SOFT MATTER PHYSICS AND THE PHYSICS OF LIVING MATTER

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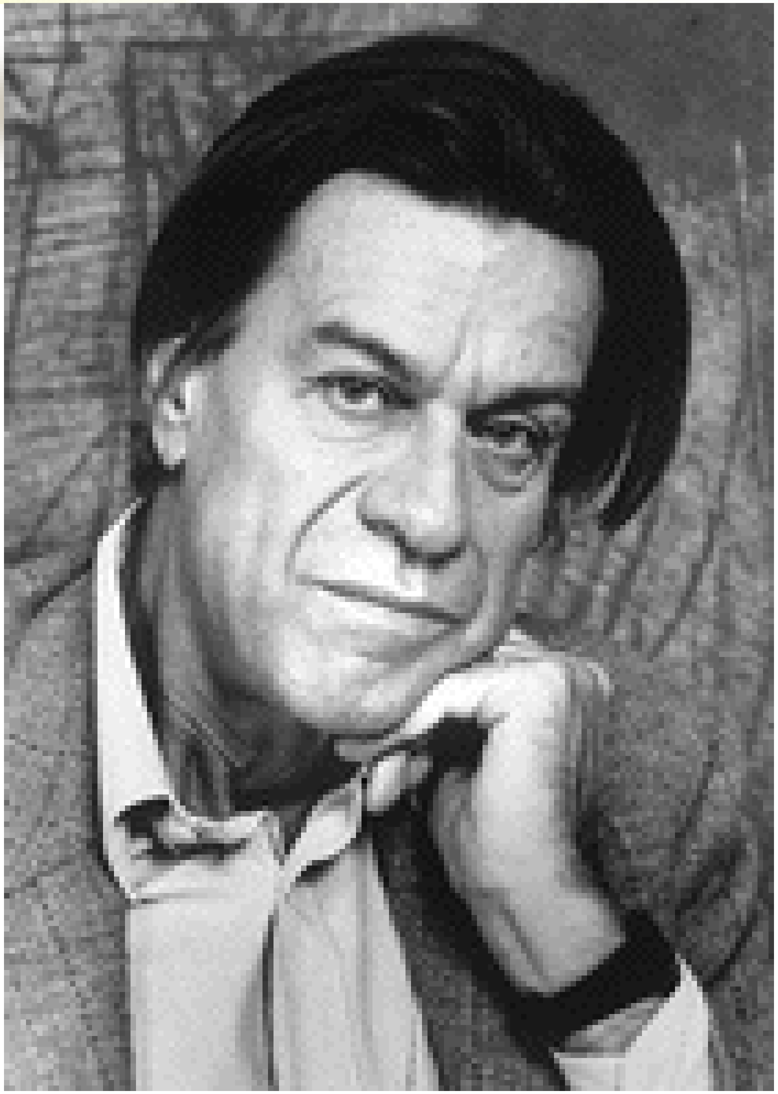
1. Soft Matter. Definition: intermediate condensed matter state between solids and liquids; structured in the intermediate range of the nanoscale.
2. Soft Matter Physics: chapters
3. Liquid crystals: translational and orientational melting or dissolving: solid, liquid and plastic crystals
4. Living matter as a soft nanocomposite
5. Theoretical description of Living Matter: Generalized Molecular Asymmetry Model
6. Flexoelectricity of Living Membranes

SOFT MATTER: new term in Condensed Matter Physics



First introduced by Pierre-Gilles de Gennes, NPW, in his Nobel Lecture (1991)

Angew. Chem. Int. Ed. Engl. ***31****, 842-845, (1992)*

(1932-2007)

- Complex liquids: caoutchouc. Milk, blood, ink, latex, mayonnaise.
- Soft condensed media: colloids, emulsions, suspensions, polymers, liquid crystals, etc.
- Mechanical properties of soft media: shear elastic modulus drastically lower than bulk compressibility modulus.

- Space scales of molecular organization:
  - microscopic (< 1 nm) isotropic liquids
  - mesoscopic (1-100 nm) soft matter
  - macroscopic (> 1 μm) solid crystals

