SEMMELWEIS EGYETEM

Biofizikai és Sugárbiológiai Intézet,
Nanokémiai Kutatócsoport

Lágy Anyagok Laboratóriuma

Makromolekulák konformációja

Zrínyi Miklós

egyetemi tanár, az MTA tagja

mikloszrinyi@gmail.com

2015

Makromolekulák

Kolloid asszociátumok, vagy kovalens kötésű molekulák?

Hermann Staudinger (1881- 1962)

The Nobel Prize in Chemistry 1953

Valamennyi elem közül a szén az egyetlen, amelynek atomjai korlátlan számban kapcsolódhatnak közvetlenül egymással, a létrejövő molekulák stabilitásának csökkenése nélkül.

Kötési energiák és a molekulák stabilitása

Single Bonds

H	C	N	O	F	Si	P	S	Cl	Br	I	
436	415	390	464	569	395	320	340	432	370	295	H
	345	290	350	439	360	265	260	330	275	240	C
		160	200	270	—	210	—	200	245	—	N
			140	185	370	350	—	205	—	200	O
				160	540	489	285	255	235	—	F
					230	215	225	359	290	215	Si
						215	230	330	270	215	P
							215	250	215	—	S
								243	220	210	Cl
									190	180	Br
										150	I

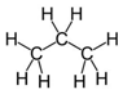
Multiple Bonds

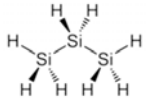
C=C, 611	C=N, 615	C=O, 741	N=N, 418	O=O, 498
C≡C, 837	C≡N, 891	C≡O, 1080	N≡N, 946	

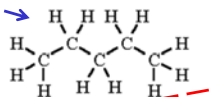
Szerves és szervetlen polimerek

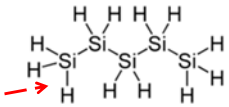
Kötési energiák; kJ/mol

bond	Energy kJ/mol
C-C	345
C-O	350
C-N	290
C-P	265
Si-Si	226

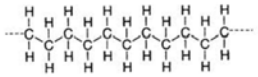








Nagyobb kötési energia stabilabb molekula!



poliszilán

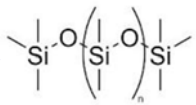
Nem stabil!

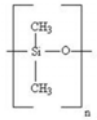
kötés	Energia kJ/mol
C-C	345
Si-H	395
Si-Si	226

SiH_4 stabil molekula

Si_5H_{12} ***igen bomlékony***

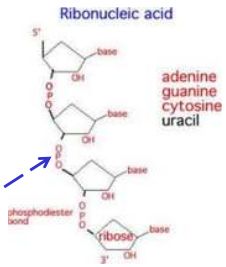
kötés	Energia kJ/mol
C-C	345
Si-O	370

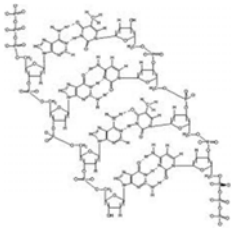




PDMS

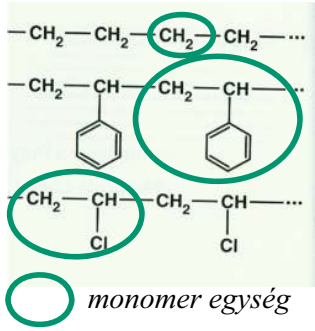
kötés	Energia kJ/mol
C-O	350
C-N	290
P-O	350





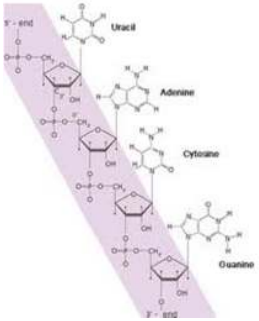
Polimerek és makromolekulák **óriás molekulák**!

szintetikus *biopolimer*

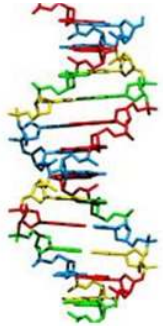


monomer egység

Monomer egységek száma: N



RNA

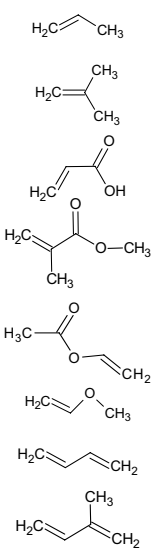


DNA

A leghosszabb makromolekula a **DNS** : $10^9 < N < 10^{10}$

Néhány méter is lehet!

