

BIOHYSICS OF WATER

KELLERMAYER MIKLÓS

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Water

- Source of *inspiration* (music, paintings).
- Thales (580, B.C.): "...water is source of all things..."
- Henry Cavendish (1783): water is H_2O .
- Only chemical that naturally exists in *all three states* (solid, liquid, gas).
- Numerous anomalous properties.
- 71% of the Earth's surface is covered with water ("blue planet").
- Water is of utmost importance for *life*:
98% of jellyfish
94% of three-month human fetus
72% of newborn
60% of adult
- Average daily water intake: 2.4 liters.



Georg Friedrich Händel (1685-1759): "Water music".



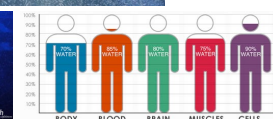
Georg Friedrich Händel (center) and King George I (right) on the Thames River, 17 July 1717.



Hokusai (1760-1849): Great wave off Kanagawa



Perpetual motion of oceans on Earth's surface.

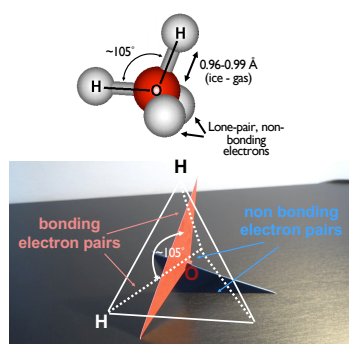


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Structure of the water molecule

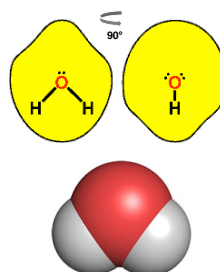
One of the smallest molecules barely larger than an atom

Electron pair geometry is tetrahedral



Shape is angular, „V“-like

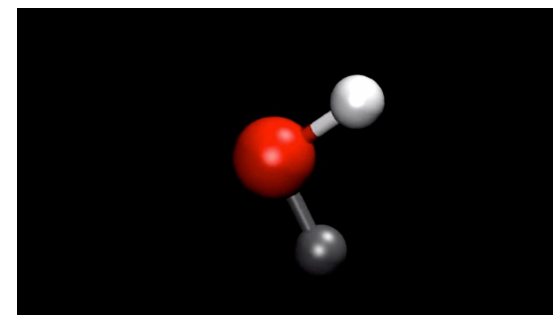
van der Waals radius: ~ 3.2 Å
Its shape is not spherical



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Dynamics of the water molecule

Rotational and vibrational motion

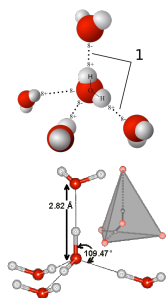


Absorption in the infrared and red spectral region →
"blue" color of natural waters: *blue planet*

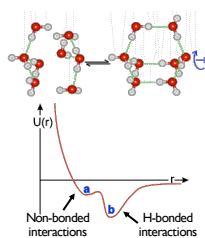
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Structure of liquid water

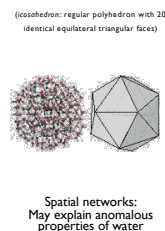
Hydrogen bonds in the vicinity of a water molecule: formation of the water pentamer



H-bridge: cohesion + repulsion
Cluster formation: bicyclo-octamer



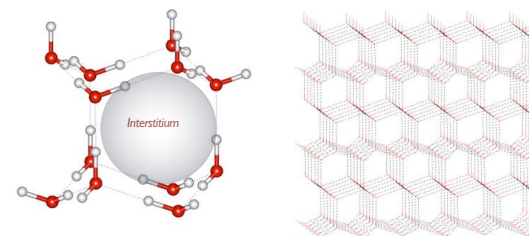
From clusters to networks:
280 molecules form icosahedral structure



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Structure of ice

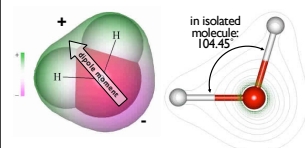
- 9 different forms
- Conventional ice: hexagonal structure
- Coordination number: 4 (each molecule coordinates another four)
- Interstitium: could incorporate a water molecule - important in the diffusion of gases



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Physical properties of water I.

