INTERNATIONAL COLLEGE OF PHARMACEUTICAL INNOVATION

国际创新药学院

Fundamentals of Medicinal and Pharmaceutical Chemistry

FUNCHEM.24 Molecularities of reactions, reaction mechanisms and reaction orders and the Arrhenius equation.

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Learning Objectives

- In terms of reaction mechanisms, define ‘reaction mechanism’, ‘elementary step’, ‘rate determining step’ and ‘molecularity’.
- Deduce the order of a reaction from a single step reaction.
- Deduce the order of a reaction from the rate determining step of a multi-step mechanism.
- Draw and explain an energy profile diagram for a single step and multi-step mechanism, clearly indicating activation energy and enthalpy change involved.
- Recall the Arrhenius equation, both in exponential and natural log form, clearly defining all parameters.
- Given a set of data of rate constants versus temperature, employ the Arrhenius equation in graphical form, to work out the activation energy and frequency factor.

Factors Affecting Reaction Rates

1. **Concentration** of reactants e.g. use of penicillin
   - Experimental Rate Equation

2. **Temperature** e.g. fever, open heart surgery, surface anaesthetic
   Arrhenius Equation

3. **Catalysis** e.g. biological enzymes

4. **Surface area** e.g. chewing, bile, crushed aspirin!

Reaction Mechanisms

In general:

Overall Balanced Chemical Equation

Overall: $2NO_{(g)} + O_{2(g)} \longrightarrow 2NO_{2(g)}$

- does not tell you **how** the reaction takes place.
- represents the sum of a series of simple reactions - **elementary steps**

Reaction Mechanisms – An Example

Overall: $2NO_{(g)} + O_{2(g)} \longrightarrow 2NO_{2(g)}$

<u>Mechanism</u>

Step 1 $2NO_{(g)} \longrightarrow N_2O_{2(g)}$

Step 2 $N_2O_{2(g)} + O_{2(g)} \longrightarrow 2NO_2$

Overall: $\mathbf{2NO_{(g)} + O_{2(g)} \longrightarrow 2NO_{2(g)}}$

(same as above)

Definitions

Reaction Mechanism

- tells you the sequence of elementary steps that leads to product formation.

Elementary Step

- each individual step in the overall reaction.

Molecularity

- tells you the number of molecules reacting in an elementary step.

Definitions

Unimolecular = 1 reactant

Bimolecular = 2 reactants

Termolecular = 3 reactants

Most reactions are <u>multi-step</u>
i.e. made up of a sequence of elementary steps

1. The slowest elementary step is the **RATE DETERMINING STEP (RDS)**

2. The **order of reaction** is deduced from this step

<u>Mechanism</u>

1.	**A + B**	$\longrightarrow$	**X + Y**	**Slow**	**RDS**
2.	X + B	$\longrightarrow$	Y	Fast	
3.	X + Y	$\longrightarrow$	C	Fast	

Rate equations and reaction mechanisms

For a **single step** reaction mechanism, reaction order can be predicted directly from the stoichiometry.

Examples of single step mechanisms

1. $\mathbf{A \longrightarrow P}$

Rate depends only on [A]

$\boxed{\text{Rate} = k[A] \quad (1^{st} \text{ order})}$

More examples of single step mechanisms

2. $A + B \longrightarrow P$

$$\boxed{\text{Rate} = k[A][B] \quad (2^{nd}\text{ order})}$$

3. $2A \longrightarrow P$

$$\boxed{\text{Rate} = k[A]^2 \quad (2^{nd}\text{ order})}$$

4. $2A + B \longrightarrow P$

$$\boxed{\text{Rate} = k[A]^2[B] \quad (3^{rd}\text{ order})}$$

Rate equations and reaction mechanisms

If given a multi-step reaction mechanism and if told which is the rate-determining step, you can deduce the rate law.

RDS	Molecularity	Rate Law
$A \longrightarrow X$	Unimolecular	Rate = k[A]
$A + A \longrightarrow X$	Bimolecular	Rate = $k[A]^2$
$2A + B \longrightarrow X$	Termolecular	Rate = $k[A]^2[B]$

Reaction orders and mechanisms

If you know the rate equation,
you can predict the mechanism……

Example:

Overall Reaction : $A_2 + B_2 \longrightarrow 2AB$

Rate Equation : Rate $= k[A_2]^1$

$A_2 + B_2 \longrightarrow 2AB$ Told: Rate = $k[A_2]^1$

Which mechanism is correct ?