Monomerek **Monomer egységek**



Propylene

Isobutylene

Acrylic acid

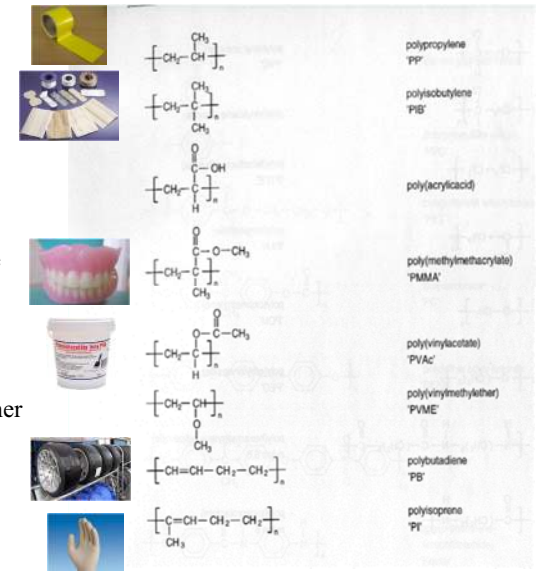
Methacrylate

Vinylacetate

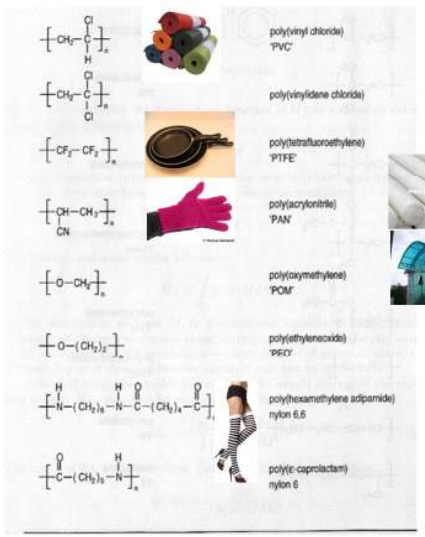
Vinylmethylether

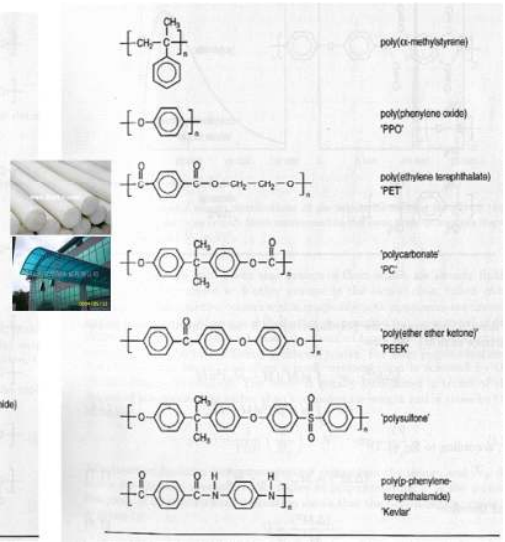
Butadiene

Isoprene

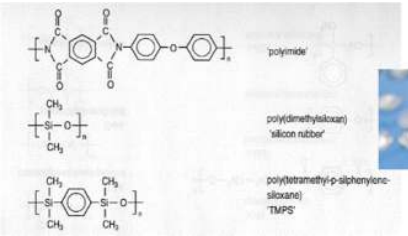


Monomerek **Monomer egységek**





Monomer egységek



Homopolimer

A A A A A A A A A A A A

Kopolimer nomenklatura

A A A B B B A A A B B B **blokkos**

A B A B A B A B A B A B **alternáló**

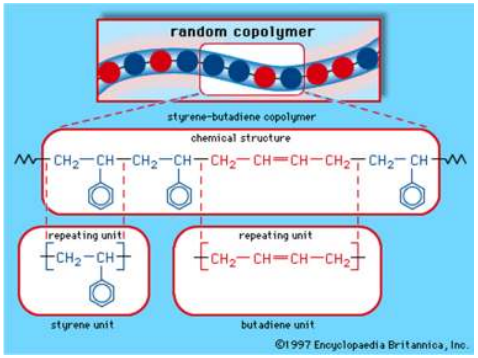
A A B B A B B A A B A B **statisztikus**