Large permanent dipole moment → Good solvent



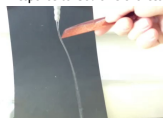
Dipole moment: A measure of the separation of positive and negative electrical charges within a system, that is, a measure of the system's overall polarity.

$$p = q \cdot d$$

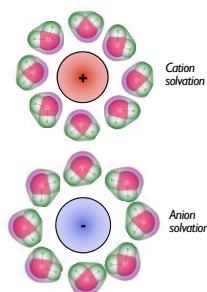
p – dipole moment (unit: $C \cdot m$)
 q – charge (unit: C)
 d – distance between charges (unit: m)

Chemical	Dipole moment ($\times 10^{-30} C \cdot m$)
CO_2	0
CO	0.4
O_3	1.8
NH_3	4.7
H_2O	6.2
KBr	34.7

Water stream bends in response to Coulombic forces



Courtesy of Prof. Miklós Zsigyi



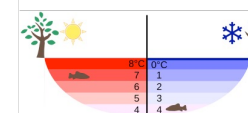
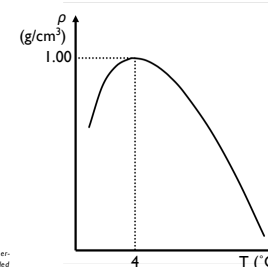
In the microwave oven: dipoles rotate according to the oscillating electromagnetic field. Water molecules acquire kinetic energy, which dissipates into the surroundings.

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Physical properties of water II.

Anomalous density-temperature function

Temperature ($^{\circ}C$)	Density (kg/m^3)
+100	958.4
+80	971.8
+60	983.2
+40	992.2
+30	995.6502
+25	997.0479
+22	997.7735
+20	998.2071
+15	999.1026
+10	999.7026
+4	999.9720
0	999.8395
-10	998.117
-20	993.547
-30	983.854



Consequences:

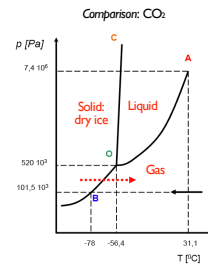
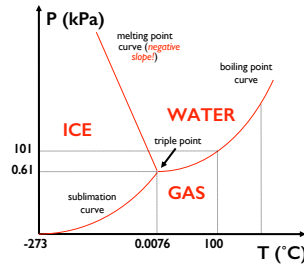
- 4 $^{\circ}C$ water is always at the bottom of the lake.
- Life persists under frozen lake.
- Creek runs under ice.

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Physical properties of water III.

Anomalous phase diagram

- Phase curve: two phases are in equilibrium
- Area between phase curves: a single phase is present
- Intersection of phase curves: triple point



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Physical properties of water IV.

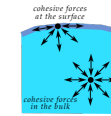
Large surface tension

Surface tension (γ): contractive tendency of the liquid that resists external force.

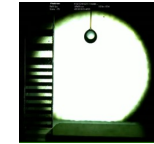
Work required to increase the surface area.

$$\gamma = \frac{W}{A} = \left[\frac{J}{m^2} = \frac{N}{m} \right]$$

Inequality between the cohesive forces inside and on the surface of a fluid.



Consequences on **hydrophobic** surface



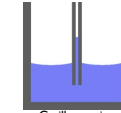
Persisting droplet on a superhydrophobic surface

Consequences in macroscopic living systems



Water striders

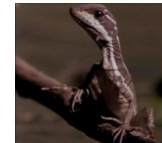
Consequences on **hydrophilic** surface



Capillary action (model)



Capillary action aiding plant root function



"Jesus Christ lizard" (basilisk)

Chemical	Surface tension (mN/m)
Ethanol	24.4
Methanol	22.7
Acetone	23.7
Chloroform	27.1
Benzene	28.5
Water	72.9

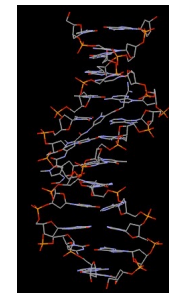
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BIOHYSICS OF BIOLOGICAL MACROMOLECULES

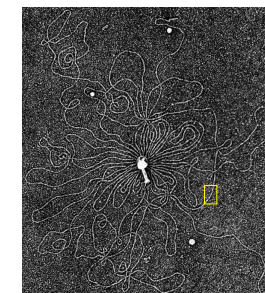
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Biological macromolecules are **GIANT** molecules