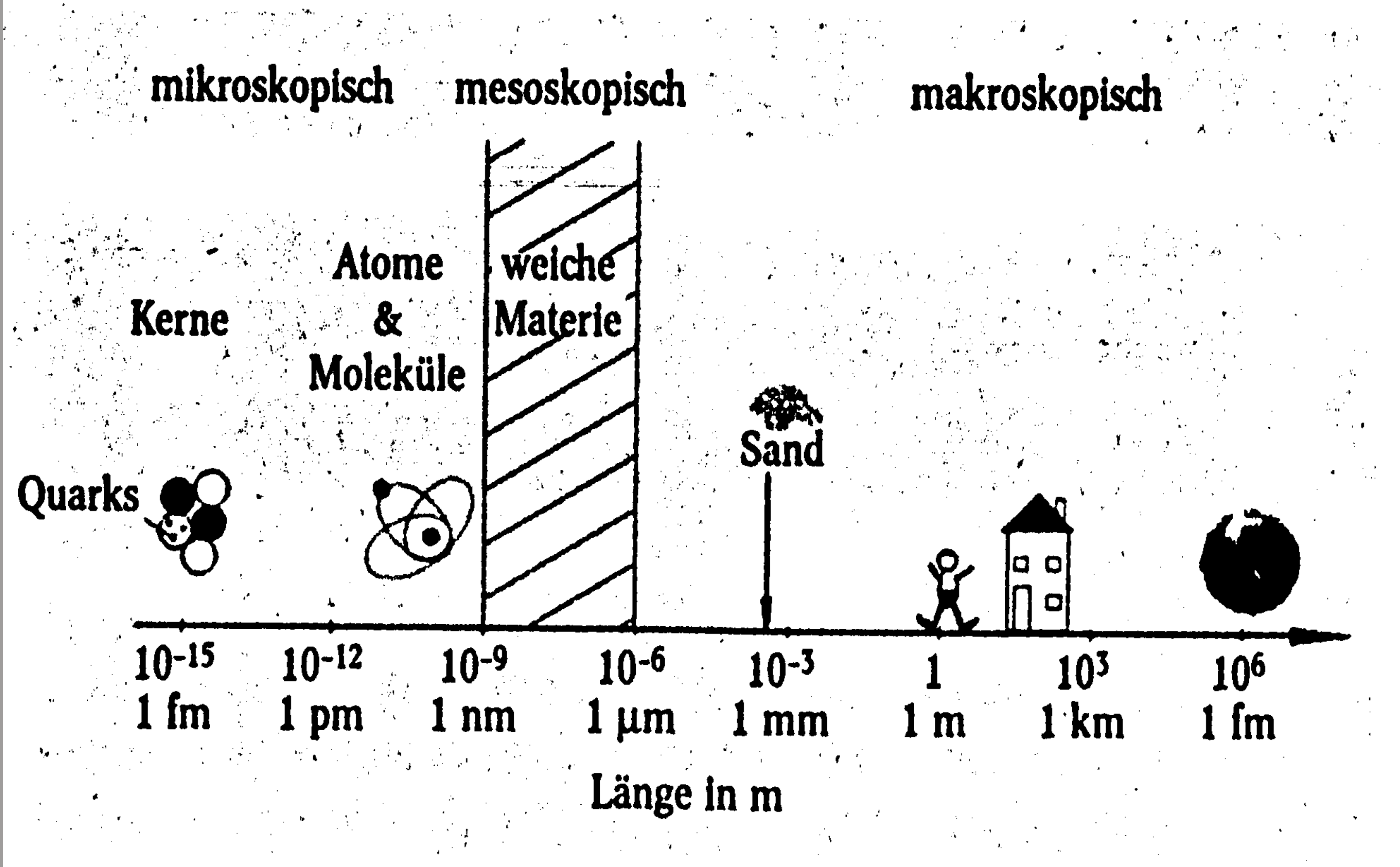
SOFT MATTER PHYSICS CHAPTERS:

- **Liquid crystal physics.** Thermotropics and lyotropics. Plastic crystals.
- **Polymer physics.** Melts, solutions, biopolymers
- **Physical chemistry.** Colloids and surfactans, foams, emulsions
- **Physics of networks.** Glues, rubbers, gels, cytoskeletons
- **Living matter physics.** Liquid crystalline biostructures, notably biomembranes
- **Physics of granular matter.** Sand, snow

