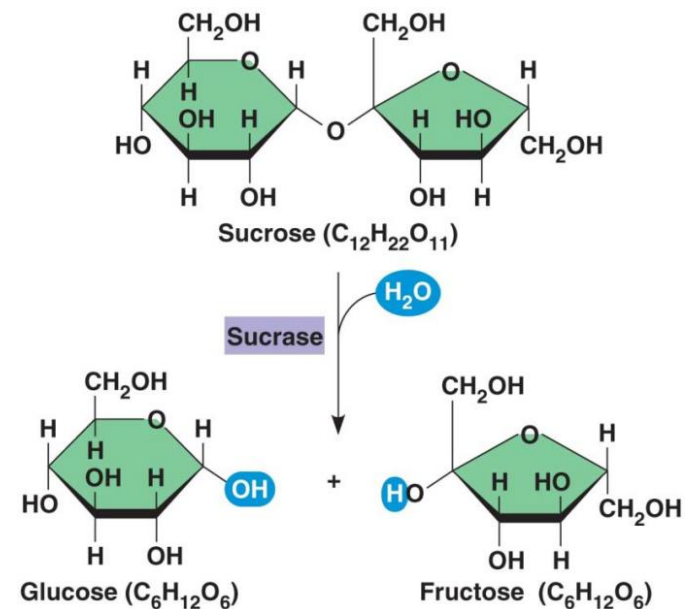


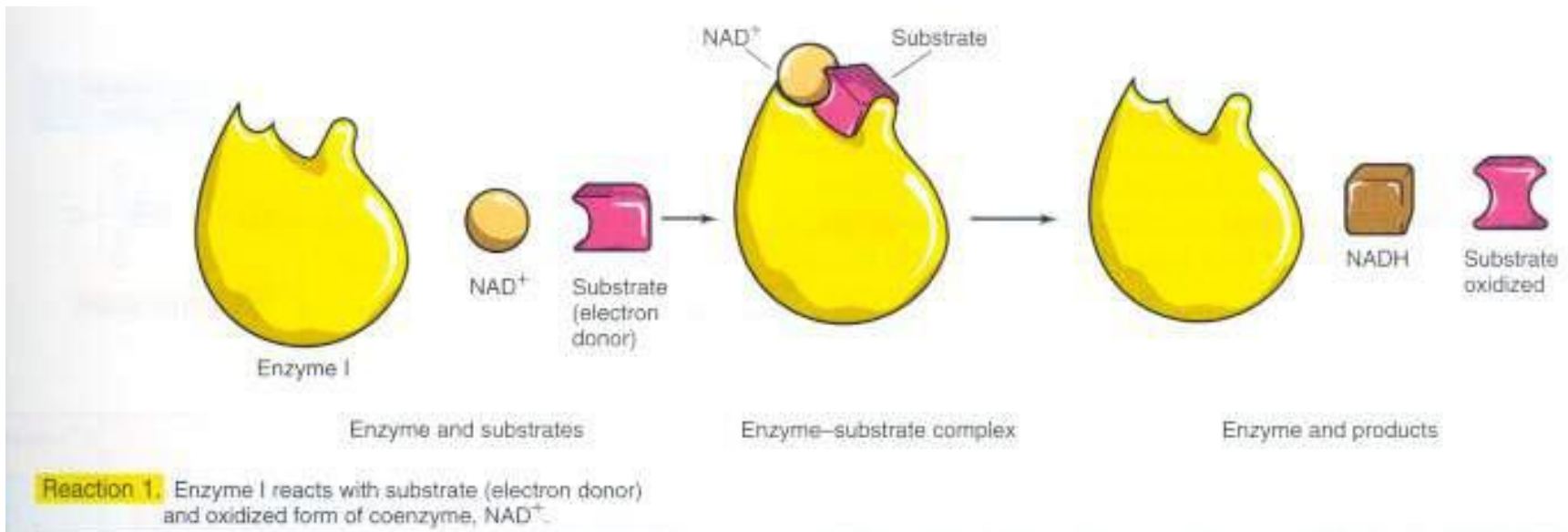
Ch. 3 효소

3.1 서론

- 효소: 촉매작용을 하는 고분자 단백질 (분자량: 15,000~수백만)
- cf) ribozyme or RNA 효소: 촉매특성을 갖는 RNA 분자들
- 화학촉매에 비해 높은 반응속도, 특이적, 다양 (2000개 이상)
- 명명: 기질명 뒤에 -ase, ex) urease, 반응명 뒤에 -ase, ex) alcohol dehydrogenase



- 완전효소 (holoenzyme): 비단백질기 포함 (Mg, Zn, Mn, Fe, NAD, FAD, CoA, 비타민), 순효소 (apoenzyme) + 보조인자
- 유사효소 (isoenzyme): 다른 분자구조를 갖지만 동일한 반응 촉매



EC (Enzyme Commission) Classification

1. Oxidoreductases (oxidation–reduction reactions)
2. Transferases (transfer of functional groups)
3. Hydrolases (hydrolysis reactions)
4. Lyases (addition to double bonds)
5. Isomerases (isomerization reactions)
6. Ligases (formation of bonds with ATP cleavage)

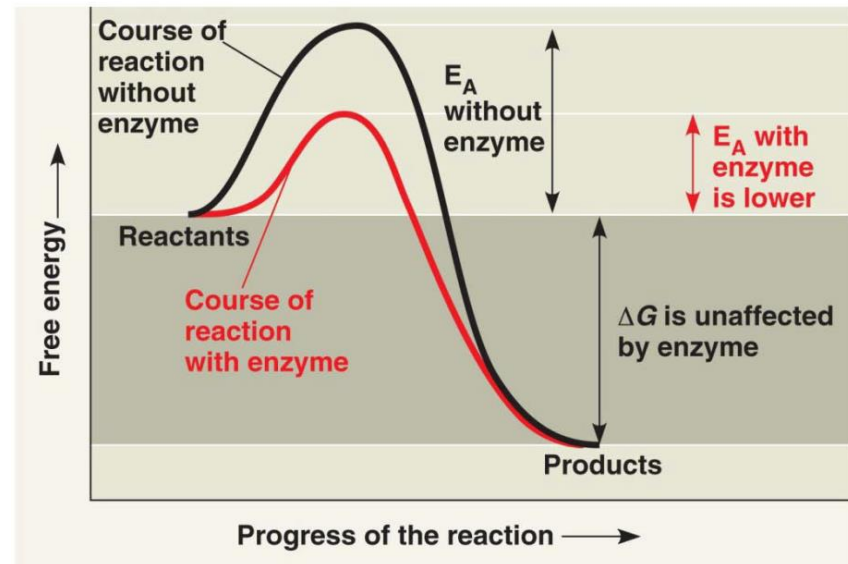
ex) alcohol dehydrogenase: EC 1.1.1.1.

→ Table 3.1

3.2 효소의 작용

- 기질과 결합, 효소-기질 복합체 형성, 활성화에너지를 낮춤.
- 자유에너지, 평형상수에 영향주지 않음.

과산화수소 분해반응	활성화에너지 (kcal/mol)
20°C 비촉매 반응	18
화학촉매 반응	13
효소촉매 반응 (catalase)	7

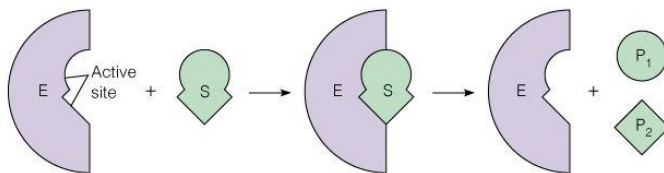


ES 복합체

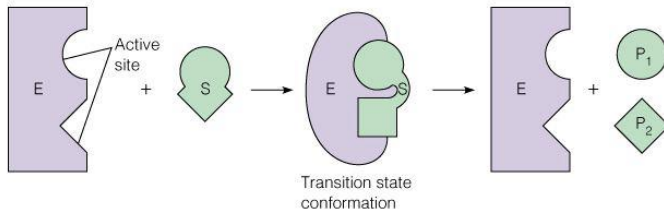
- X-선, 라만 분광기로 존재 확인
- 상호작용: van der Waals 결합, 수소결합.

활성부위 (active site)