1.	$A_2 + B_2 \longrightarrow 2AB$		SLOW

2.	$B_2 \longrightarrow 2B$	SLOW
	$2B + A_2 \longrightarrow 2AB$	FAST

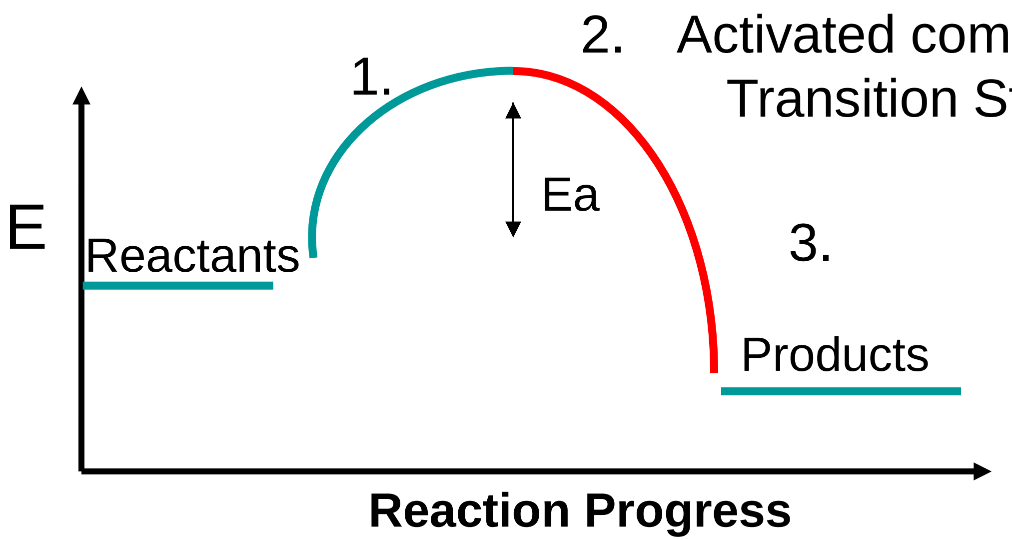
3.	$A_2 \longrightarrow 2A$	SLOW
	$2A + B_2 \longrightarrow 2AB$	FAST

Answer: Work out rate equation for RDS for each

3. Rate = $k[A_2]^1$

$\therefore$ 3 is correct mechanism

Energy Profile Diagram
What happens during a reaction?