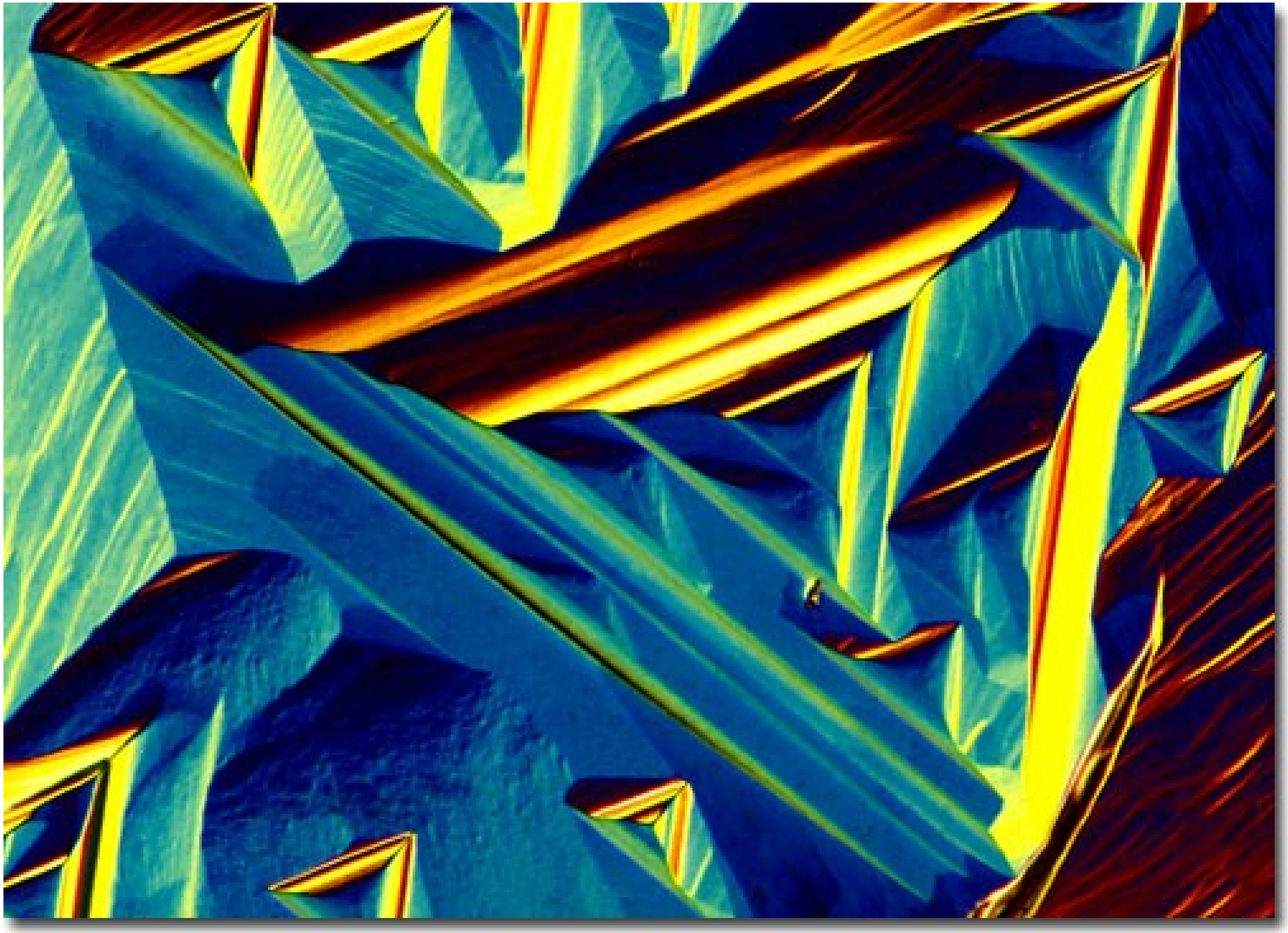
- *Basic question:*

Why is living matter soft?