- 기질과 특이적으로 결합하는 효소의 위치
- 열쇠-자물쇠 모형

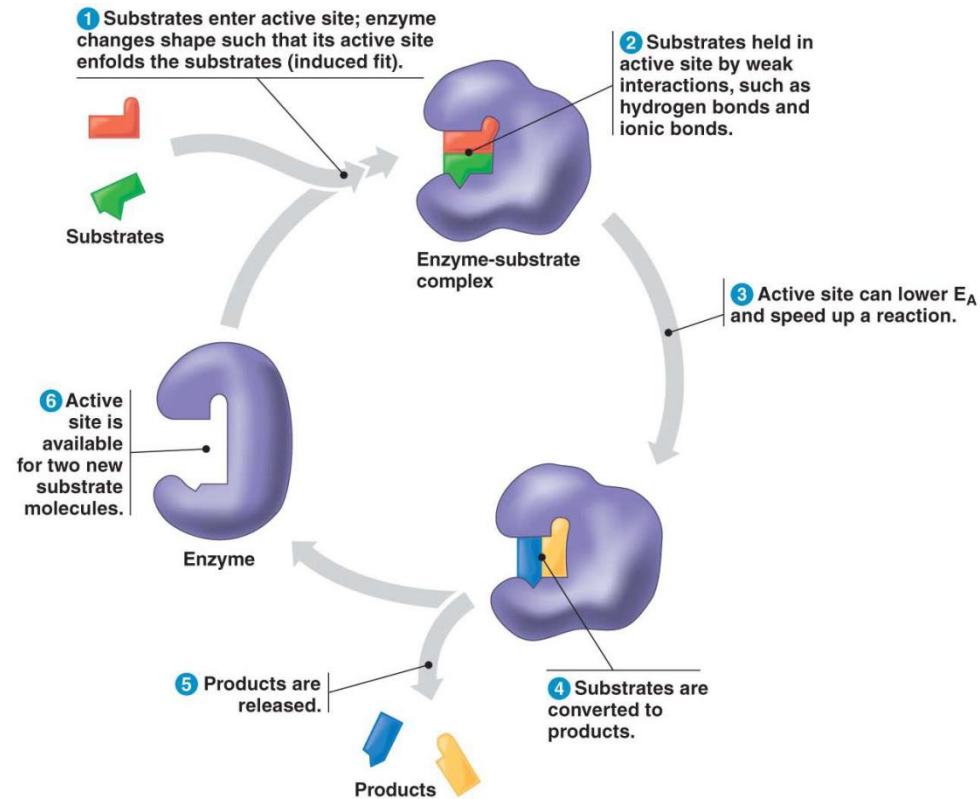


(a) Lock-and-key model

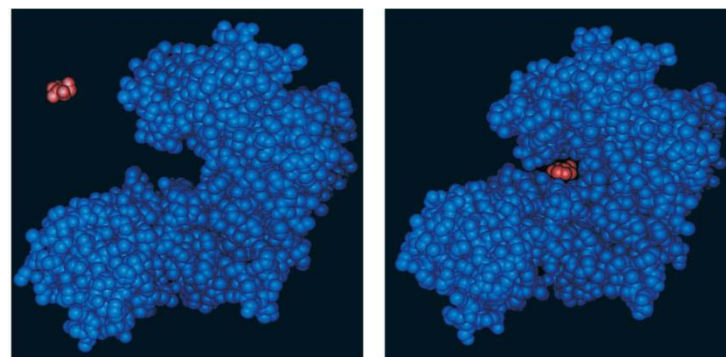
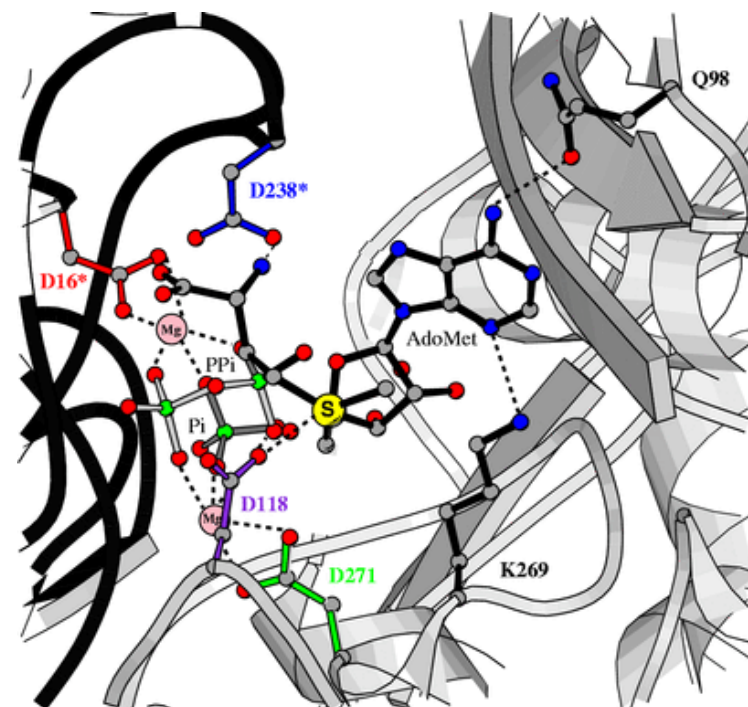


(b) Induced fit model

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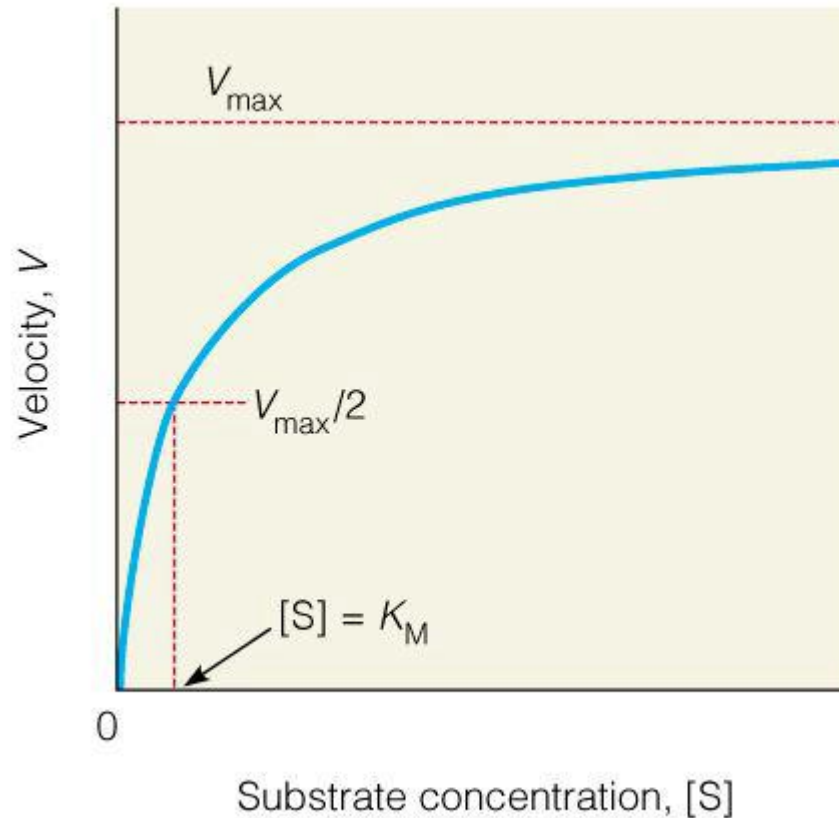


- 효소는 매우 큰 고분자이나, 실제 반응에 참여하는 부분은 작음
- 활성부위는 두 부분으로 구성: catalytic site, binding site
- 근접효과 (proximity effect): 효소가 활성부위와 근접하도록 기질을 끌어당김.
- 방향효과 (orientation effect): 반응속도 증가를 위해 특정 각도나 위치에서 기질과 결합
- ES 복합체 형성 → 효소의 3차 구조 변화



3.3 효소 속도론

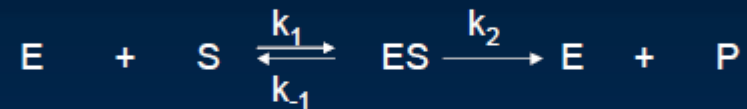
- Michaelis-Menten 속도론 (1913) or 포화속도론



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3.3 효소 속도론

Simple Mechanistic Model



$$v = \frac{d[P]}{dt} = k_2[ES] \quad (1)$$

$$\frac{d[ES]}{dt} = k_1[E][S] - k_{-1}[ES] - k_2[ES] \quad (2)$$

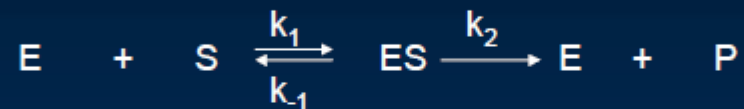
$$[E] = [E_0] - [ES] \quad (3)$$

3.3 효소 속도론

(1) Rapid Equilibrium Assumption

Assumption:

Rapid equilibrium between [E] and [S] to form [ES] complex



$$K'_m = \frac{k_{-1}}{k_1} = \frac{[E][S]}{[ES]} \quad (1)$$

$$[E] = [E_0] - [ES] \quad (2)$$

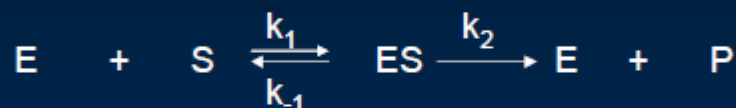
$$[ES] = \frac{[E_0][S]}{K'_m + [S]} \quad (3)$$

$$v = \frac{d[P]}{dt} = k_2 \frac{[E_0][S]}{K'_m + [S]} = \frac{V_m[S]}{K'_m + [S]} \quad (4)$$

3.3 효소 속도론

(2) Quasi-Steady-State Assumption

Assumption: $[E_0] \ll [S_0]$, $d[ES]/dt = 0$



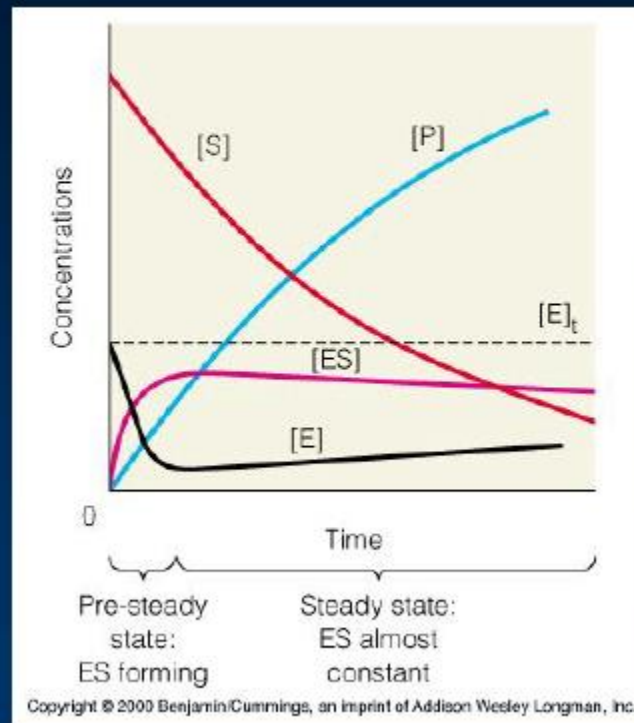
$$\frac{d[ES]}{dt} = k_1[E][S] - k_{-1}[ES] - k_2[ES] \quad (1)$$

$$[ES] = \frac{k_1[E][S]}{k_{-1} + k_2} = \frac{k_2[E_0][S]}{\frac{k_{-1} + k_2}{k_1} + [S]} \quad (2)$$