A A A C A A A A C A A A **graftolt**

B B B B B B

Kopolimer példák

Szintetikus polimerek



Biopolimerek

DNS:
négy különböző monomer egység

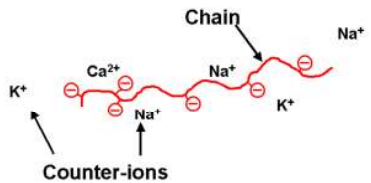
fehérjék:
húsz különböző aminosav

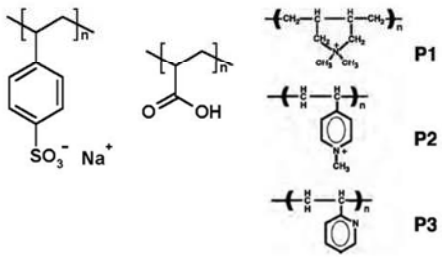
↓

aminosavak

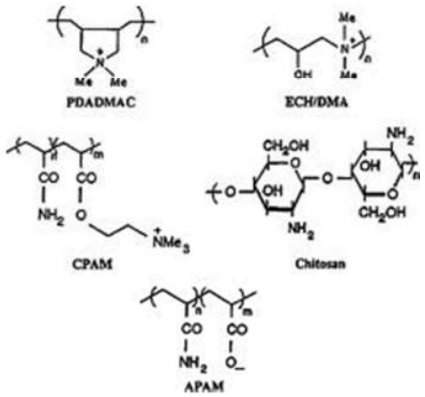
Polielektrolitok

Anionos



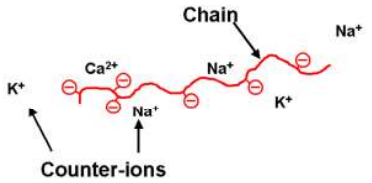


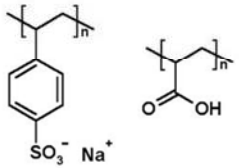
Kationos

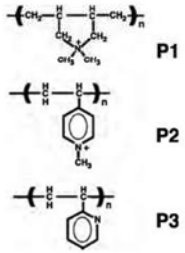


Polielektrolitok

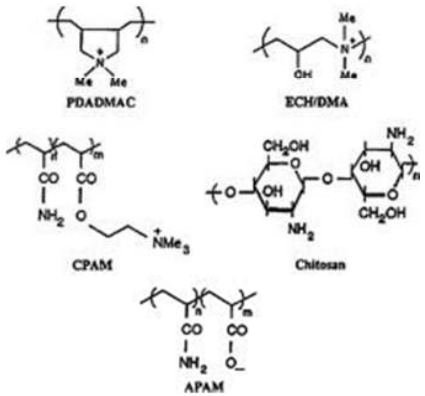
Anionos



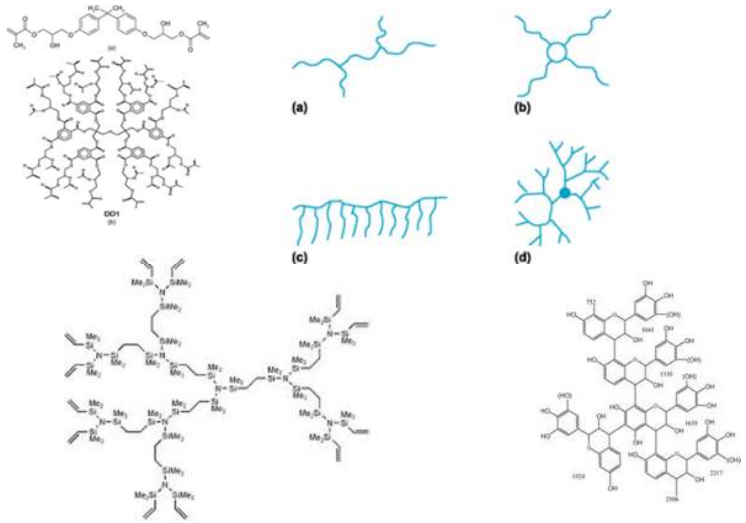




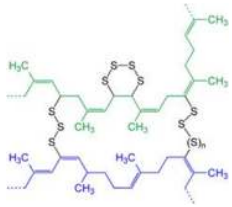
Kationos



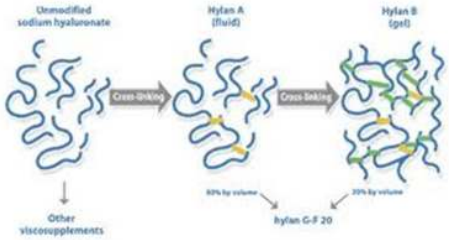
Elágazó polimerek

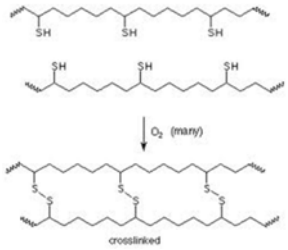


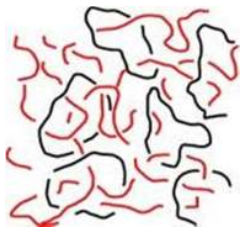
Térhálós polimerek



Vulcanised rubber







IPN
Interpenetrated network

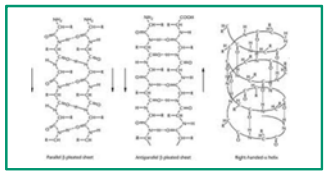
Polimerek szerkezete

Konstitució konfiguráció konformáció

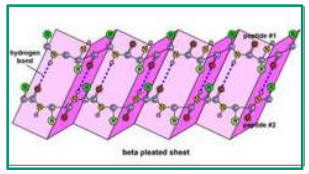
Elsődleges szerkezet:

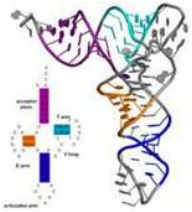
Human's genom project: complete primary structure of a human's DNA molecule
if $N \sim 10^2$ and 20 different monomer units, then 20^{100} different molecules!