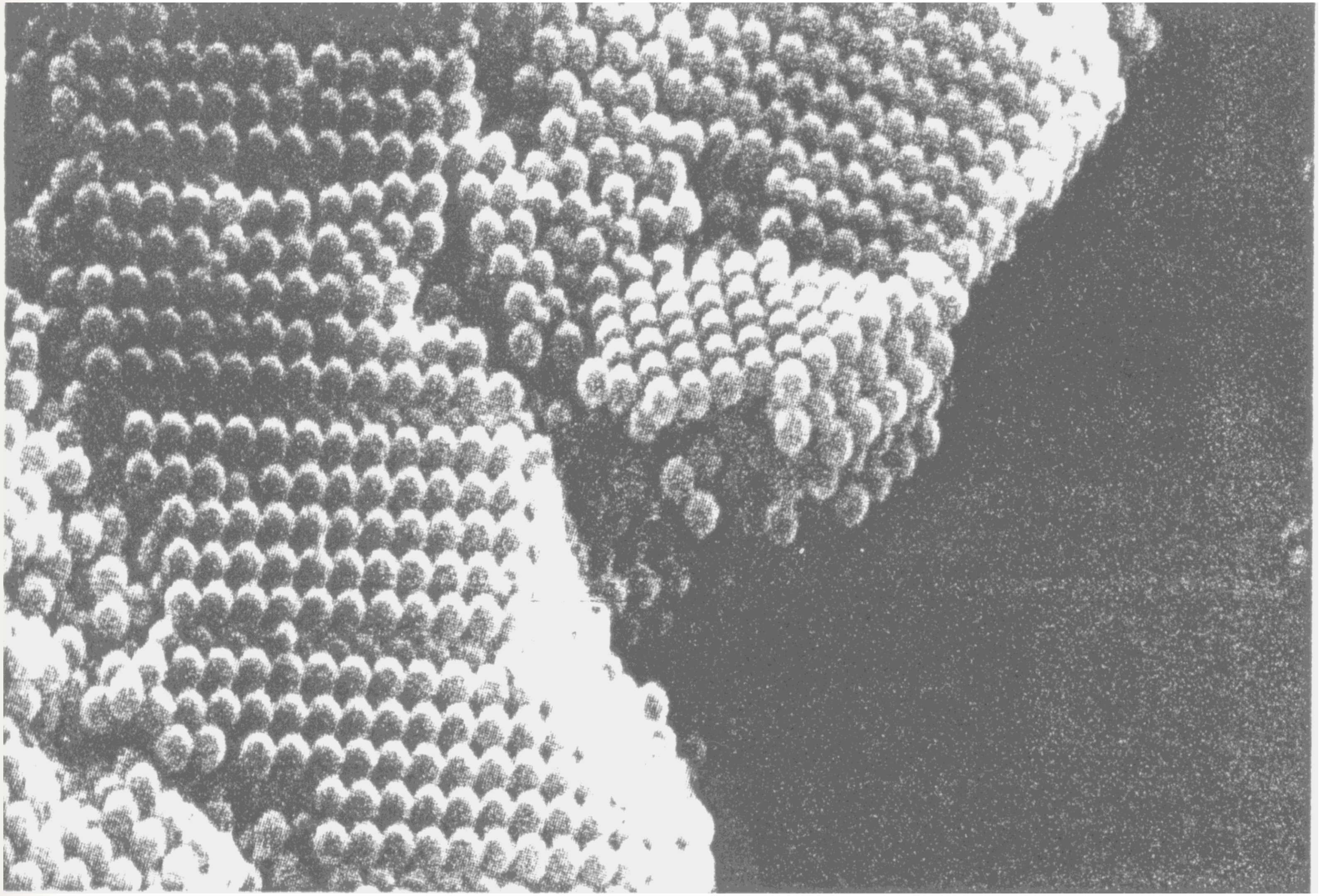
Space scales of molecular organization



DIAMOND UNDER MICROSCOPE

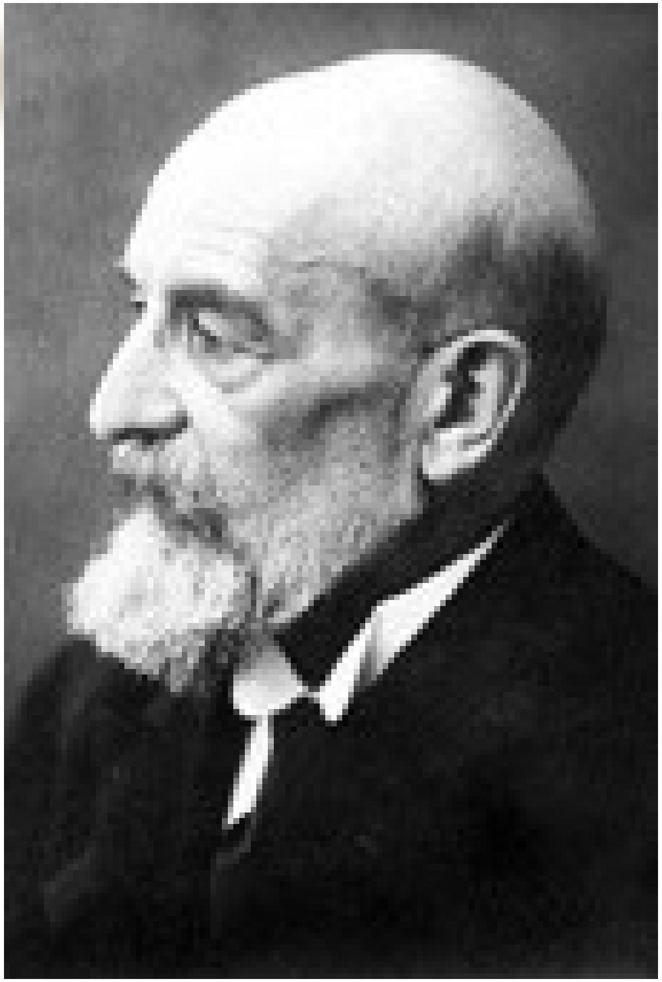


Colloid crystal of latex spheres in water: plastic crystal



Liquid Crystal Physics:

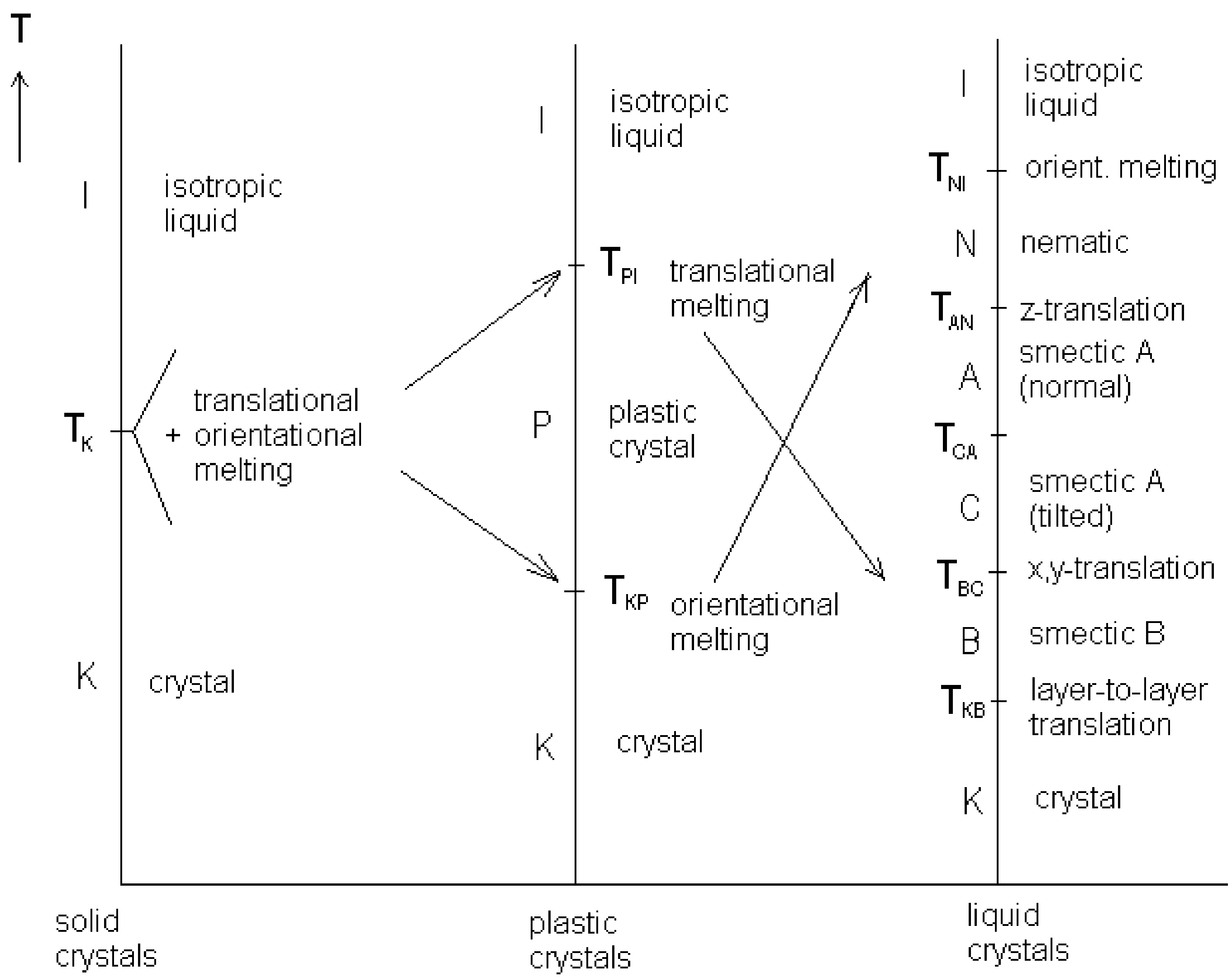
Georges Friedel



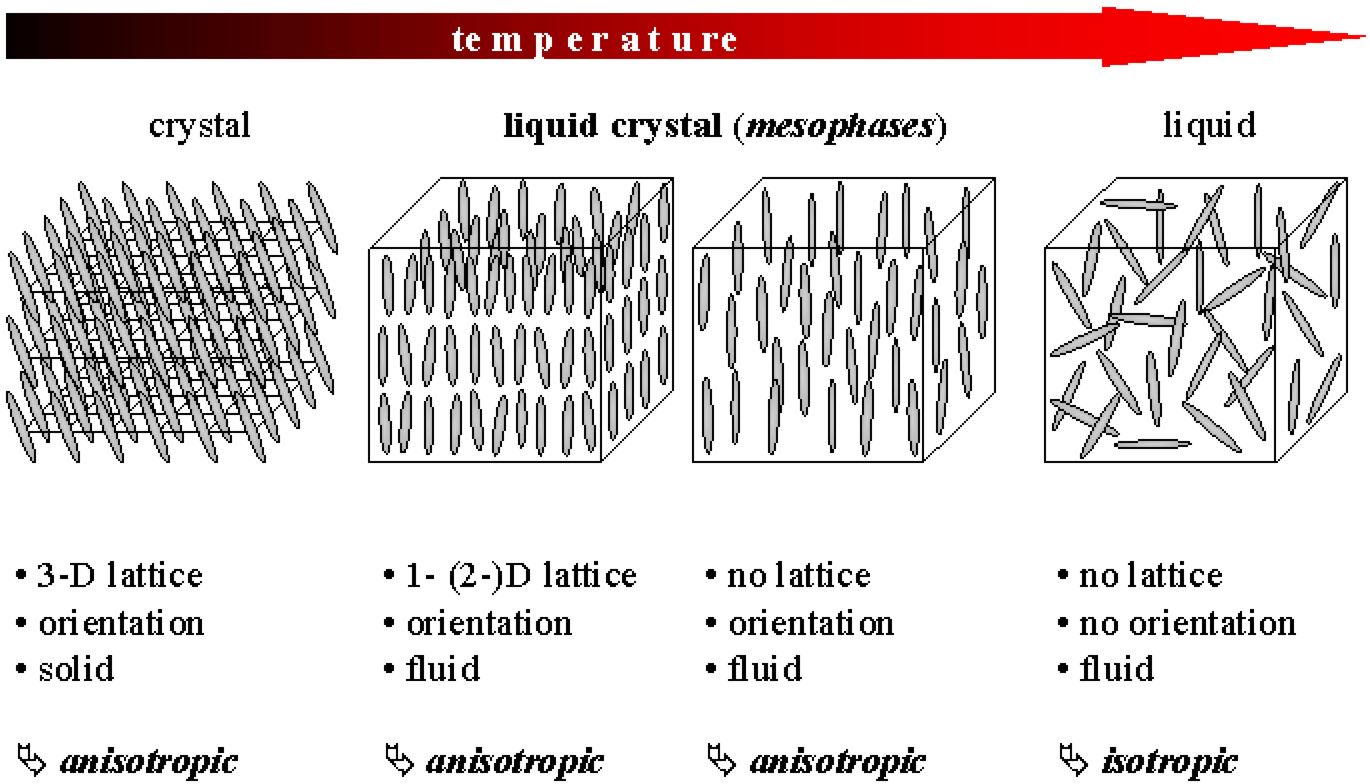
États mésomorphes de la matière (*Annales de Physique*, ***18,*** *273, 374, 1922*)