$$v = \frac{d[P]}{dt} = k_2[ES] = \frac{V_m[S]}{K_m + [S]} \quad (3)$$

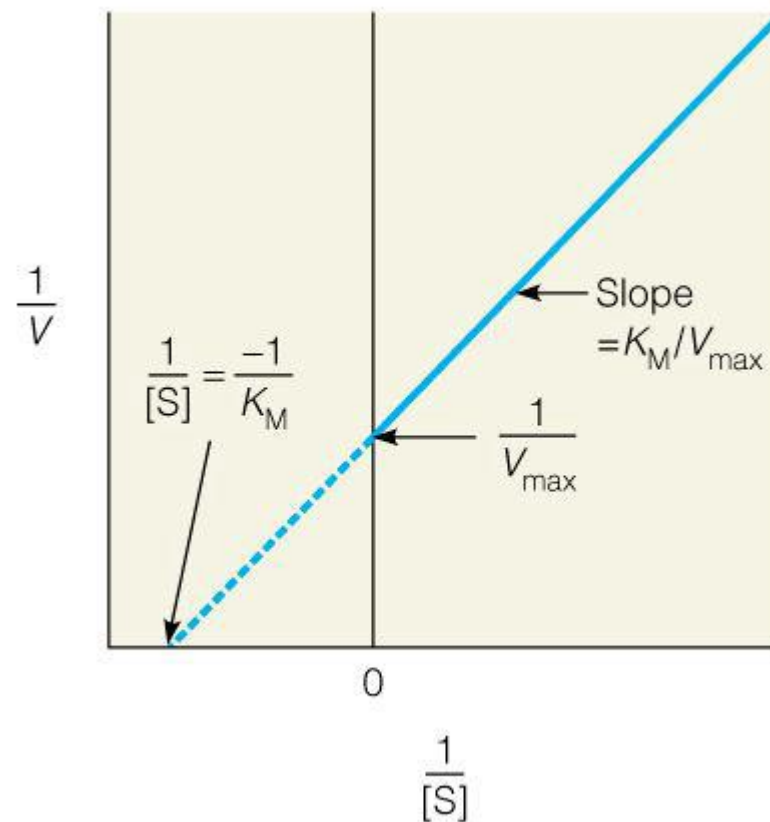
3.3 효소 속도론

(2) Quasi-Steady-State Assumption



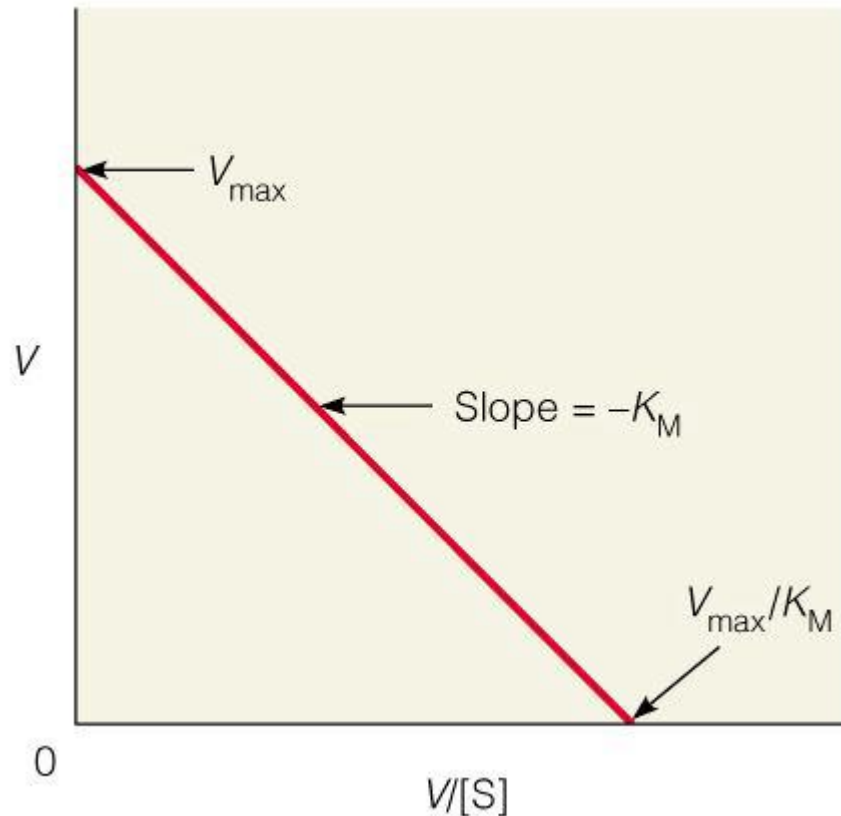
→ Figure 3. 4

- 이중역수 도표 (Lineweaver-Burk plot): v_{\max} 정확



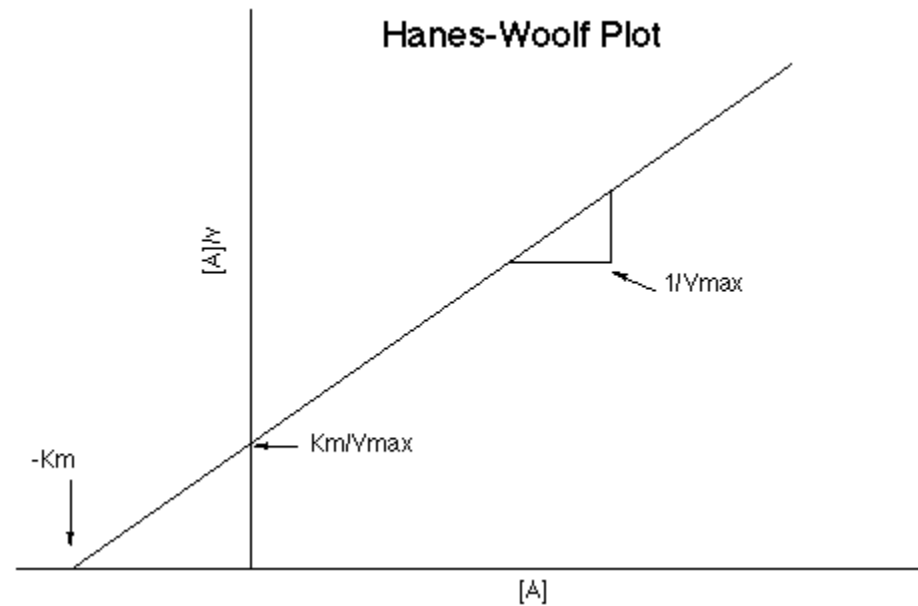
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- Eadie-Hofstee plot: K_M 정확



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- Hanes-Woolf plot: v_{max} 정확



- Batch kinetics

$$v = \frac{d[P]}{dt} = -\frac{d[S]}{dt} = \frac{v_{\max}[S]}{K_M + [S]}$$



$$-v_{\max}[S]dt = d[S](K_M + [S])$$

$$-v_{\max}dt = K_M \frac{d[S]}{[S]} + d[S]$$

$$v_{\max}dt = -d[S] - K_M \frac{d[S]}{[S]}$$

Integration

$$v_{\max}t = [S_0] - [S] + K_M \ln \frac{[S_0]}{[S]}$$

$$v_{\max} - \frac{[S_0] - [S]}{t} = \frac{K_M}{t} \ln \frac{[S_0]}{[S]}$$

Plot $\frac{1}{t} \ln \frac{[S_0]}{[S]}$ versus $\frac{[S_0] - [S]}{t}$

slope $-\frac{1}{K_M}$ intercept $\frac{v_{\max}}{K_M}$

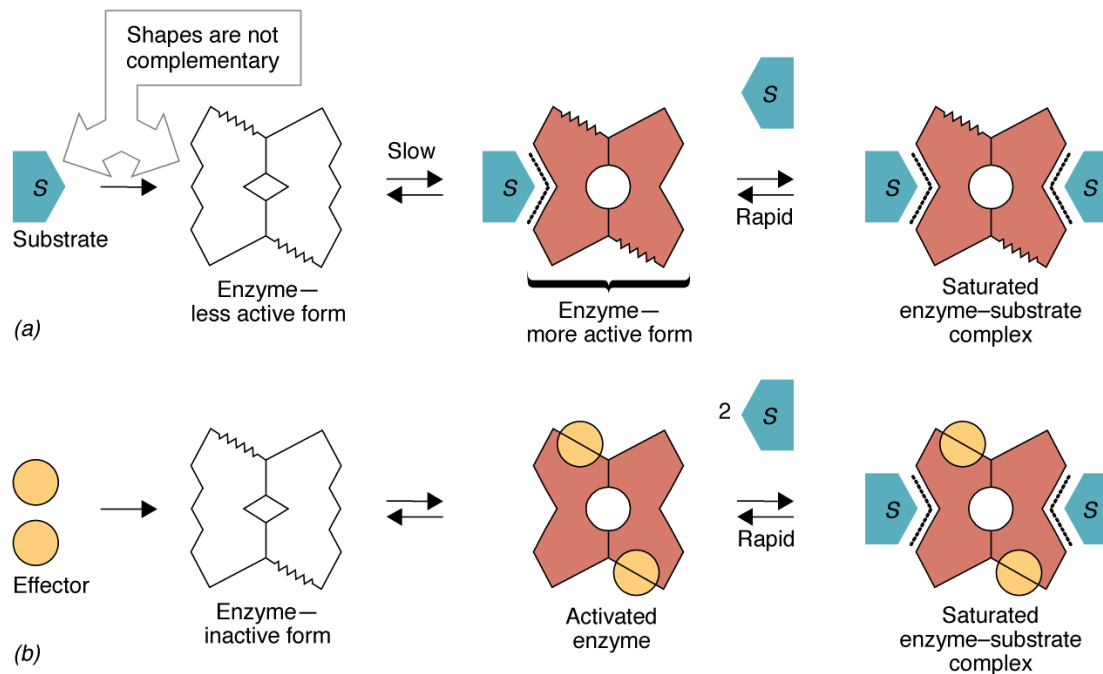
TABLE 6–6 K_m for Some Enzymes and Substrates

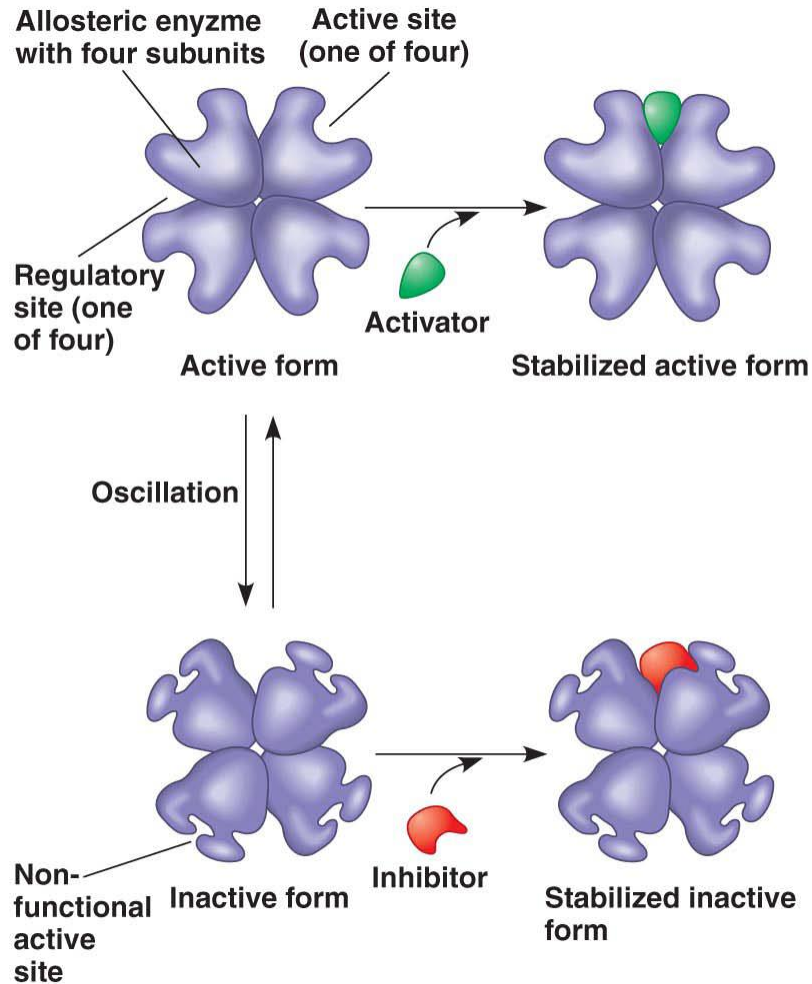
<i>Enzyme</i>	<i>Substrate</i>	K_m (mM)
Hexokinase (brain)	ATP	0.4
	D-Glucose	0.05
	D-Fructose	1.5
Carbonic anhydrase	HCO_3^-	26
Chymotrypsin	Glycyltyrosinylglycine	108
	N-Benzoyltyrosinamide	2.5
β -Galactosidase	D-Lactose	4.0
Threonine dehydratase	L-Threonine	5.0

- Enzyme unit : 특정조건에서 특정 촉매 활성을 나타내는 미리 결정된 효소의 양
→ (1 unit = 1 μmol product/min, at pH 7 and 25°C)
- Specific activity: 단위 효소의 질량 당 나타내는 효소의 단위
→ (0.2 units/mg protein)

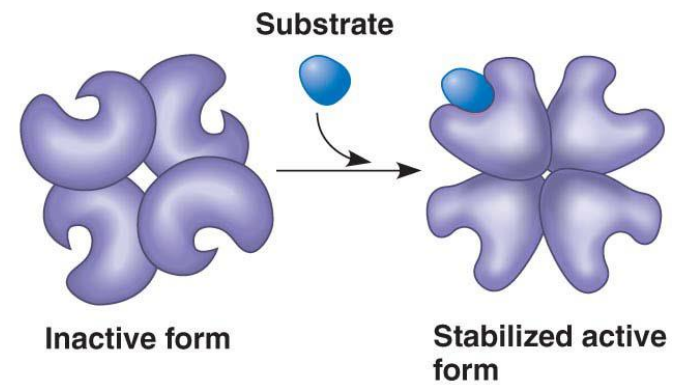
알로스테릭 효소 (allosteric enzyme)

- 효소는 initiators, effectors, inhibitors, genes, poisons, hormones 등에 의해 조절된다.
- 예: 효소 내 다른 부위의 구조적 변화에 의해 active site가 활성화 됨 (allosteric effect)