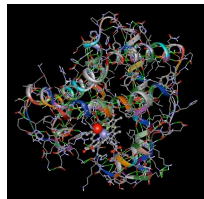
DNA double helix



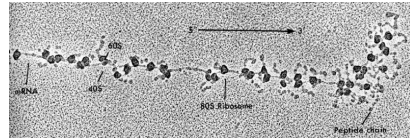
DNA released from bacteriophage head

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Biological macromolecules are **EXCITING** molecules



Structure of hemoglobin subunit



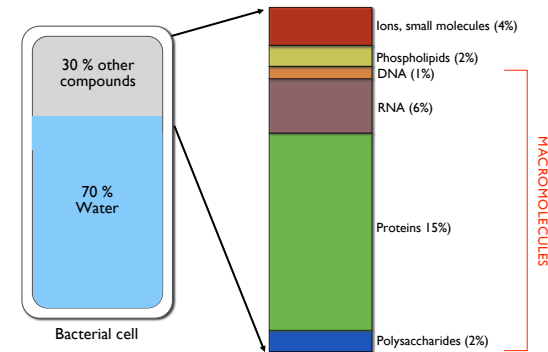
Newly synthesized protein (silk fibroin)



Folding of nascent protein (on the ribosome)

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Proportion of macromolecules in the cell by mass is **LARGE**



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Biological macromolecules: biopolymers

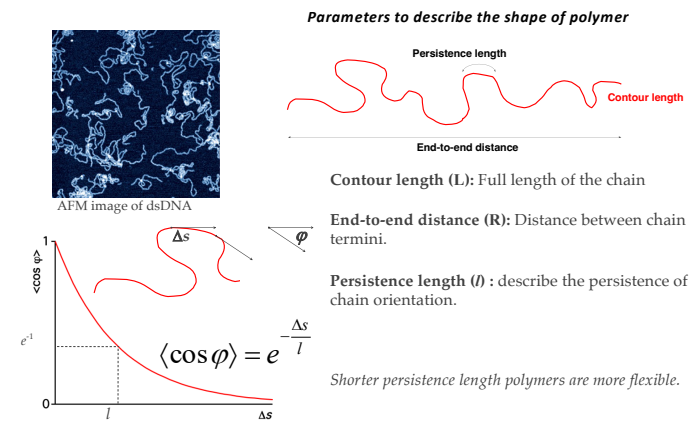
Polymers:
chains built up from monomers

Number of monomers: $N \gg 1$;
Typically, $N \sim 10^2 - 10^4$,
but, in DNA, e.g.: $N \sim 10^9 - 10^{10}$

Biopolymer	Monomer	Bond
Protein	Amino acid	Covalent (peptide bond)
Nucleic acid (RNA, DNA)	Nucleotide (CTUGA)	Covalent (phosphodiester)
Polysaccharide (e.g., glycogen)	Sugar (e.g., glucose)	Covalent (e.g., α -glycosidic)
Protein polymer (e.g., microtubule)	Protein (e.g., tubulin)	Secondary

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What is the shape of biopolymers?



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Biopolymer classification based on flexibility

l = persistence length
 L = contour length

RIGID
 $l \gg L$

Microtubules

SEMIFLEXIBLE
 $l \approx L$

Microfilaments

FLEXIBLE
 $l \ll L$

DNA

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Are biopolymers elastic?

Yes, but Hooke's law is not valid! Non-linear elasticity.

Entropic elasticity

Thermal energy ($k_B T$) excites bending movements in the chain

The chain's disorder (configuration entropy) increases

Due to entropy maximization the chain shortens

Force is needed to stretch an entropic chain

$$F \sim \frac{k_B T}{L} \cdot \frac{R}{l} + \left(\frac{R}{L}\right)^a$$

F = force
 l = persistence length
 k_B = Boltzmann constant
 T = absolute temperature
 L = contour length
 R = end-to-end distance
 R/L = relative extension

Nonlinear elasticity

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Shape of the polymer chain resembles random walk

Brownian motion:
"random walk"

Shape of polymer:
"random chain"

"Square-root law":

$$\langle R^2 \rangle = Nl^2 = Ll$$

R = end-to-end distance
 N = number of elementary vectors
 $l = |\vec{r}|$ = correlation length
 \vec{r}_i = elementary vector
 $Nl = L$ = contour length
 l is related to **bending rigidity**.