(1865-1933)

MELTING


T
I
isotropic liquid
T_K
translational + orientational melting
K
crystal
solid crystals
I
isotropic liquid
T_PI
translational melting
P
plastic crystal
T_KP
orientational melting
K
crystal
plastic crystals
I
isotropic liquid
T_NI
orient. melting
N
nematic
T_AN
z-translation
A
smectic A (normal)
T_CA
C
smectic A (tilted)
T_BC
x,y-translation
B
smectic B
T_KB
layer-to-layer translation
K
crystal
liquid crystals

thermotropic liquid crystals

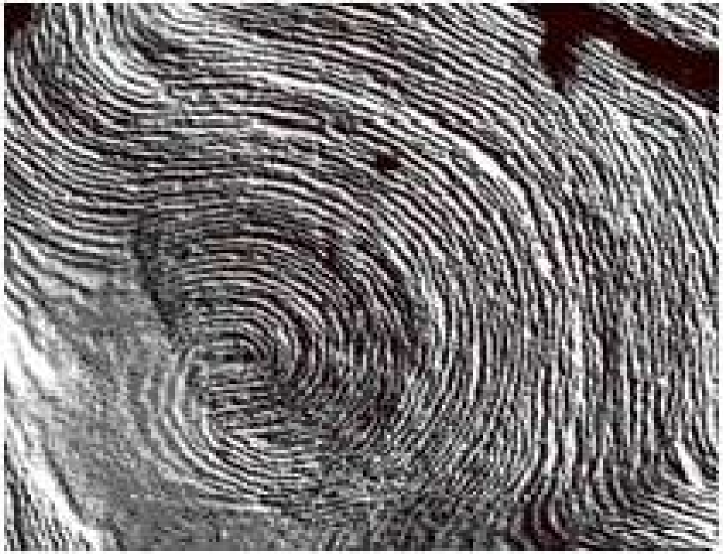


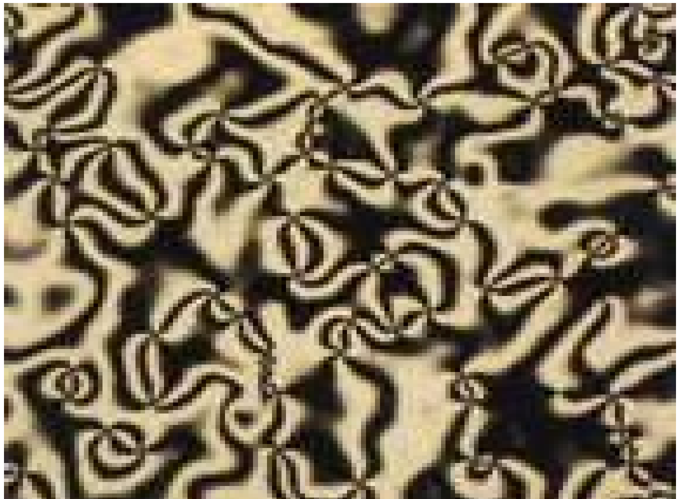
Liquid crystalline mesophases between the solid and isotropic liquid phase

SMECTIC A

Photo courtesy Dr. Mary Neubert LCI-KSU

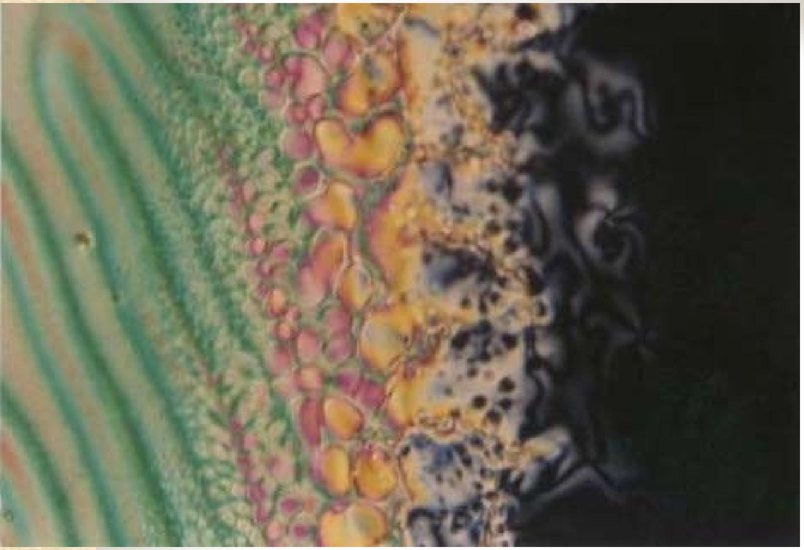
SMECTIC A (TEM)