(a) Allosteric activators and inhibitors

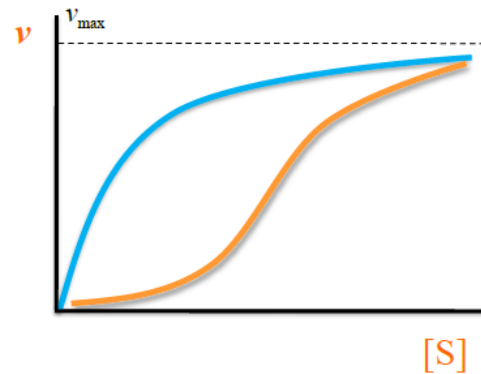


(b) Cooperativity: another type of allosteric activation

$$v = \frac{d[P]}{dt} = -\frac{d[S]}{dt} = \frac{v_{\max} [S]^n}{K_M'' + [S]^n}$$

n : cooperativity coefficient
 $n > 1$, positive cooperativity

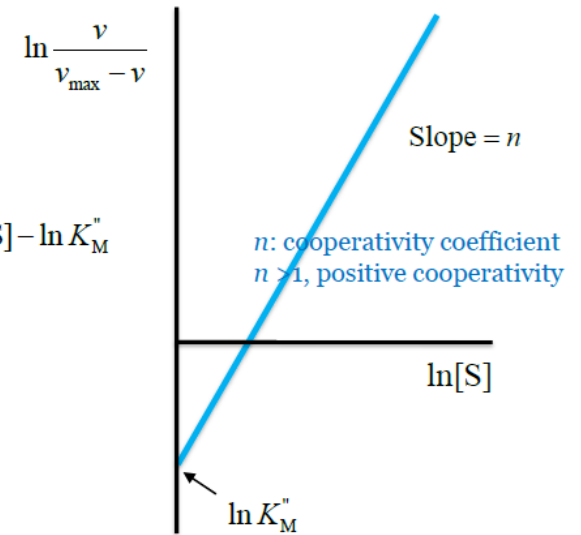
$$\ln \frac{v}{v_{\max} - v} = n \ln[S] - \ln K_M''$$



Michaelis-Menten Kinetics

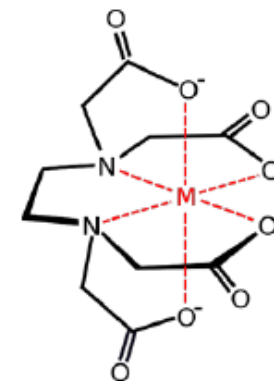
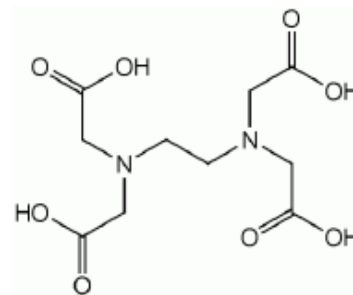
**Allosteric Enzyme Kinetics
 (Sigmoidal Shape)**

$$\ln \frac{v}{v_{\max} - v} = n \ln[S] - \ln K_M''$$

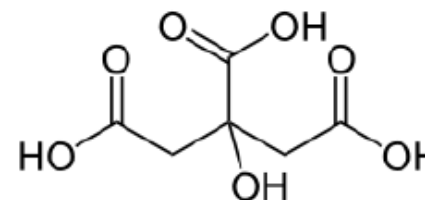


효소 저해제 (enzyme inhibitors)

- Enzyme inhibitors: Bind to enzyme and reduce their activity
- Irreversible inhibitors: form a stable complex with enzyme – heavy metals (lead, cadmium, mercury, etc)
- Maybe reversed only by using chelating agents such as EDTA (ethylenediaminetetraacetic acid) and citrate
- Reversible inhibitors: Competitive, Noncompetitive, and Uncompetitive



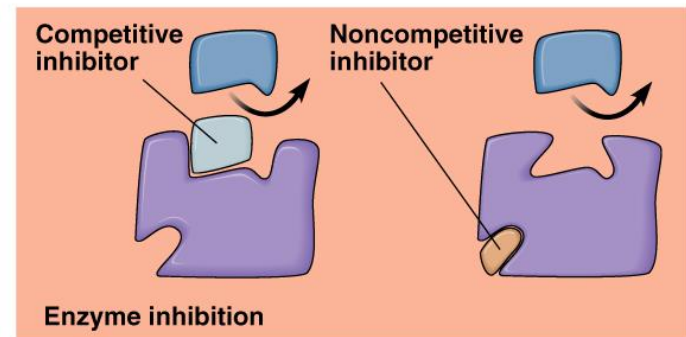
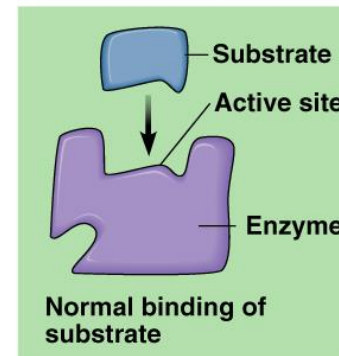
EDTA



Citric acid

효소 저해제 (enzyme inhibitors)

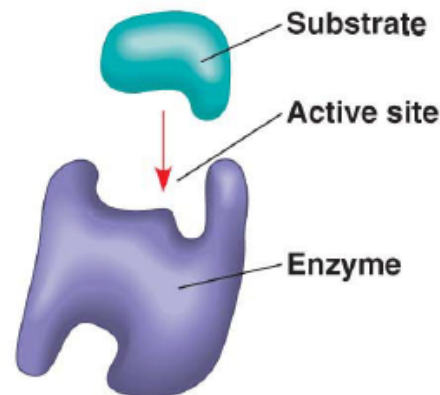
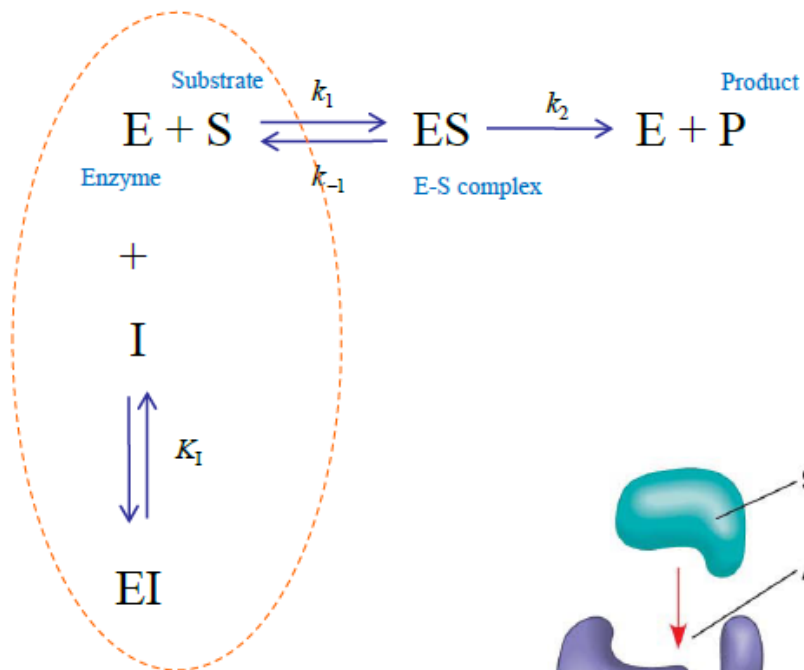
- 경쟁적 저해제 (competitive inhibitor)
- 비경쟁적 저해제 (noncompetitive inhibitor)
- 반경쟁적 저해제 (uncompetitive inhibitor)



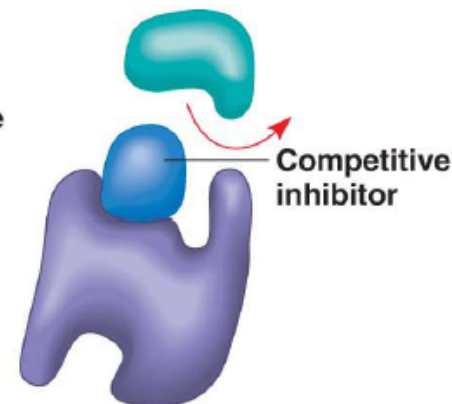
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Competitive Inhibitors

- Usually substrate analogs
- Compete with substrate for the active site of the enzyme



(a) Normal binding



(b) Competitive inhibition

Competitive Inhibitors

$$v = \frac{d[P]}{dt} = \frac{v_{\max}[S]}{K_M + [S]}$$

$$K_M = \frac{k_{-1} + k_2}{k_1} \quad v_{\max} = k_2[E_0]$$

No inhibitors

$$v = \frac{v_{\max}[S]}{K_M + [S]} \quad \frac{1}{v} = \left(\frac{K_M}{v_{\max}} \right) \frac{1}{[S]} + \frac{1}{v_{\max}}$$

$$K_M = \frac{[E][S]}{[ES]} \quad K_I = \frac{[E][I]}{[EI]}$$



$$\frac{d[ES]}{dt} = k_1[E][S] - (k_{-1} + k_2)[ES] = 0$$

$$[E_0] = [E] + [ES] + [EI]$$

$$v = \frac{d[P]}{dt} = k_2[ES]$$

Competitive Inhibitors

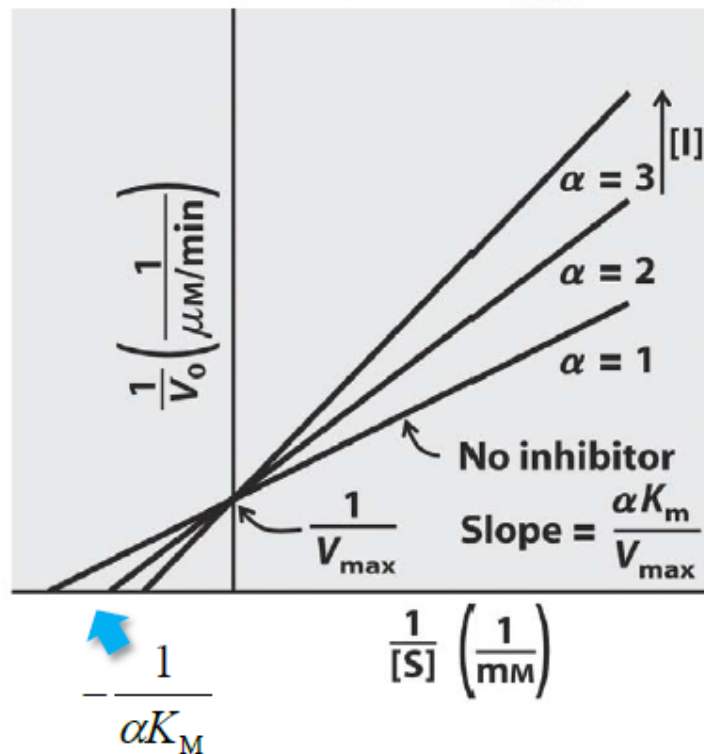
$$v = \frac{v_{\max}[S]}{K_M \left(1 + \frac{[I]}{K_I} \right) + [S]} = \frac{v_{\max}[S]}{\alpha K_M + [S]} = \frac{v_{\max}[S]}{K_{M,app} + [S]}$$

$$K_{M,app} = K_M \left(1 + \frac{[I]}{K_I} \right) = \alpha K_M$$

- The net effect: an increased value of K_M
- Can be overcome by high $[S]$

Competitive Inhibition

$$\frac{1}{V_0} = \left(\frac{\alpha K_m}{V_{\max}} \right) \frac{1}{[S]} + \frac{1}{V_{\max}}$$



No inhibitors

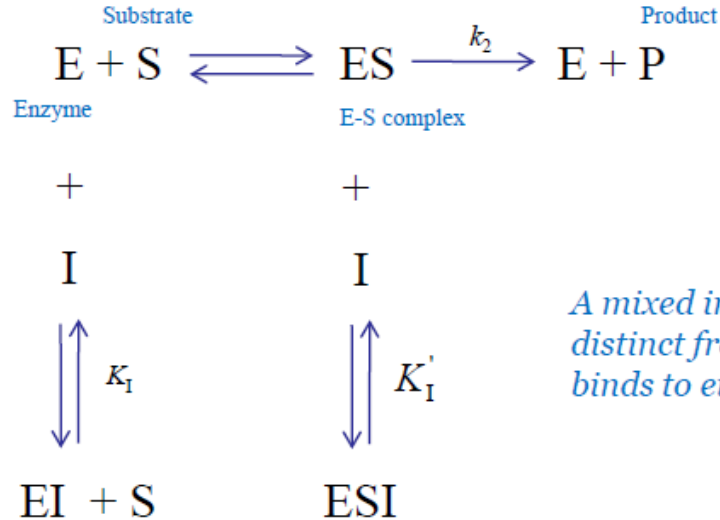
$$v = \frac{v_{\max} [S]}{\alpha K_M + [S]} \quad \alpha = \left(1 + \frac{[I]}{K_I} \right)$$

$$K_I = \frac{[E][I]}{[EI]}$$

$$\frac{1}{v} = \left(\frac{\alpha K_M}{v_{\max}} \right) \frac{1}{[S]} + \frac{1}{v_{\max}}$$

- The effect on apparent K_M , combined with the absence of an effect on v_{\max} : diagnostic of competitive inhibition

Noncompetitive Inhibition



A mixed inhibitor also binds at a site distinct from the substrate active site, but it binds to either E or ES.