In case of Brownian-movement R = displacement, N = number of elementary steps, L = total path length, and l = mean free path length.

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I. DNA: deoxyribonucleic acid

Function: molecule of biological information storage

Chemical structure

Thymine, Adenine, Cytosine, Guanine, Phosphate-deoxyribose backbone, 5' end, 3' end

3D structure: double helix

Various DNA structures

A-DNA, B-DNA, Z-DNA

Depends on hydration, ionic environment, chemical modification (e.g., methylation), direction of superhelix

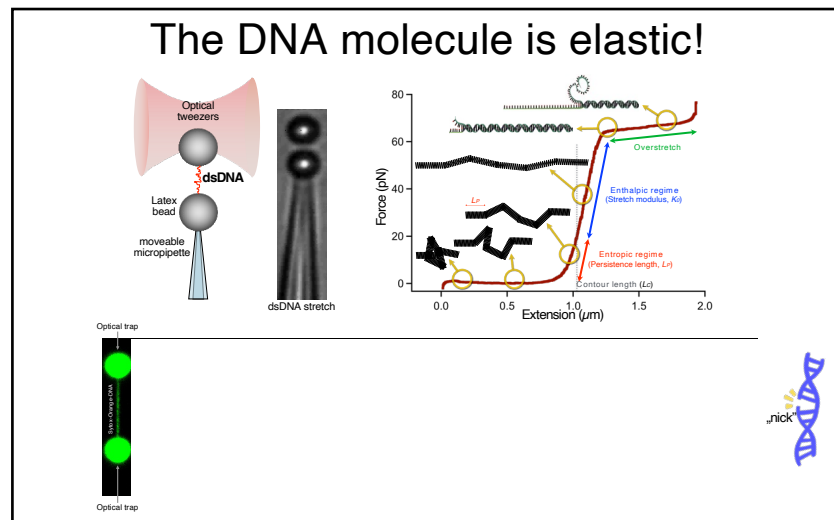
"Watson-Crick" base pairing via H-bonds
Gene sequence is of central significance in molecular genetics