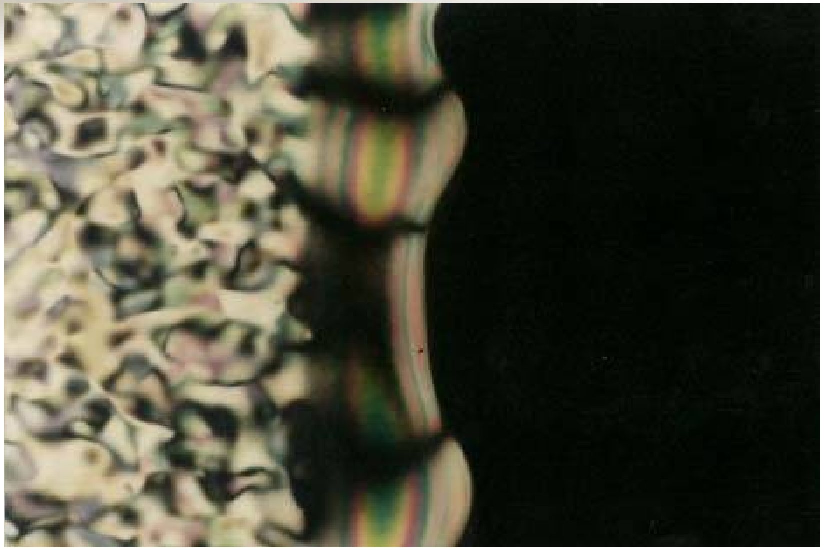


NEMATIC

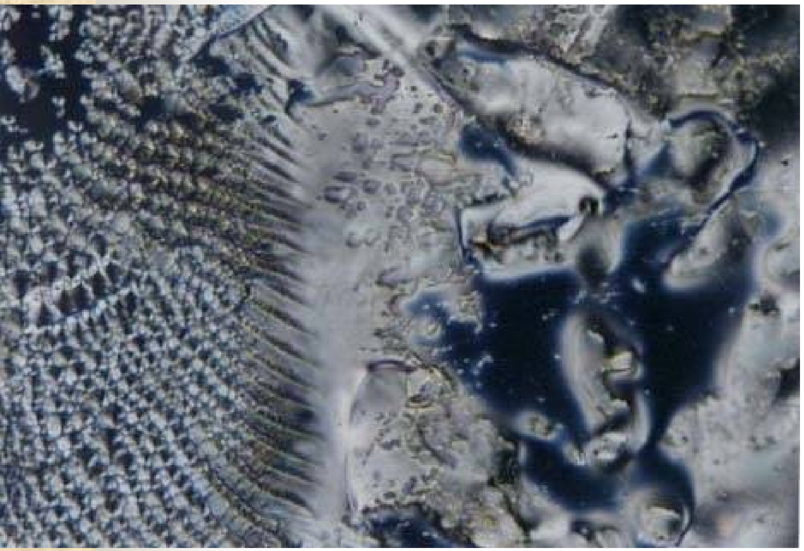
Phase transitions in thermotropics. Temperature wedge