Másodlagos szerkezet:
Azonos konformációjú egységek rendezett strukturája!
Pl. keratin, fibroin



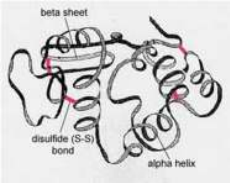
α *helix*



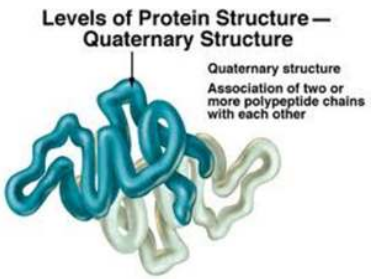


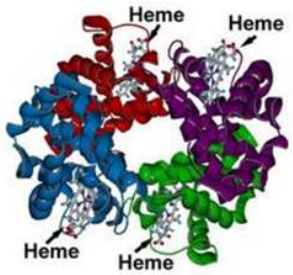
β structure

Harmadlagos szerkezet (globuláris fehérjék):



Negyedleges szerkezet (több fehérjéből álló komplex egység):

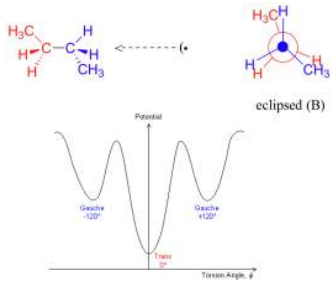




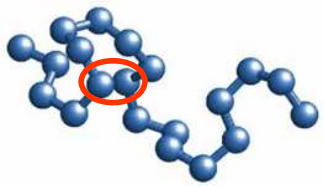
A térszerkezetet meghatározó alapvető kölcsönhatások

Makromolekulák szerkezetét kialakító kémiai kötések és molekuláris kölcsönhatások minden tekintetben egyenértékűek a kismolekulájú anyagok hasonló kémiai környezetben lévő kötéseivel és csoportjainak kölcsönhatásaival.

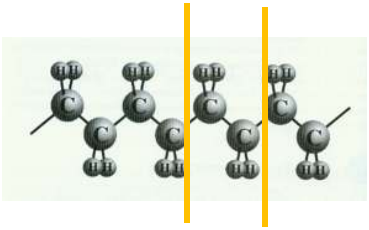
Rövidtávú kölcsönhatások

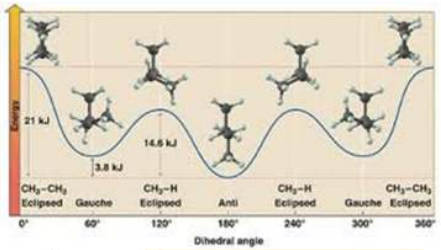


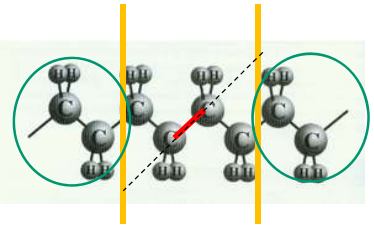
Hosszútávú kölcsönhatások

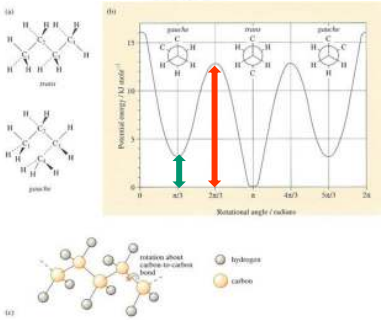


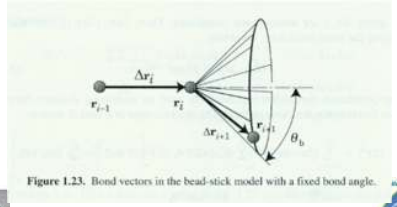
Polimerek hajlékonyságát a rövidtávú kölcsönhatások- és a termikus energia viszonya határozzák meg



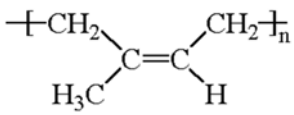




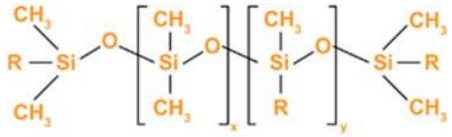




Hajlékony láncú polimerek



kaucsuk,
polyisoprene



szilikon gumi,
polidimetilsziloxán

A rotáló egységek közötti távolság növelése kedvez a hajlékonyságnak!