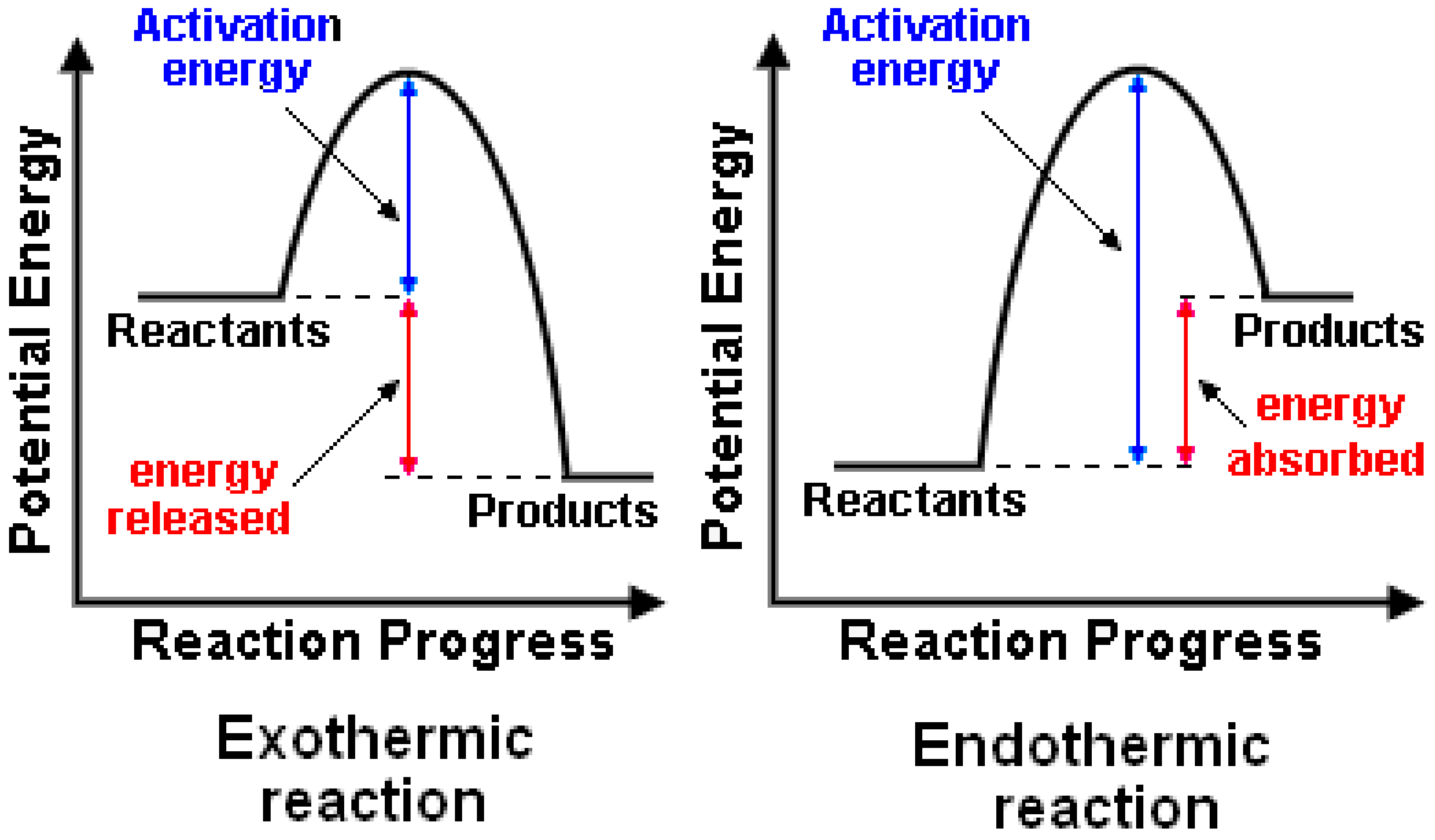


1. **Reactant molecules collide.**
   Bonds between atoms in molecules break.
   Energy required.

2. **Activated complex:** cannot be isolated, (very short-lived). May form products or may revert to reactants.

3. **Products forming.** Bonds are being made.
   Energy released. Exothermic reaction.

Energy Profile Diagrams



A Multi-Step Reaction

Overall Reaction: $CH_3CH{=}CH_2 + HBr \longrightarrow CH_3CHBrCH_3$

Mechanism:

1. $CH_3CH{=}CH_2 + HBr \longrightarrow CH_3CH^{+}CH_3 + Br^{-}$

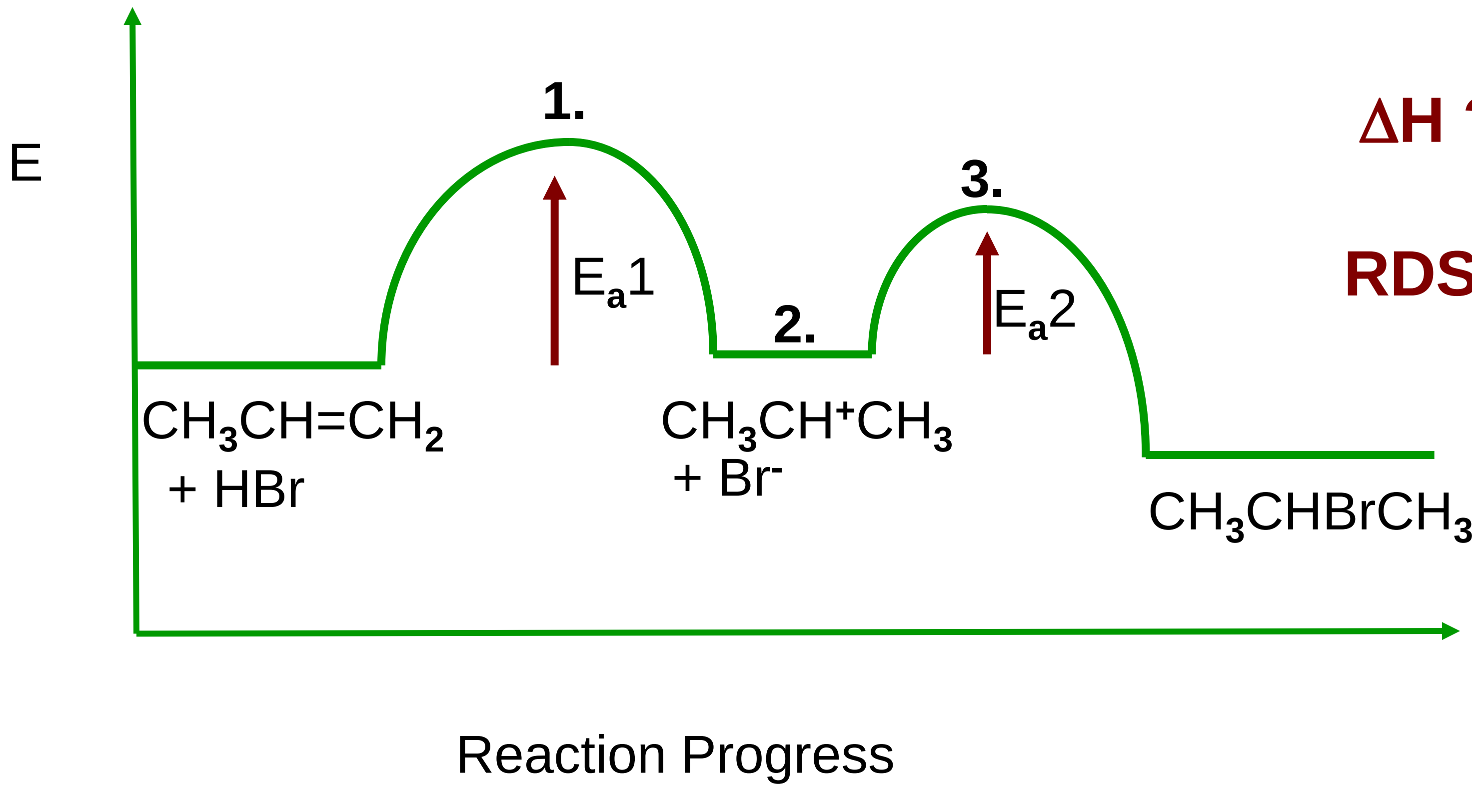
2. $CH_3CH^{+}CH_3 + Br^{-} \longrightarrow CH_3CHBrCH_3$

A Multi-Step Reaction

Mechanism:

1. $CH_3CH{=}CH_2 + HBr \longrightarrow CH_3CH^+CH_3 + Br^-$

2. $CH_3CH^+CH_3 + Br^- \longrightarrow CH_3CHBrCH_3$



ΔH ?

RDS?

Summary so far …….

1. Single-step reaction mechanism

$$\boxed{A + 2B \rightarrow C}$$

Look at balanced equation
Deduce rate equation

Rate = $k[A][B]^2$

Summary so far ....

2. Multi-step reaction mechanism

Look at mechanism

Find the rate-determining (slow) step

Deduce rate equation from the slow step

Overall $A + 2B \rightarrow C$

Mechanism

$A + B \rightarrow X + X$ (slow)

$X + B \rightarrow Y$ (fast)

$X + Y \rightarrow C$ (fast)

Rate = k[A][B]

Collision Theory and Arrhenius Equation

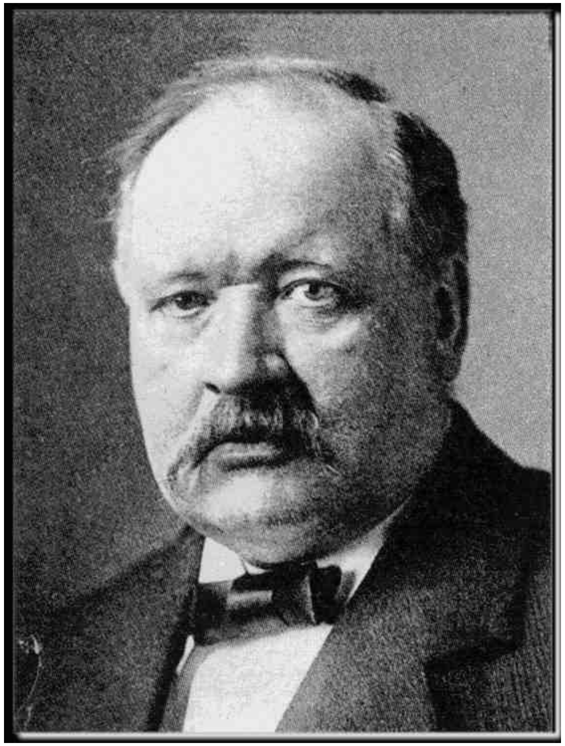
Rate of Reaction depends on:

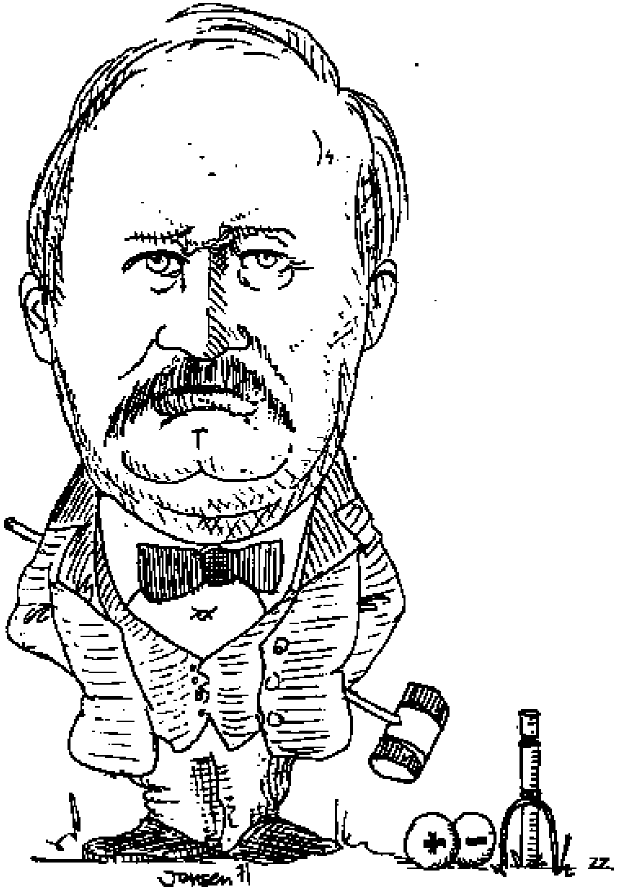
* Orientation of molecules
* Number/frequency of collisions
* Energy of collisions

Linked by Arrhenius equation

$$k = Ae^{-Ea/RT}$$

Collision Theory and Arrhenius Equation





Arrhenius studied reaction rates as a function of temperature, and in 1889 he introduced the concept of activation energy as the critical energy that chemicals need to react.

Collision Theory and Arrhenius Equation

Activation Energy

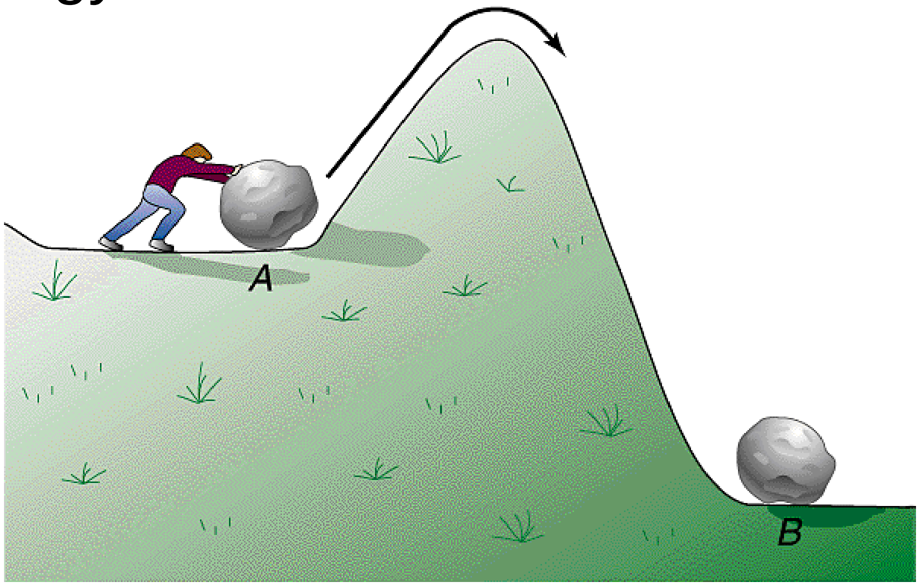
Arrhenius: molecules must possess a minimum amount of energy to react.

Why?

In order to form products, bonds must be broken in the reactants.

Bond breakage requires energy.

