} = \text{Rate}_{\text{reverse}}$ (THE defining condition)
3. At equilibrium, macroscopic properties are constant but microscopic activity continues
4. Equilibrium requires a closed system (no matter can enter or leave)

5. Concentration vs. time graphs show equilibrium when lines become horizontal
6. Rate vs. time graphs show equilibrium when forward and reverse rates converge

📖 Study Resources

Official AP Chemistry Study Guide:
Unit 7 Part 1 Study Guide - AP Chemistry Rescue