Hajlékonyláncú polimerek térszerkezete

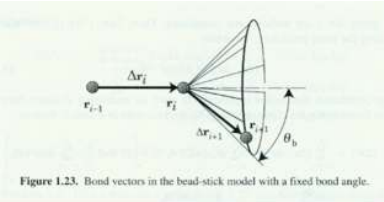
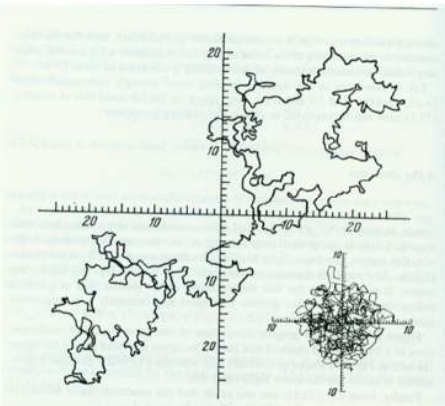
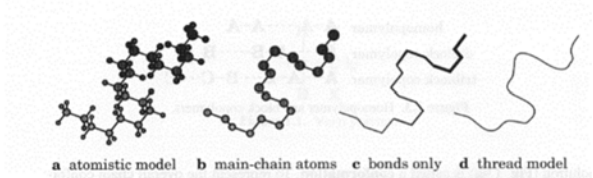


Figure 1.23. Bond vectors in the bead-stick model with a fixed bond angle.

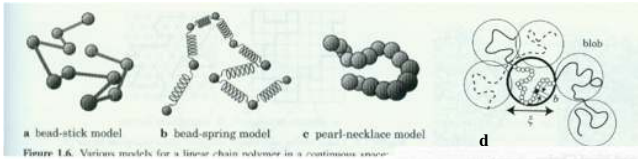


Tipikus konformáció: **statisztikus gombolyag**.

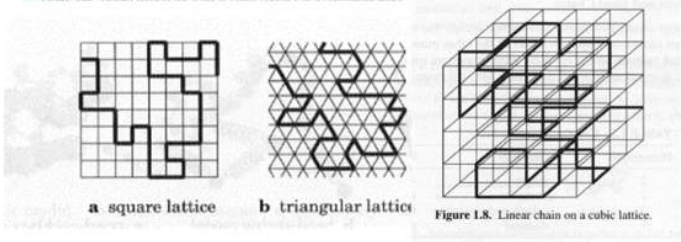
Hajlékony polimerek modelljei



a atomistic model b main-chain atoms c bonds only d thread model



a bead-stick model b bead-spring model c pearl-necklace model

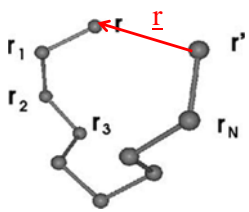


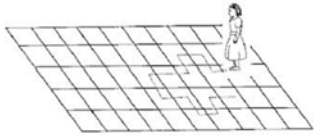
a square lattice b triangular lattice

Figure 1.8. Linear chain on a cubic lattice.

Ideális makromolekula

Analógia a bolyongás és a konformáció között.





$$\underline{r} = \sum_{i=1}^{N_s} \underline{r}_i \qquad <\underline{r}>= 0$$

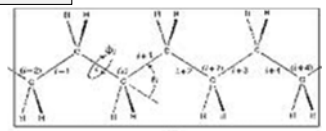
$$<\underline{r}^2> \neq 0$$

$$r^2 = \sum_{i=1}^{N_s}\sum_{j=1}^{N_s} \underline{r}_i \underline{r}_j = \sum_{i=1}^{N_s} r_i^2 + 2\sum_{i<j}^{N_s} r_i r_j = N a_s^2 + 2\sum_{i<j}^{N_s} a_s^2 \cos\alpha_{ij}$$

$$R_o \equiv <r^2>^{1/2}$$

$$\boxed{R_0 = a_s N_s^{1/2}}$$

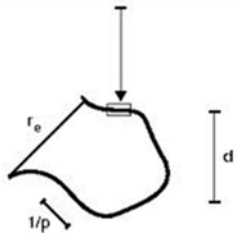
Rövidtávú kölcsönhatások (kémiai szerkezet)



Vegyérték szög → $R_\vartheta = 1\left(\frac{1+\cos\vartheta}{1-\cos\vartheta}\right)^{1/2} . N^{1/2}$

Vegyérték szög + Rotációs energia → $R_{\vartheta,\varphi} = 1\left(\frac{1+\cos\vartheta}{1-\cos\vartheta}\,\frac{1+<\cos\varphi>}{1-<\cos\varphi>}\right)^{1/2} N^{1/2}$

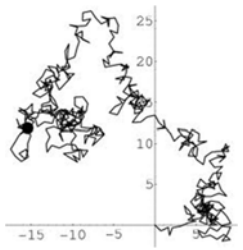
$$<\cos\varphi> = \int_{-\pi}^{\pi} \cos\varphi . e^{-\frac{U(\varphi)}{RT}} d\varphi$$

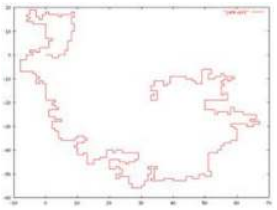


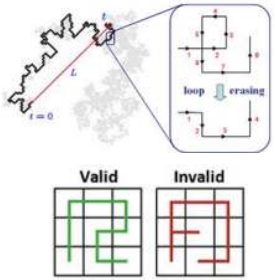
Ideális makromolekula

$$\boxed{R_\Theta = \ell \cdot C_\infty \cdot N^{1/2} = C_\infty R_0 \longrightarrow R_\Theta = \ell \cdot C_\infty \cdot N^{1/2} = a_s N_s^{1/2}}$$