Activation energy, E_a, is the minimum energy required to initiate a chemical reaction.



$$k = Ae^{-Ea/RT}$$

k	=	rate constant
A	=	frequency factor
e	=	exponential
E_a	=	experimental activation energy
R	=	gas constant
T	=	temperature

$$k = Ae^{-Ea/RT}$$

Since $k = Ae^{-Ea/RT}$

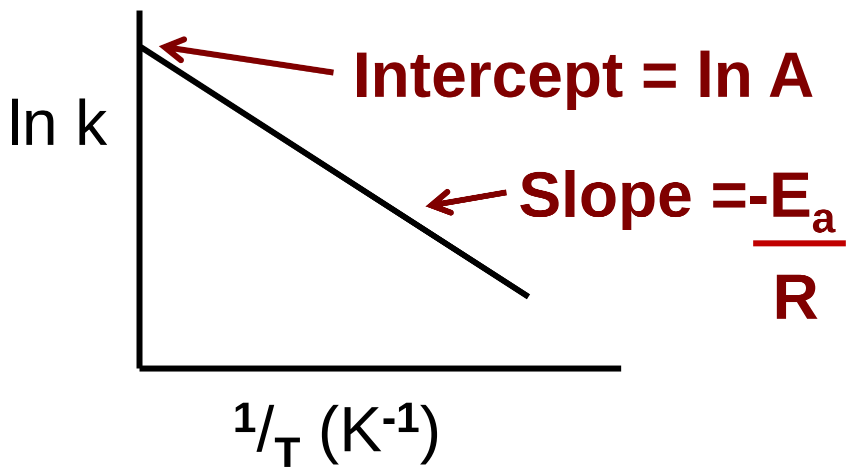
$$\ln k = \ln A - \frac{Ea}{RT}$$

$$\boxed{\begin{array}{c} \ln k = \dfrac{-Ea}{R} \cdot \dfrac{1}{T} + \ln A \\ \\ y = m\ x + c \end{array}}$$

$$k = Ae^{-Ea/RT}$$

$$\ln k = \frac{-Ea}{R}\,\frac{1}{T} + \ln A$$

$$y = m\,x + c$$



If you measure rate constant at different temperatures, you can work out activation energy.

Example

$$\ln k = \ln A - \frac{Ea}{RT}$$

Given how rate constant varies with temperature

T/Kelvin	500	520	540	560	580	600
$k/10^{-8}\ s^{-1}$	1.29	8.20	45.3	231	977	3910

Find activation energy and frequency factor

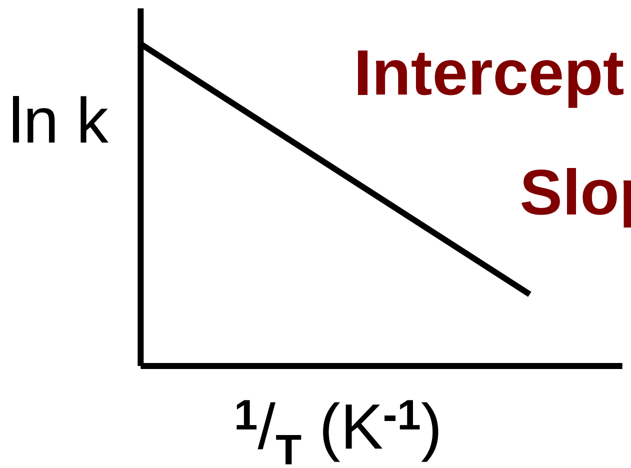
$1/T/K^{-1}$	2×10^{-3}	1.9×10^{-3}	1.85×10^{-3}	1.78×10^{-3}	1.72×10^{-3}	1.66×10^{-3}
$\ln k/10^{-8}$	-18.1	-16.3	-14.6	-12.9	-11.5	-10.1

Example:
Answer

Using Arrhenius equation:

$$\ln k = \frac{-E_a}{R} \cdot \frac{1}{T} + \ln A$$

$$y = m\,x + c$$



Intercept = ln A

Slope = $-\dfrac{E_a}{R}$

Summary of Kinetics So Far!

Reaction Rate Factors and Rate Equation

Reaction Order: Zero, First, Pseudo- First, Second

Determination of Reaction Order:

Initial Rates Method
Graphical method
Half Life Method

Collision Theory: Molecular Orientation
Frequency of Collisions
Energy of Collisions

Reaction mechanisms and energy profile diagrams

Arrhenius Equation: Work out activation energy

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