No inhibitors

$$v = \frac{v_{\max} [S]}{K_M + [S]} \quad \frac{1}{v} = \left(\frac{K_M}{v_{\max}} \right) \frac{1}{[S]} + \frac{1}{v_{\max}}$$

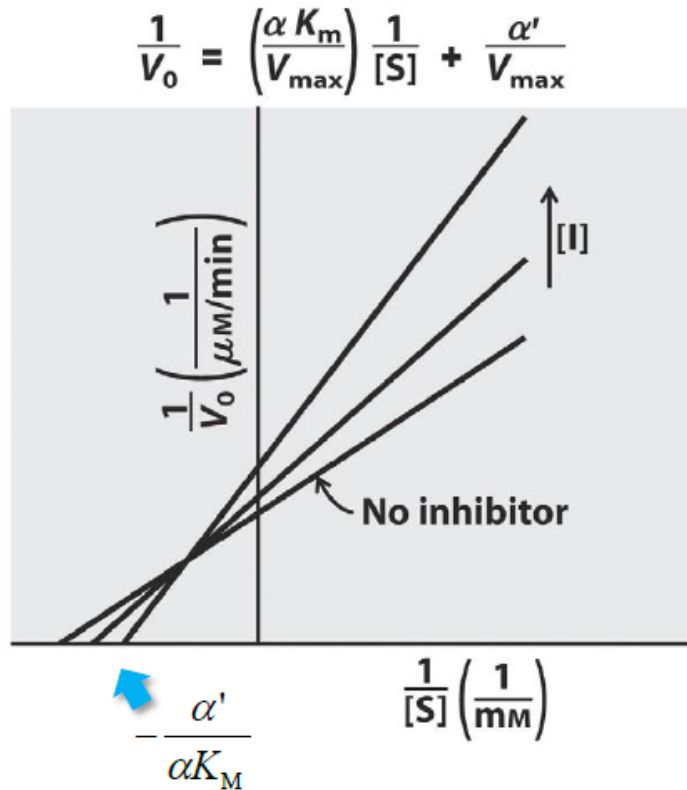
Mixed Inhibitors

$$v = \frac{v_{\max} [S]}{\alpha K_M + \alpha' [S]}$$

$$\alpha = \left(1 + \frac{[I]}{K_I} \right) \quad \alpha' = \left(1 + \frac{[I]}{K'_I} \right)$$

$$[E_0] = [E] + [ES] + [EI] + [ESI]$$

Noncompetitive Inhibition



- Affects both K_M and v_{\max}
- If $\alpha = \alpha'$: Noncompetitive inhibitors

No inhibitors

$$v = \frac{v_{\max}[S]}{K_M + [S]} \quad \frac{1}{v} = \left(\frac{K_M}{v_{\max}} \right) \frac{1}{[S]} + \frac{1}{v_{\max}}$$

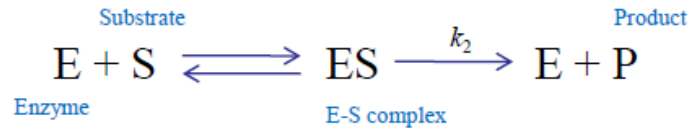
Mixed Inhibitors

$$v = \frac{v_{\max}[S]}{\alpha K_M + \alpha'[S]}$$

$$\alpha = \left(1 + \frac{[I]}{K_I} \right) \quad \alpha' = \left(1 + \frac{[I]}{K_I'} \right)$$

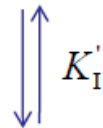
$$\frac{1}{v} = \left(\frac{\alpha K_M}{v_{\max}} \right) \frac{1}{[S]} + \frac{\alpha'}{v_{\max}}$$

Uncompetitive Inhibition



+

I



ESI

An uncompetitive inhibitor binds at a site distinct from the substrate active site and, unlike a competitive inhibitor, binds only to the ES complex.

$$v = \frac{v_{\max} [S]}{K_M + \alpha' [S]} \quad \alpha' = \left(1 + \frac{[I]}{K'_I} \right)$$

$$\frac{d[ES]}{dt} = k_1 [E][S] - (k_{-1} + k_2)[ES] = 0$$

$$K_M = \frac{[E][S]}{[ES]} \quad K'_I = \frac{[ES][I]}{[ESI]}$$

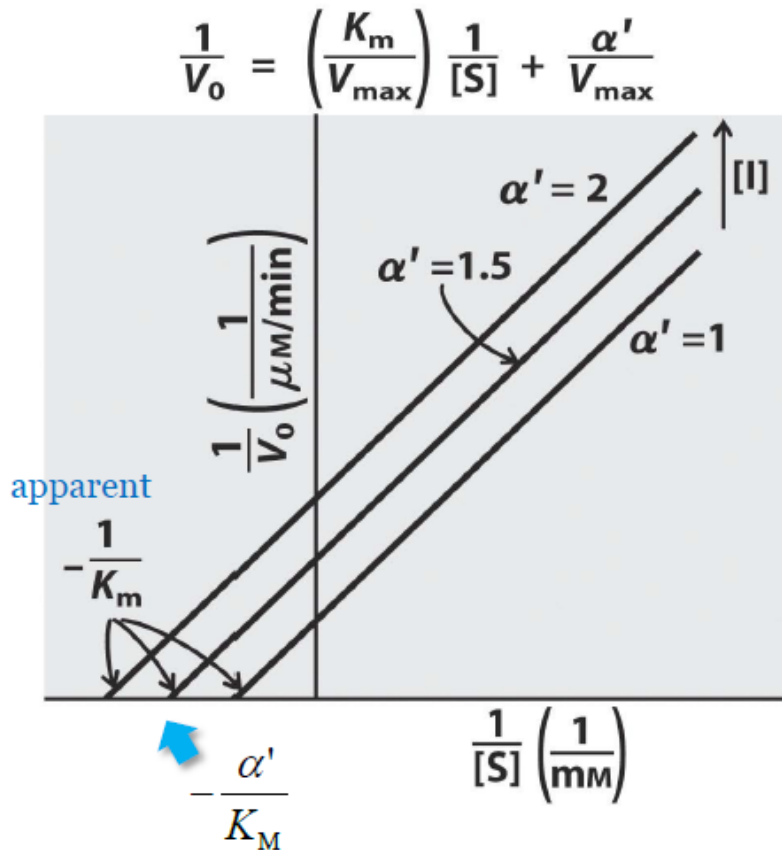
No inhibitors

$$v = \frac{v_{\max} [S]}{K_M + [S]} \quad \frac{1}{v} = \left(\frac{K_M}{v_{\max}} \right) \frac{1}{[S]} + \frac{1}{v_{\max}}$$

$$[E_0] = [E] + [ES] + [ESI]$$

$$v = \frac{d[P]}{dt} = k_2 [ES]$$

Uncompetitive Inhibition



- Lowers the v_{\max}
- Apparent K_M also decreases

No inhibitors

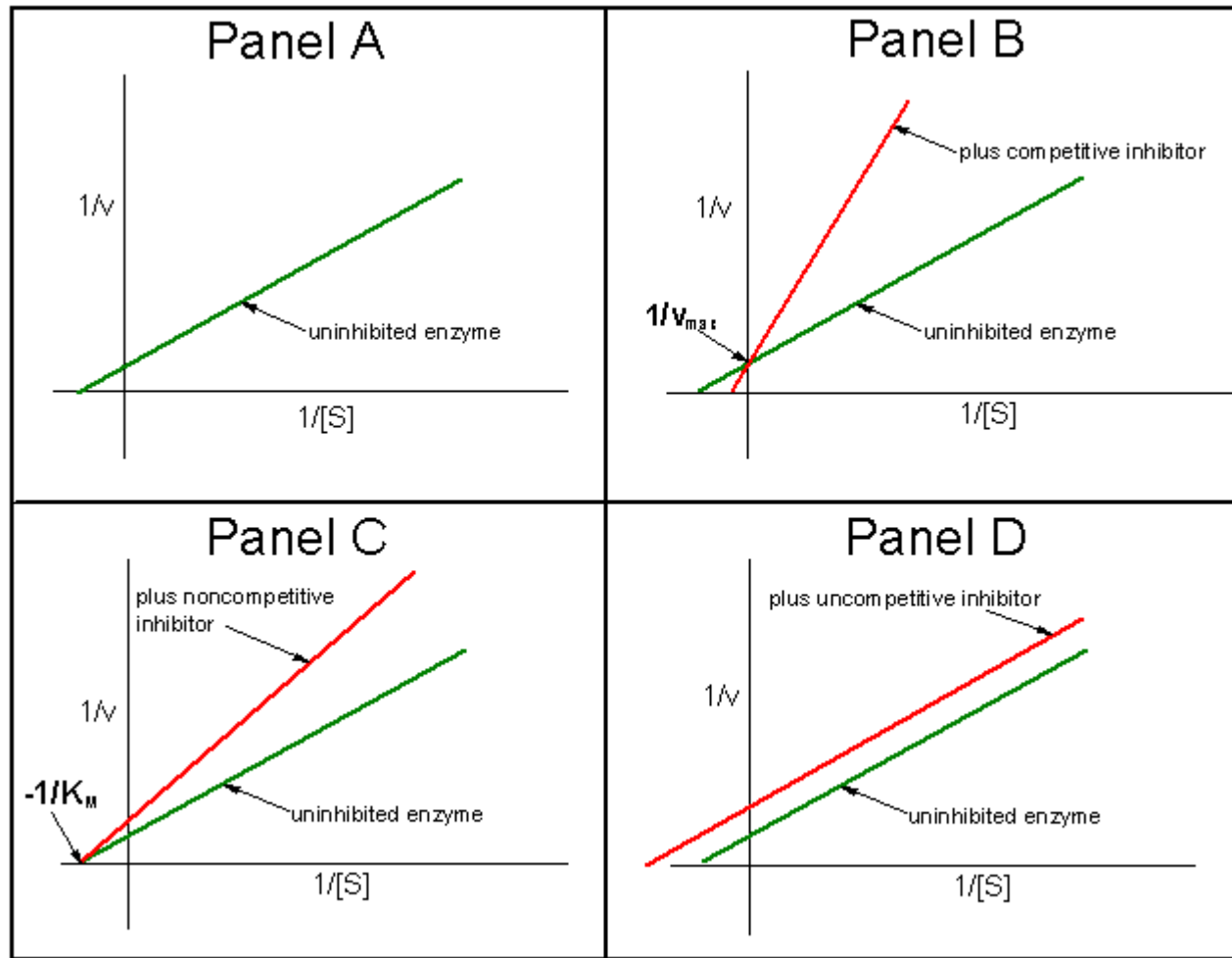
$$v = \frac{v_{\max}[S]}{K_M + [S]} \quad \frac{1}{v} = \left(\frac{K_M}{v_{\max}} \right) \frac{1}{[S]} + \frac{1}{v_{\max}}$$