Karakterisztikus arány







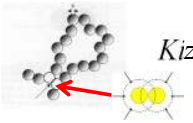
bolyongás
random walk (RW)

→

önelkerülő bolyongás
self avoiding walk (SAW)

$$R_0 = a_s N_s^{1/2}$$

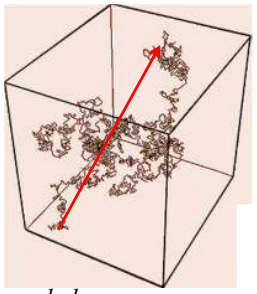
$$R_0 = a_s N_s^{\nu} \qquad \nu = 0.588 \approx 3/5$$



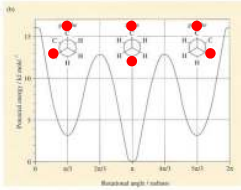
Kizárt térfogat hatás!

A ***W* termodinamikai valószínűség** megadja az adott **makroállapot**hoz tartozó **mikroállapot**ok számát.

példa: **makroállapot**: láncvégtávolság
mikroállapot: lehetséges konformációk száma



gombolyag, g



nyújtott, ny

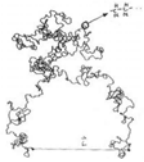
$$S = k_B \ln W$$

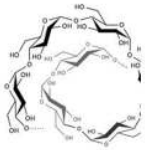
$$N_{C-C} = 10^4$$
$$W_g = 3^{10000}$$
$$S_g = k_B T \ln(3^{10000})$$
$$\boxed{S_g = 10^4 k_B T \ln 3}$$

$$N_{C-C} = 10^4$$
$$W_{ny} = 1$$
$$S_{ny} = k_B T \ln 1$$
$$\boxed{S_{ny} = 0}$$

Térszerkezet és konformációss entrópia

konstitúció - konfiguráció - konformáció



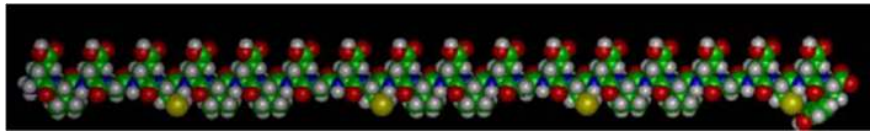


Statisztikus gombolyag

Szabályos térszerkezet

Nagy konformációs entrópia

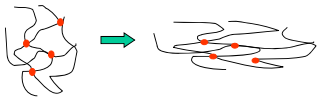
Jóval kisebb konformációs entrópia



W=1 → $S_{konf} = 0$

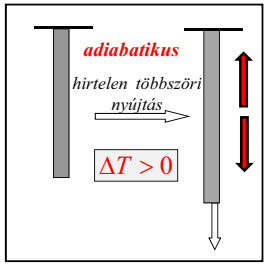
MAKROMOLEKULÁK RUGALMASSÁGA

Entrópia rugalmasság



$$\Delta S_{konfig} < 0$$

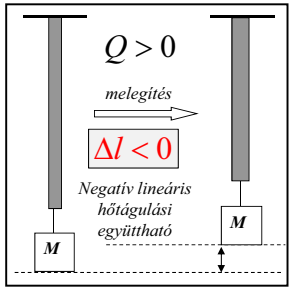
$$\Delta S = \Delta S_{konfig} + \Delta S_{term} = 0 \Rightarrow \Delta S_{term} > 0$$



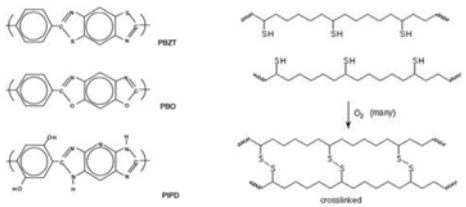
$$\Delta S_{term} \rightarrow \Delta S_{konfig} \qquad \Delta S_{konfig} > 0$$