Intercalation

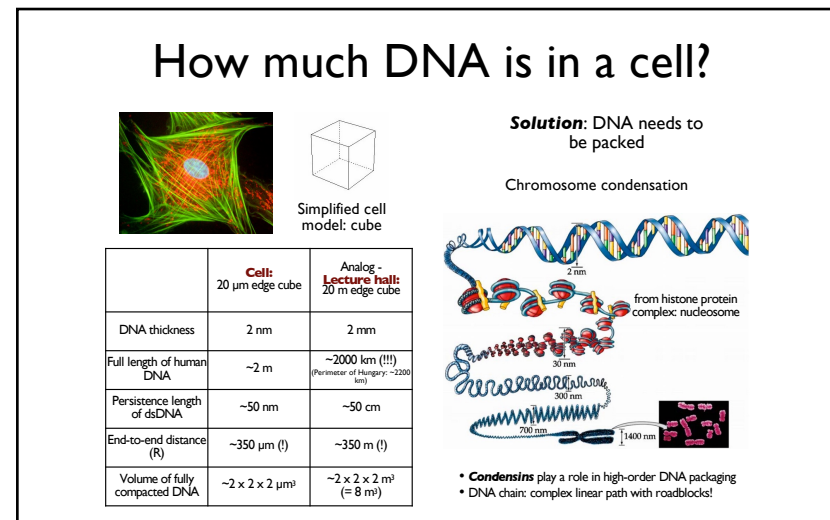
Large groove, Small groove

DNA nanostructures (origami)
Depends on base-pairing order and hierarchy

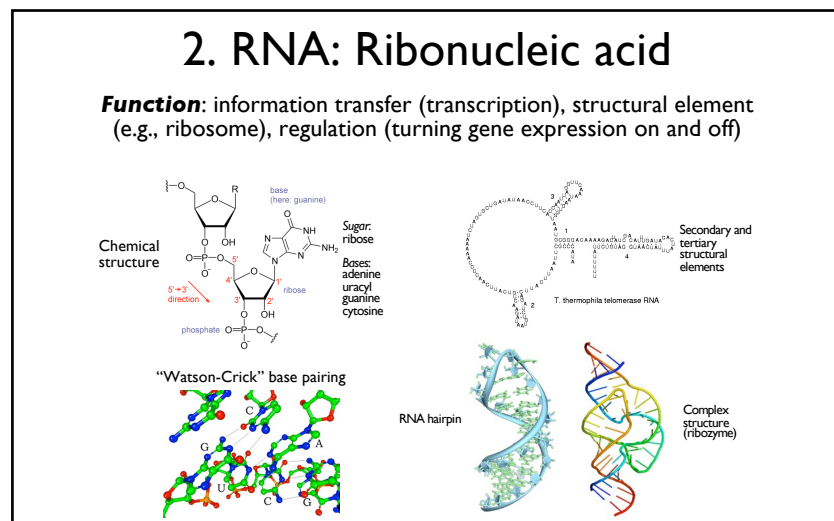
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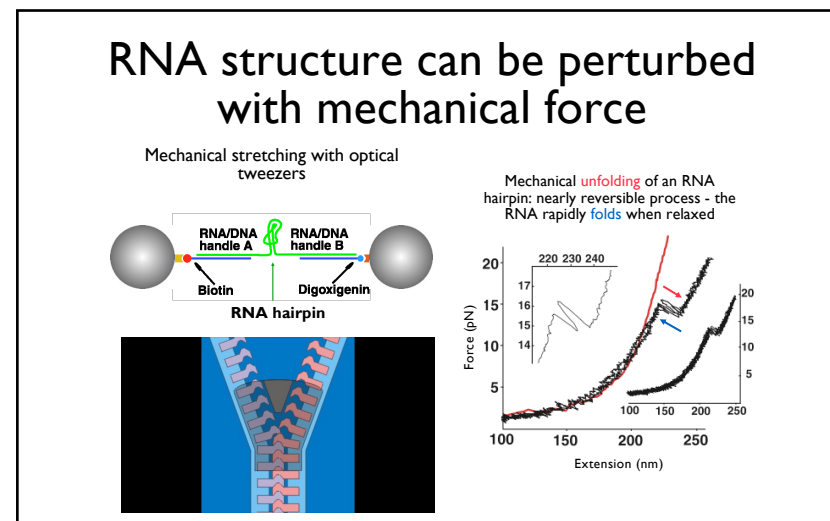
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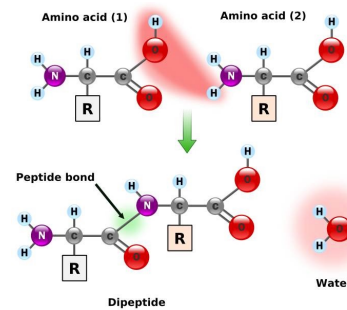
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3. Proteins: polymers connected with peptide bonds

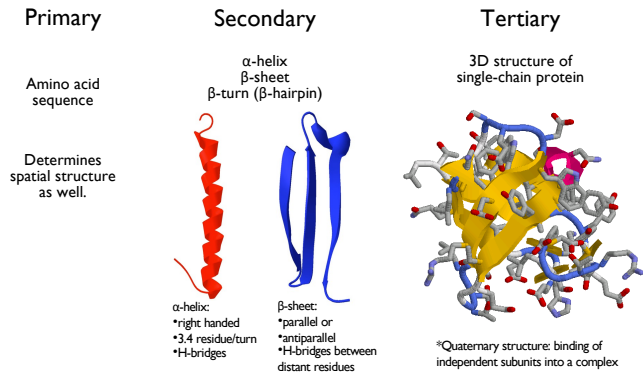
Function: most important molecules of the cell. Highly diverse functions - structure, chemical catalysis energy transduction, motoric functions, etc.



Formation of the peptide bond: condensation reaction followed by the release of water

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Protein structure



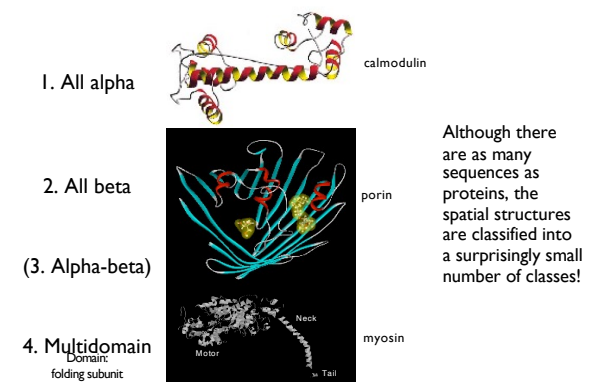
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Bonds holding protein structure together