Uncompetitive Inhibitors

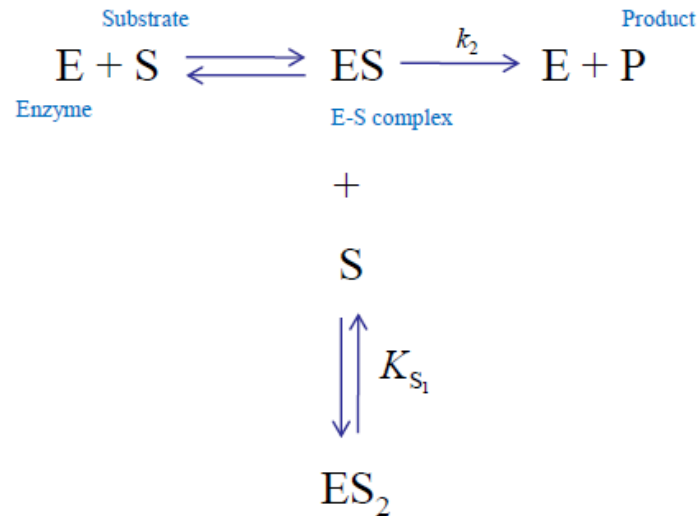
$$v = \frac{v_{\max}[S]}{K_M + \alpha'[S]} \quad \alpha' = \left(1 + \frac{[I]}{K_I} \right)$$

$$\frac{1}{v} = \left(\frac{K_M}{v_{\max}} \right) \frac{1}{[S]} + \frac{\alpha'}{v_{\max}}$$

효소 저해제 (enzyme inhibitors)



Substrate Inhibition



High substrate concentration may cause inhibition in some enzymatic reactions

$$v = \frac{v_{\max} [S]}{K_M + [S] + \frac{[S]^2}{K_{S_1}}}$$

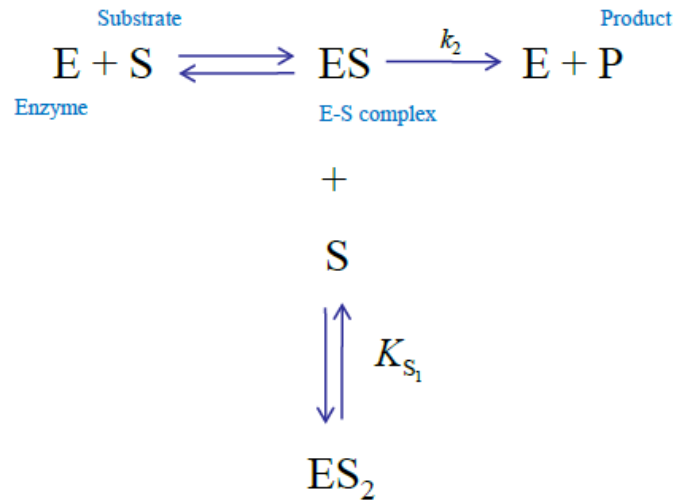
$$K_M = \frac{[E][S]}{[ES]} \quad K_{S_1} = \frac{[ES][S]}{[ES_2]}$$

$$\frac{d[ES]}{dt} = k_1[E][S] - (k_{-1} + k_2)[ES] = 0$$

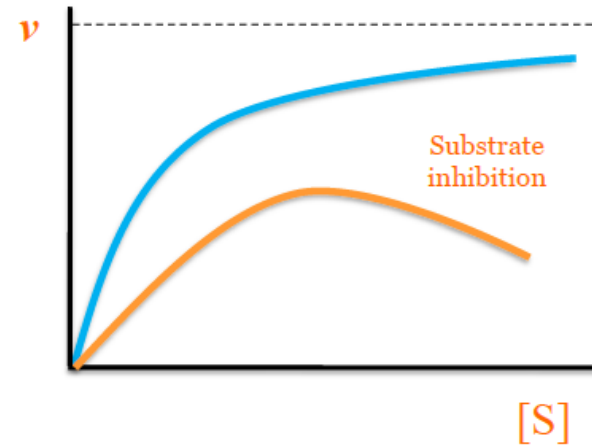
$$[E_0] = [E] + [ES] + [ES_2]$$

$$v = \frac{d[P]}{dt} = k_2[ES]$$

Substrate Inhibition



$$v = \frac{v_{\max} [S]}{K_M + [S] + \frac{[S]^2}{K_{S_1}}}$$



At low substrate conc.

$$v = \frac{v_{\max} [S]}{K_M + [S]}$$

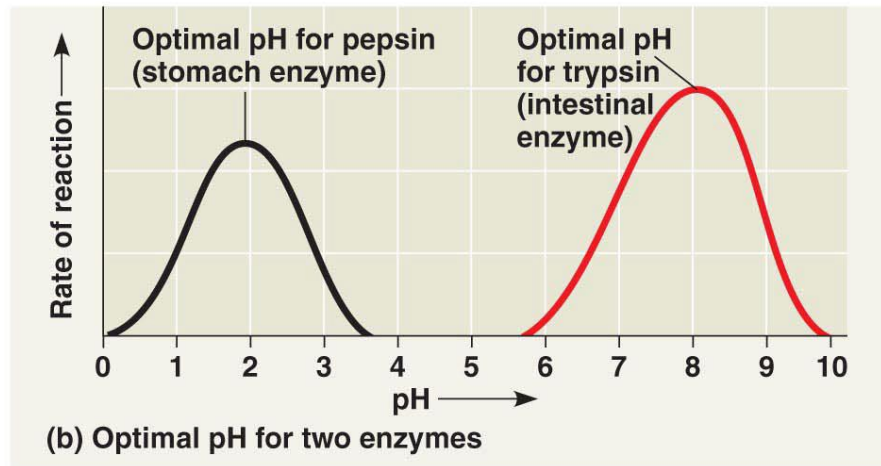
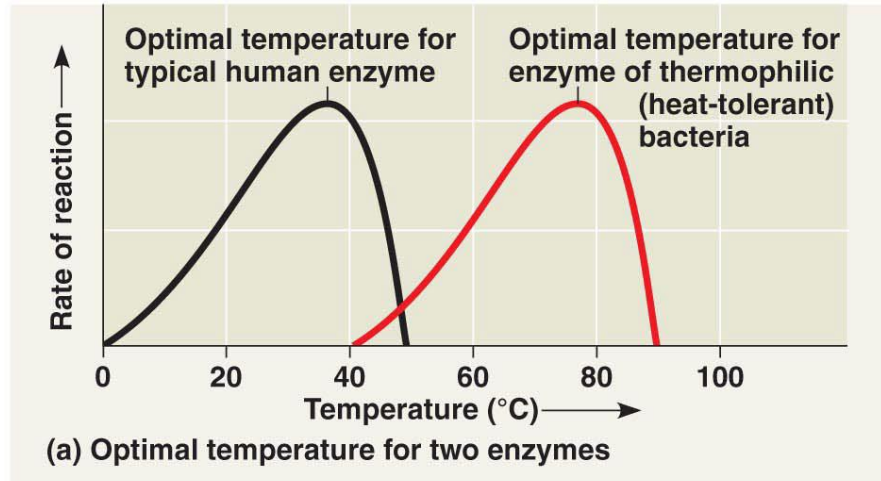
At high substrate conc.

$$v = \frac{v_{\max}}{1 + \frac{[S]}{K_{S_1}}} \quad \frac{1}{v} = \frac{1}{v_{\max}} + \frac{[S]}{K_{S_1} v_{\max}}$$