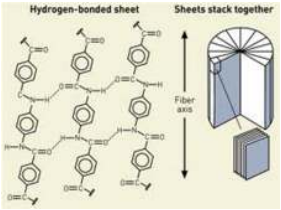
nyújtott → gombolyodott

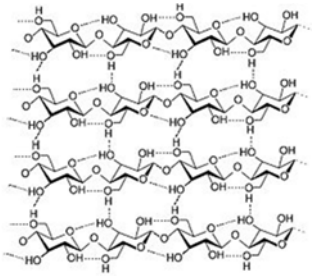
összehúzódás



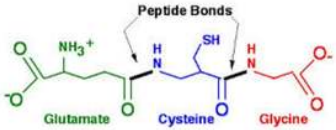
Merev polimer láncok

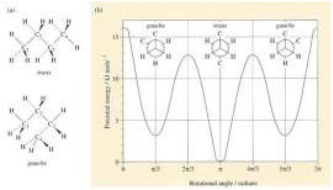




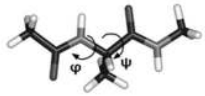


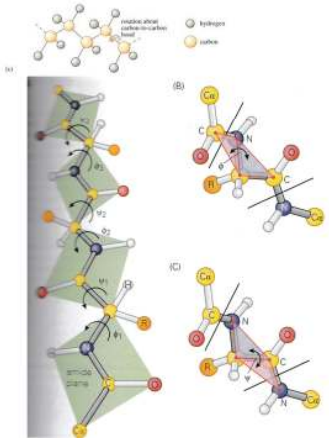
A láncokon belüli és a láncok közötti H-hidak, valamint a delokalizált π kötések merevítik a szerkezetet.

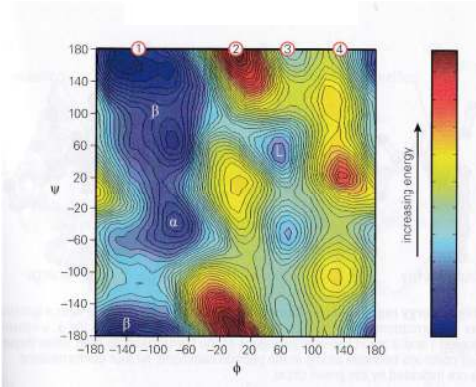




Ramachandram diagram



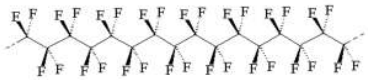


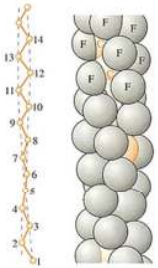


alanin dipeptid

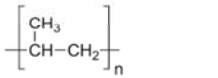
Rendezett szerkezetek

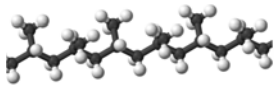
Teflon hélix

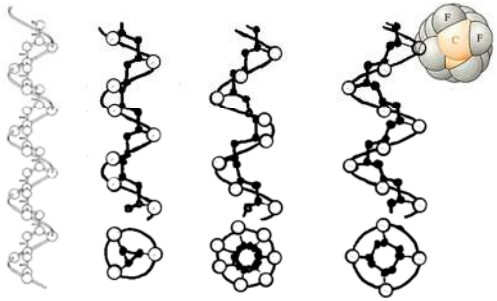




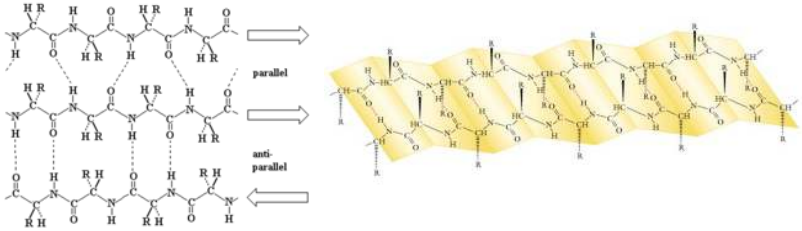
Izotaktikus szerkezetek hélixei

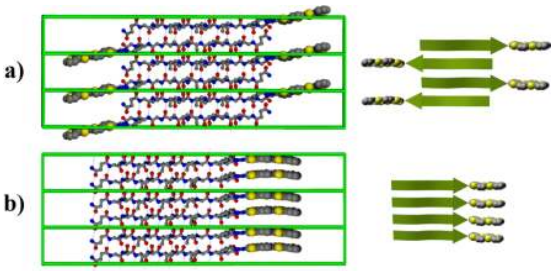






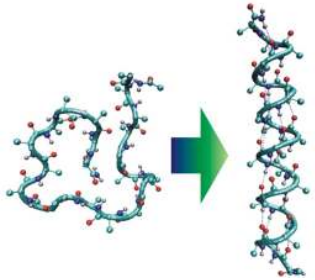
Rendezett szerkezetek





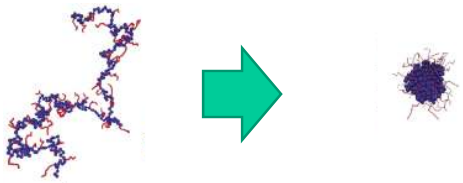
Molekuláris rendeződés

gombolyag ➡ hélix



$\Delta S_{konfig} < 0$

gombolyag ➡ globula



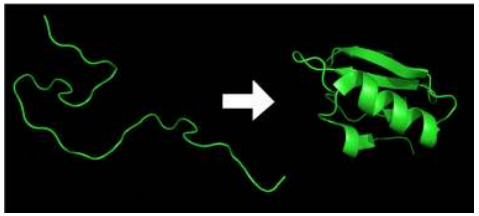
$\Delta S_{konfig} < 0$

Akkor mi a hajtóerő?