- | | | |
|------------------------|---|--|
| Weak (secondary) bonds | ↑ | 1. Hydrogen bond: proton sharing between proton-donor side chains. |
| | ↓ | 2. Electrostatic interaction (salt bridge): between oppositely charged residues. |
| | ↓ | 3. van der Waals bond: weak interaction between atoms (molecules) with closed electron shells. |
| | ↓ | 4. Hydrophobe-hydrophobe interaction: between hydrophobic residues (in the interior of the molecule). |
| Covalent bond | ↑ | 5. Disulfide bridge: between cysteine side chains; connects distant parts of the protein chain. |

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Protein structure classes

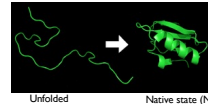


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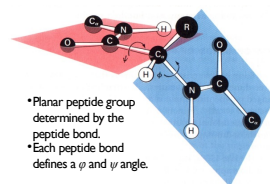
How is the three-dimensional structure acquired?



Anfinsen: proteins fold spontaneously (sequence determines structure)



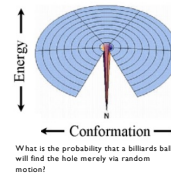
Levinthal's paradox (Cyrus Levinthal, 1969):
Are all available conformations explored?



Number of possible conformations (degrees of freedom): i^n

i = number of possible angular positions of a given ϕ or ψ angle
 n = total number of ϕ and ψ angles

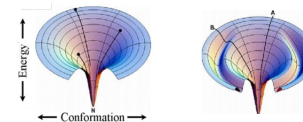
Example: in a peptide composed of 100 residues the number of possible ϕ or ψ angles is 2, $n=198$. Number of possible conformations: 2^{198} (!!!)



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Protein folding is guided by the shape of its conformational space

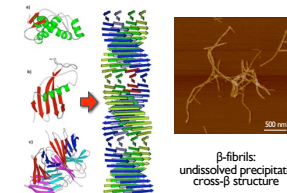
Shape of conformational space:
"Folding funnel"



- Proteins "slide down" the wall of the funnel.
- Folding funnel shape can be complex (determination of the shape is usually very difficult).
- A protein may get stuck at intermediate states (pathology).
- In the living cell chaperones assist folding.

Pathology

- Protein "folding diseases"
- Alzheimer's disease
- Parkinson's disease
- II-type diabetes
- Familial amyloidotic neuropathy

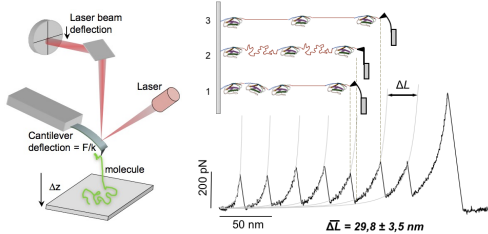


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Methods of protein unfolding (denaturation)

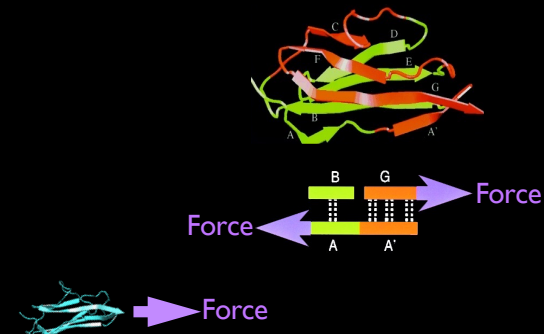
- Heat
 - Chemical agent
 - Mechanical force
- Break secondary chemical bonds
Disrupt secondary and tertiary structure

Mechanical unfolding of a single protein with atomic force microscope



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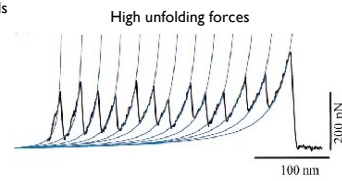
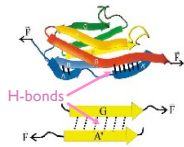
Structural basis of mechanical stability



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Biological logic of mechanical stability

Parallel coupling of structure-stabilizing H-bonds



Serial coupling of structure-stabilizing H-bonds