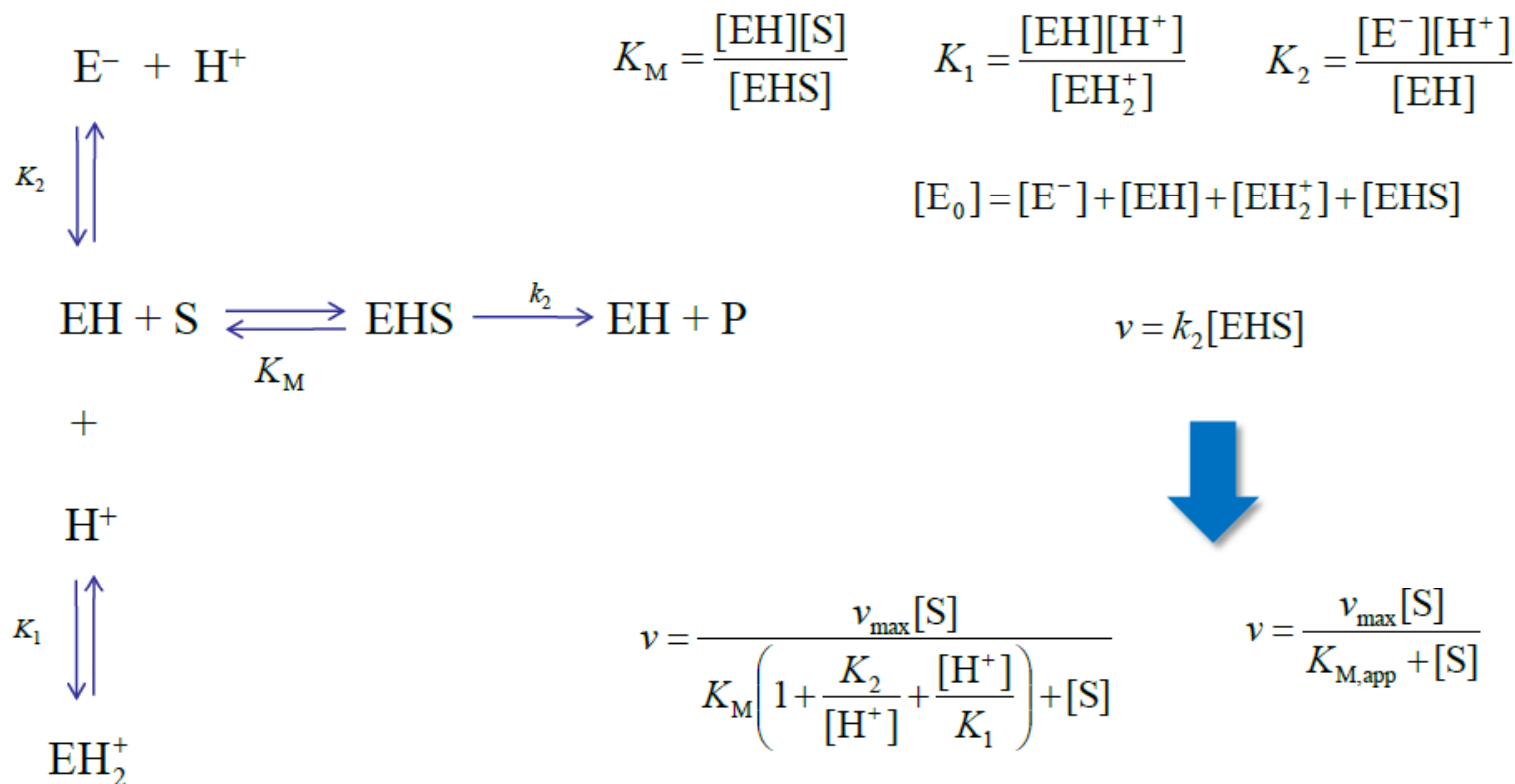
$$[S]_{\max} = \sqrt{K_M K_{S_1}}$$

$$\frac{dv}{d[S]} = 0$$

pH와 온도의 영향

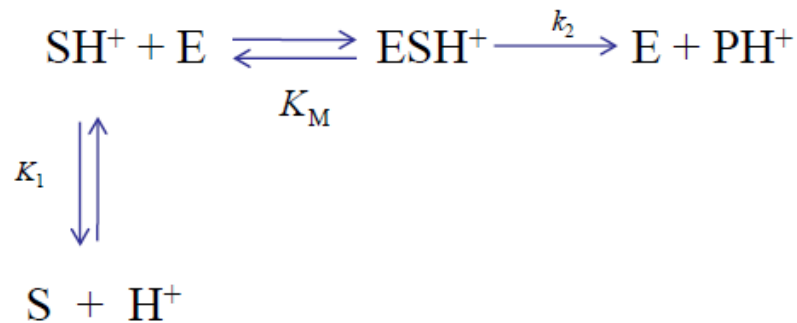


pH Effects



$$K_{M,app} = K_M \left(1 + \frac{K_2}{[H^+]} + \frac{[H^+]}{K_1} \right)$$

Ionizing Substrates



The pH optimum for an enzyme is usually determined experimentally

$$v = \frac{d[\text{P}]}{dt} = k_2[\text{ESH}^+]$$

$$K_M = \frac{[\text{SH}^+][\text{E}]}{[\text{ESH}^+]} \quad K_1 = \frac{[\text{S}][\text{H}^+]}{[\text{SH}^+]}$$

$$[\text{E}_0] = [\text{E}] + [\text{ESH}^+]$$

$$\frac{d[\text{ESH}^+]}{dt} = k_1[\text{SH}^+][\text{E}] - (k_{-1} + k_2)[\text{ESH}^+] = 0$$

$$v = \frac{v_{\max}[\text{S}]}{\frac{K_1 K_M}{[\text{H}^+]} + [\text{S}]}$$

Temperature Inactivation

$$-\frac{d[E]}{dt} = k_d[E]$$

$$[E] = [E_0] \exp(-k_d t)$$

$$k_d = A_d \exp\left(-\frac{E_d}{RT}\right)$$

The denaturation
constant

- E_a : 4 ~ 20 kcal/g mol (mostly about 11 kcal/g mol)
- E_d : 40 ~ 130 kcal/g mol (mostly about 70 kcal/g mol)

- Enzyme denaturation by temperature is much faster than enzyme activation.
- A rise in temperature from 30 to 40 °C results in a 1.8-fold increase in enzyme activity, but a 41-fold increase in enzyme denaturation.

$$v = A \exp\left(-\frac{E_a}{RT}\right) [E_0] \exp(-k_d t)$$

3.4 고정화 효소 시스템

효소 고정화 (Enzyme Immobilization)

- 정의 : 고정된 공간에 효소의 이동성을 제한하면서도 촉매 활성은 유지 또는 향상시키는 기술
- 장점
 - 효소 재이용 (회수 및 정제공정 생략)
 - 효소 활성의 증대
 - 생산물의 순도 향상

고정화 방법

- 가두기 (Entrapped)
 - 격자 가두기 (Matrix-entrapped)
 - 막 가두기 (Membrane-entrapped)
 - ▶ Macroscopic membrane
 - ▶ Microcapsule
- 표면 고정화 (Bound)
 - 흡착 (Adsorbed)
 - ▶ Physical adsorption
 - ▶ Ionic bonding
 - 공유결합 (Covalent Bonding)
 - ▶ To support
 - ▶ To enzyme (cross-linking)

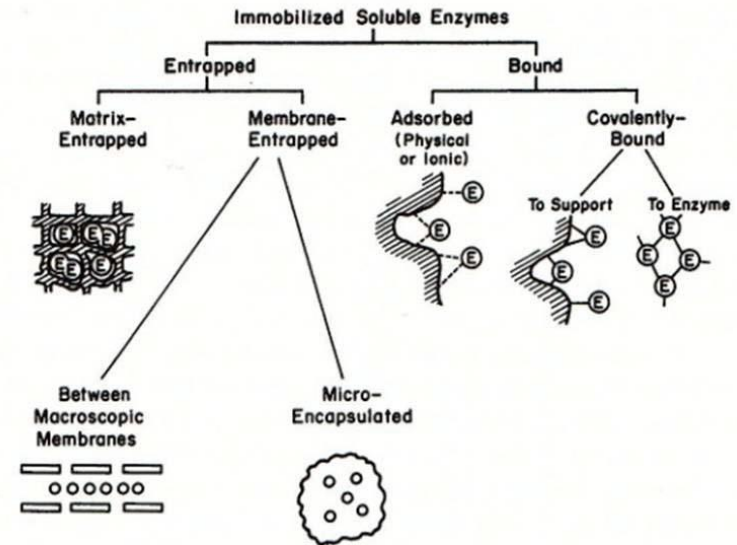
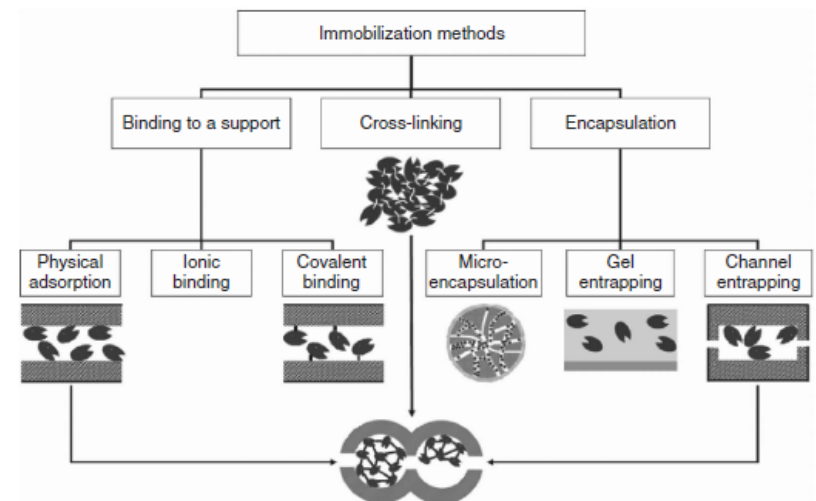
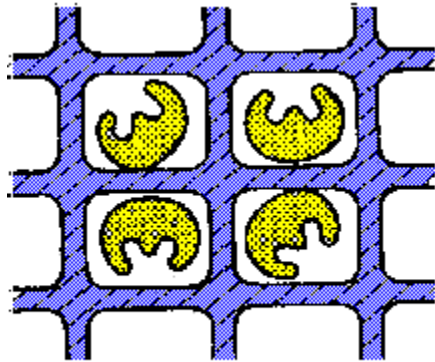


Figure 3.16. Major immobilization methods.



격자가두기 (matrix entrapment)

- 재료
 - 고분자: Ca-alginate, agar, k-carrageenin, polyacrylamide, collagen
 - 활성탄, 다공성 요업재료, 구조토
- 방법
 - 1) 효소액을 중합반응이 일어나기 전에 중합체 용액에 혼합
 - 2) 중합
 - 3) 효소를 포함한 중합된 젤을 밀어내거나 (extrude) 주형 사용



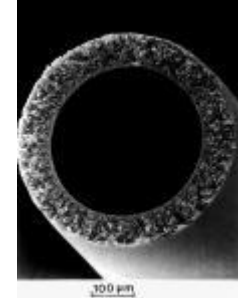
entrapped in a matrix



entrapped in droplets

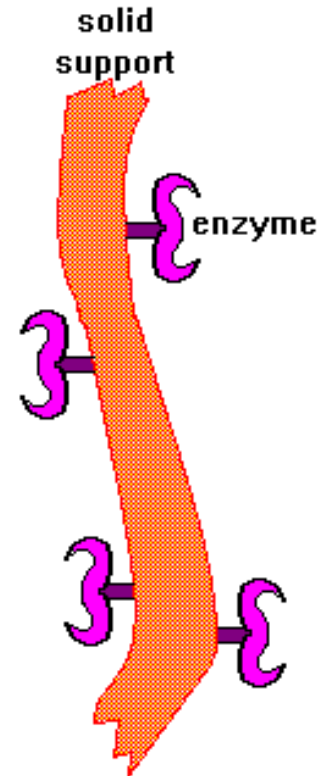
막 가두기 (membrane entrapment)

- 실관막 (hollow fiber membrane)
 - 미세캡슐화 (microencapsulation)
-
- Entrapment의 단점
 - 1) Enzyme leakage → 해결: 기공 크기 감소화
 - 2) Diffusion limitation → 해결: 입자 크기 및 캡슐 크기 감소화
 - 3) 효소 활성 및 안정성 감소
 - 4) Microenvironment 조건의 제어 어려움



표면 고정화 (Carrier-Binding)

- 흡착 (Physical adsorption)
 - van der Waals 힘, 분산력과 같은 약한 물리적 힘에 의해 표면에 부착, 탈착 문제
 - Glutaraldehyde를 사용한 가교결합 → 변성문제
 - 무기재료 (알루미나, 실리카, 다공성 유리, 세라믹 ...)
 - 유기재료 (셀룰로우스, 전분, 활성탄 ...)
 - 이온교환수지 (Amberlite, Sephadex, Dowex)
- 공유결합 (Covalent binding)
 - 효소분자의 Amino, Carboxyl, Hydroxyl 기 등과 지지물 질이 공유결합
 - 공유결합 전에 효소용액을 경쟁적 저해제에 담금으로써 활성부위 보호



고정화된 효소계의 확산 제한

❖ Damkohler number (Da)

$$Da = \frac{\text{maximum rate of reaction}}{\text{maximum rate of diffusion}} = \frac{V'_m}{k_L[S_b]}$$

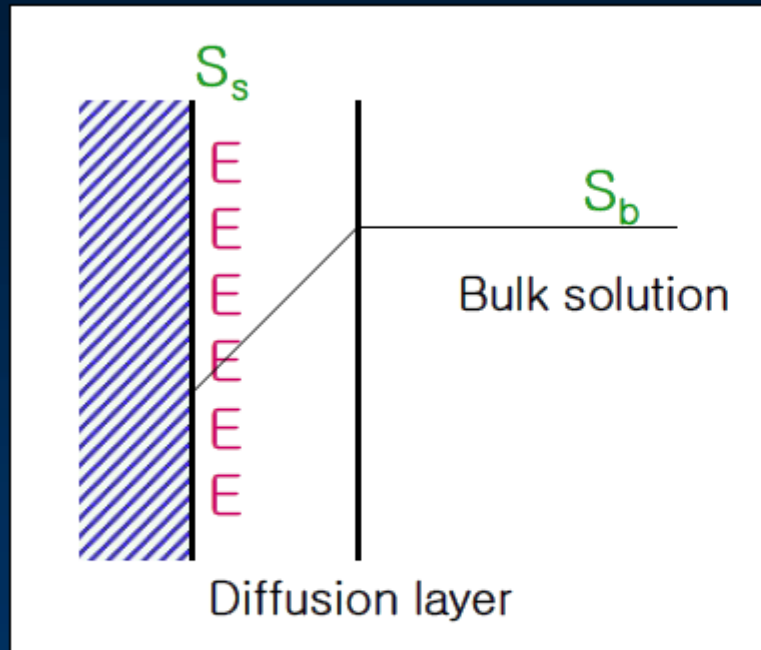
❖ $[S_b]$: (g/cm³), k_L : (cm/s)