A MÁSODLAGOS SZERKEZET KIALAKULÁSÁNAK HAJTÓEREJE

hajtóerő

$\Delta G < 0$



A konformációs entrópia csökken!

$\Delta G_{konf} = \Delta H_{konf} - T\Delta S_{konf}$ $\Delta H_{konf} \leq 0$ $\Delta S_{konf} \ll 0$ ➡ $\Delta G_{konf} > 0$?

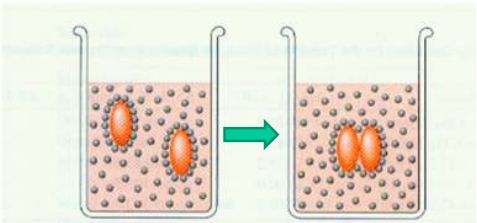
$\Delta G_{tot} = \Delta G_{konf} + \Delta G_{water}$ ← Hidrofób kölcsönhatás

Hidrofób kölcsönhatás

hajtóerő ➡ $\Delta S > 0$ ➡ $\Delta G < 0$

$$\Delta G = \Delta H - T\Delta S$$

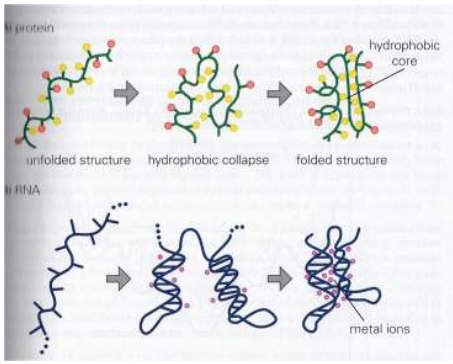
W. Kauzman

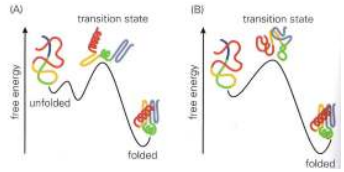


$\Delta H > 0$

$\Delta S > 0$ ➡ $\Delta G < 0$

A hajtogatódás termodinamikai hajtóereje a hidrofób kölcsönhatás





ELEGYEDÉS HAJTÓEREJE

$\Delta_e G < 0$

$$\Delta_e G = \Delta_e H - T\Delta_e S$$

elegyedési hő

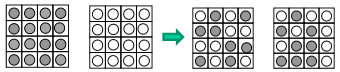
elegyedési entrópia

endoterm $\Delta_e H > 0$

atermikus $\Delta_e H = 0$

exoterm $\Delta_e H < 0$

Molekuláris rendezettség változása



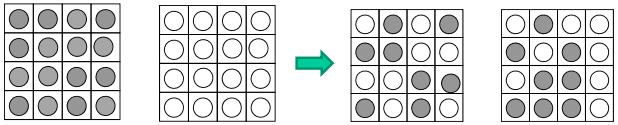
$\Delta_e S > 0$

A ***W* termodinamikai valószínűség** megadja az adott **makroállapot**hoz tartozó **mikroállapot**ok számát.

1. példa: **makroállapot**: koncentráció
mikroállapot: lehetséges

$$W = \frac{16!}{8!8!} = 12870$$

$x_A = 8/16$



$\Delta S > 0$

$S = k_B \ln W$

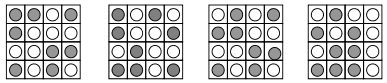
$W_A = 1$ $\quad S_B = 0$

$W_B = 1$

$W_{A,B} = 12870$

$S_{A,B} = k_B T \ln(12870)$

$$W_{A,B} = \frac{(N_A + N_B)!}{N_A! N_B!} = \frac{16!}{8!8!} = 12870$$



Négy különböző mikroállapot a lehetséges 12870 számából.

Miért oldódnak jobban a kismolekulájú anyagok?

$$\Delta_e G = \Delta_e H - T\Delta_e S$$

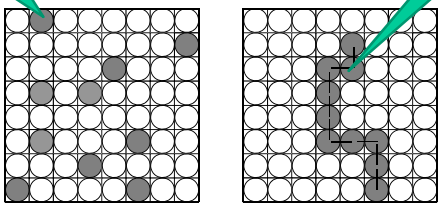
Atermikus eset: $\Delta_e G \cong -T\Delta_e S$

monomer

$$S = k_B \ln W$$

polimer

$c = \frac{10}{64}$



$c = \frac{10}{64}$

$$W_{A,B} = \frac{(N_A + N_B)!}{N_A! N_B!} = 1{,}51 \cdot 10^{11}$$

$$S_{A,B} = k_B \ln(1{,}51 \cdot 10^{11})$$

$$\Delta G_{A,B} = -k_B T \ln(1{,}51 \cdot 10^{11})$$

Nagyobb termodinamikai hajtóerő!

$$W_{A,B} = 64 \cdot 4 \cdot 3^8 = 6144$$

$$S_{P,A} = k_B \ln(6144)$$

$$\Delta G_{P,A} = -k_B T \ln(6144)$$

Kisebb termodinamikai hajtóerő!