❖ $Da \gg 1$: Diffusion limited

❖ $Da \ll 1$: Reaction limited

❖ $Da \sim 1$: Similar diffusion resistance

비공극성 지지체



$$J_s = k_L ([S_b] - [S_s]) = \frac{V'_m [S_s]}{K_m + [S_s]}$$

❖ $Da \gg 1$: Diffusion limited, $[S_s] \sim 0$

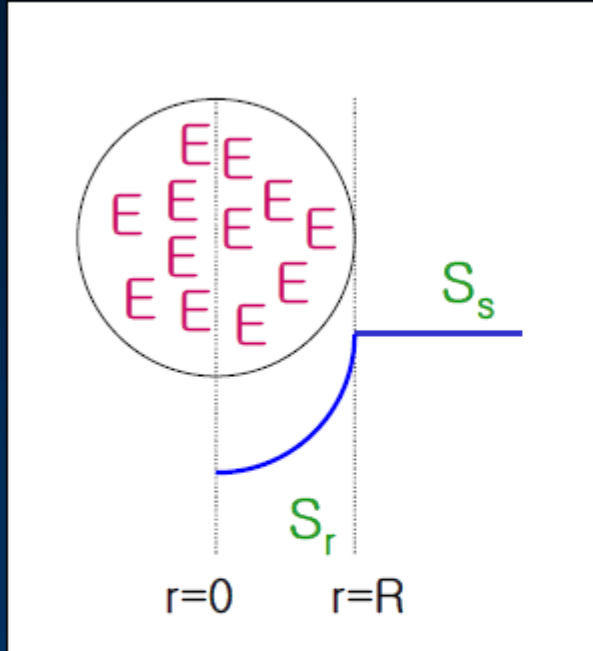
$$v = k_L [S_b]$$

❖ $Da \ll 1$: Reaction limited

$$v = \frac{V'_m [S_b]}{K_{m,app} + [S_b]}$$

Graphical solution → Figure 3.18

공극성 지지체



G. E.

$$D_e \left(\frac{d^2[S]}{dr^2} + \frac{2}{r} \frac{d[S]}{dr} \right) = \frac{V_m''[S]}{K_m + [S]}$$

D. F.

$$\bar{S} = \frac{[S]}{[S_s]}, \quad \bar{r} = \frac{r}{R}, \quad \beta = \frac{K_m}{[S]}$$

$$\frac{d^2\bar{S}}{d\bar{r}^2} + \frac{2}{\bar{r}} \frac{d\bar{S}}{d\bar{r}} = \phi^2 \frac{\bar{S}}{1 + \bar{S}/\beta}$$

Thiele Modulus

$$\phi = R \sqrt{\frac{V_m''/K_m}{D_e}}$$

B. C.

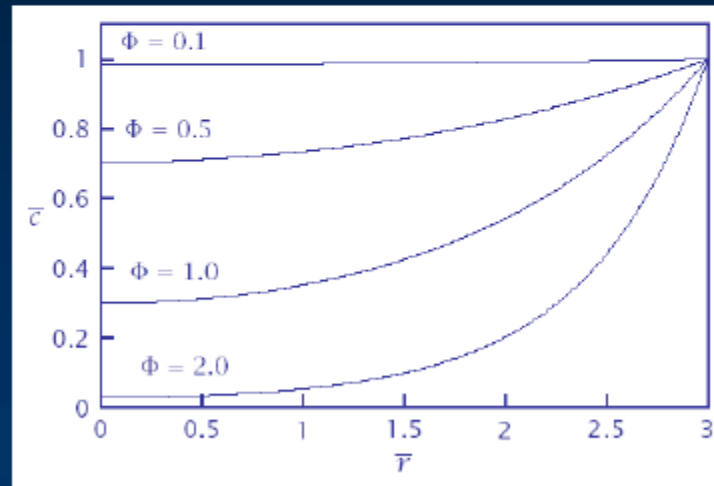
$$\bar{r} = 1 \rightarrow \bar{S} = 1, \quad \bar{r} = 0 \rightarrow \frac{d\bar{S}}{d\bar{r}} = 0$$

공극성 지지체

Thiele modulus, ϕ

ϕ : the ratio of the reaction rate
to the diffusion rate in the pellet.

$$\phi = R \sqrt{\frac{V_m'' / K_m}{D_e}}$$



Bioprocess Engineering I

공극성 지지체

Effectiveness factor, η

η : The ratio of the reaction rate with diffusion limitation to the reaction rate with no diffusion limitation

$$r_s = \eta \frac{V_m [S_s]}{K_m + [S_s]}$$

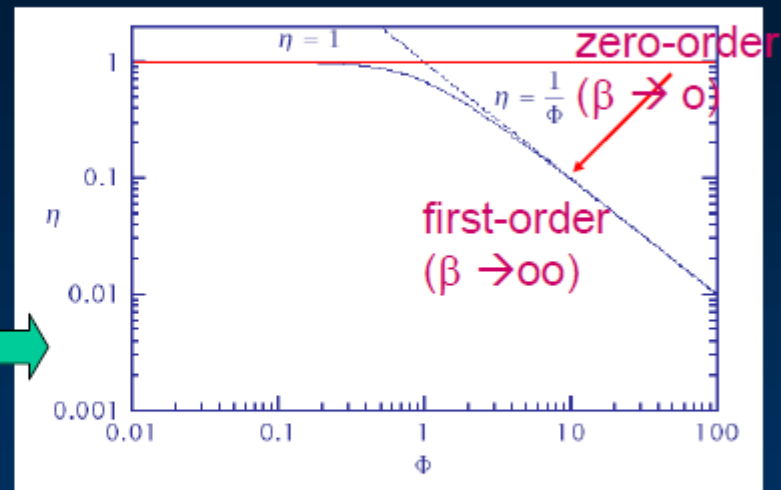
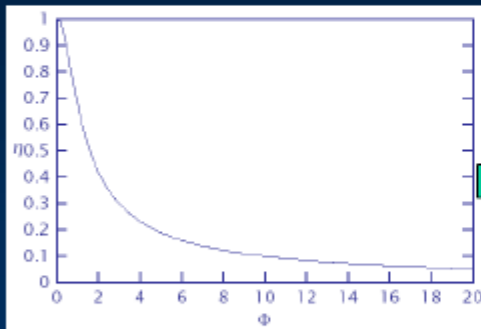
- ❖ 촉매가 얼마나 효율적으로 사용되는 지의 척도가 되는 무차원 반응속도
- ❖ 1에 가까울수록, 담체의 전체가 빠른 속도로 반응
(물질전달이 매우 빠르므로)
- ❖ 0에 가까울수록, 담체의 많은 부분이 속도가 매우 느림
(반응물이 담체 내부로의 물질전달 속도가 느리므로)

Bioprocess Engineering I

공극성 지지체

Effectiveness factor, η

$$r_s = \eta \frac{V_m'' [S_s]}{K_m + [S_s]}$$



$$\eta = \frac{3}{\phi} \left[\frac{1}{\tanh \phi} - \frac{1}{\phi} \right]$$

← first-order reaction in a sphere (log-log scale).

Bioprocess Engineering I

공극성 지지체

Design Immobilized Enzyme

- ❖ K_m , D_e : 고정값
- ❖ V_m , R : 변수
- ❖ R : 입자의 형태 유지, 압축되지 않고,
회수할 수 있는 범위에서 가능한 작게
- ❖ Maximum reaction rate : enzyme activity and content에 의해 결정됨
- ❖ High enzyme content: High enzyme activity,
Low effectiveness factor
- ❖ Low enzyme content: Low enzyme activity,
High effectiveness factor
- ❖ → Small diameter ($< 10\mu m$), optimized enzyme content

→ Figure 3.21

Bioprocess Engineering I



3.5 효소의 대규모 생산

- 대량생산효소: 과잉생산 균주로부터 생산
 - 단백질 분해효소 (subtilisin, rennet)
 - 가수분해효소 (pectinase, lipase, lactase)
 - glucose isomerase
 - glucose oxidase
- 미생물배양 (최적화) → 세포파괴 → 세포 찢꺼기, 핵산제거 → 단백질 침전 → 한외여과, 원심분리 → 선택적 분리 (크로마토그래피) → 결정화 → 건조
- Extracellular enzyme
- Intracellular enzyme : 세포파괴, 세포막 투과 분비 촉진제 (CaCl_2 , DMSO, pH 전이)

3.6 효소의 의학 및 산업적 활용

- 제약산업: 순수한 키랄(chiral) 화합물 생산 기회
- 라세믹 혼합물에서 하나의 광학 이성질체(enantiomer)가 치료제로 유용하다면 다른 하나는 부작용을 일으키거나 치료제로서 가치가 없다.
- 비정상적 조건(예: 심해, 고염 호수, 온천) 성장 미생물 유래 효소의 사용
- 무세포 시스템: 세포 용해물 사용, 100 L 이상으로 확장
- 2014년 미국 산업효소 매출 45억달러 → 2020년 65억 달러 증가 예상
- 식음료 시장: 전체 효소 시장의 1/3
- 다음으로 세제
- 동물사료, 바이오연료, 제지 및 펄프, 섬유 등

Enzyme	Applications
protease	전체 60%, 치즈(rennet), 제빵, 주류, 식품, 세제,
pectinase	주스, 포도주 생산
lipase	비누제조, 폐수처리, 향미성분 생산, 세제
amylase	포도당, 맥아당 생산
cellulase	곡류가공, 주류생산, 폐기물 처리
lactase	Lactose → glucose, galactose, 에탄올 발효
Glucose isomerase	Glucose → fructose (당도: 1.7배)

- Amylase: 전분의 가수분해
 - α -amylase: α -1,4-glycosidic bond, 전분액화효소
 - β -amylase: hydrolysis of the second α -1,4 glycosidic bond, cleaving off maltose at a time, 당화효소
 - glucoamylase: α -1,6-glycosidic bond, yielding glucose, 당화효소
- Cellulase: 섬유소의 가수분해
 - *Trichoderma* : 결정형 셀룰로오스 분해 O
 - *A. niger* : X
 - *Clostridium*
 - cellulose  cellobiose  포도당
 cellulase β -glucosidase
- Hemicellulase: hemicellulose를 5탄당으로 가수분해

의학분야

- Aminoacylase: DL-아실아미노산 \rightarrow L-아미노산 (식품, 의학 분야 중요 제품) + D-아실아미노산
- Trypsin, Streptokinase: 항염증약
- Lysozyme: 그람양성균의 세포벽 가수분해, 항균제
- Urokinase: 혈전용해, 방지
- Asparaginase: 항암제, L-asparagine \rightarrow L-aspartate
- Glucose oxidase: 혈액이나 소변에서 포도당 농도 측정
- Penicillinase: penicillin에 대한 allergy 반응 치료
- TPA, Streptokinase: 혈전용해
- Aspartase: fumarate \rightarrow L-aspartate + phenylalanine
aspartame: 저칼로리 감미료