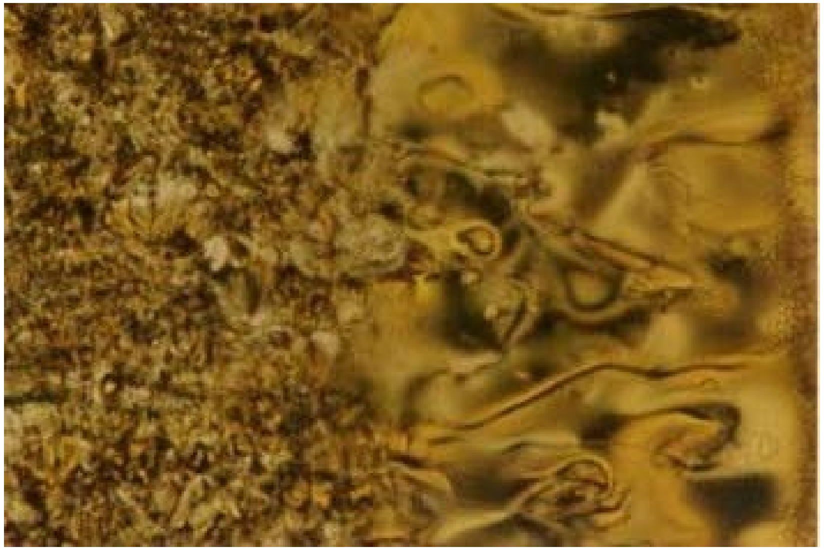
SmA - Iso



Nem - Iso



SmA - Nem



SmC - Nem

unique properties

orientational order + fluidity

☞ **"soft materials"**

→ *anisotropic fluids*
e.g. ***birefringent***

↓

easily manipulated by external fields

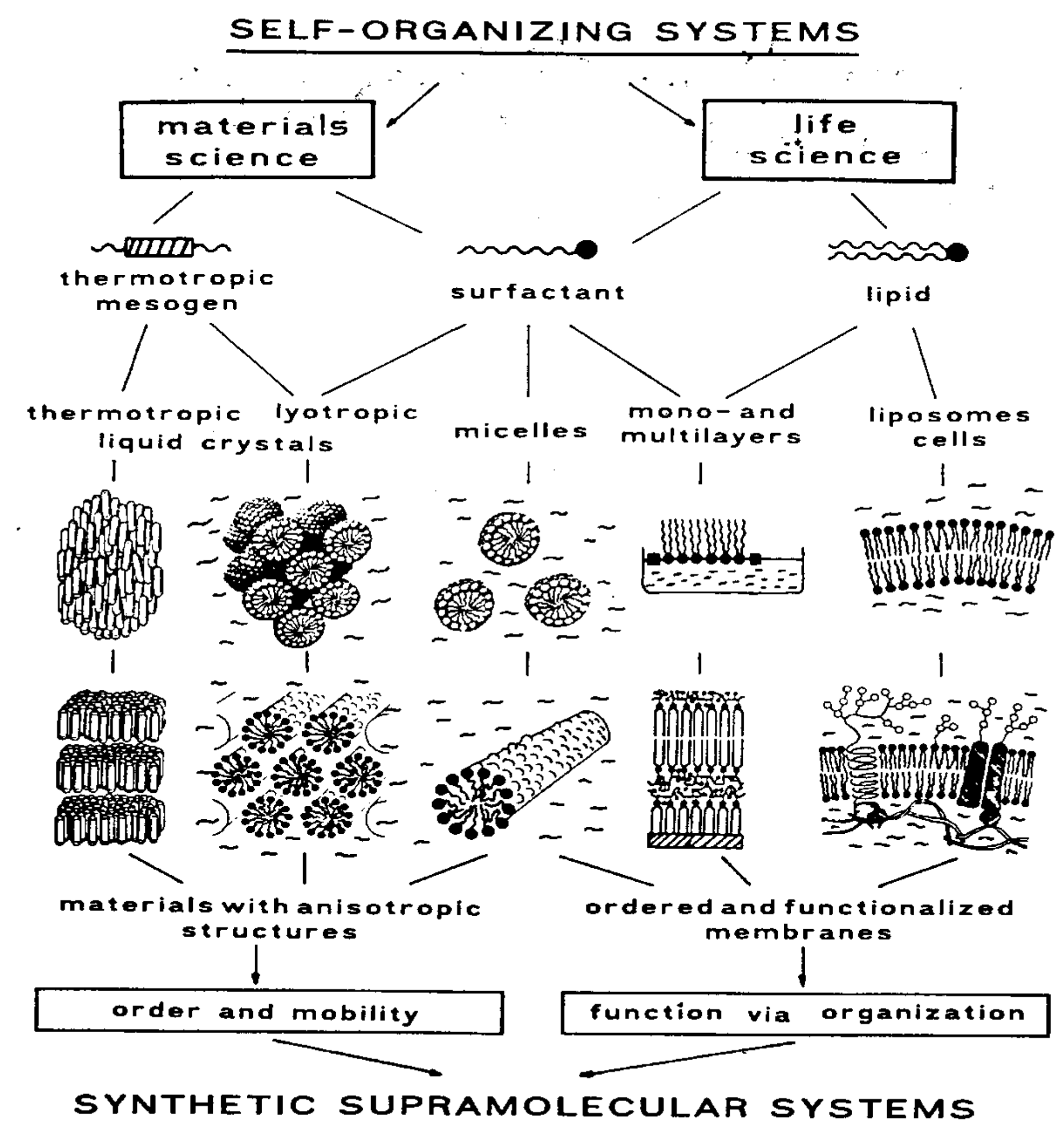
↓

strong: *magneto-optical*
electro-optical
opto-optical
effects

→ ***displays***
→ ***nonlinear optics***

THERMOTROPIC AND LYOTROPIC MESOGENS

LIQUID CRYSTAL WORLD: H. Ringsdorf

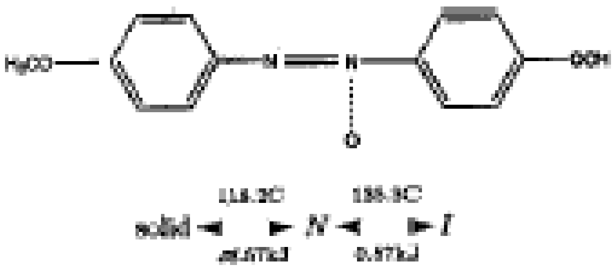


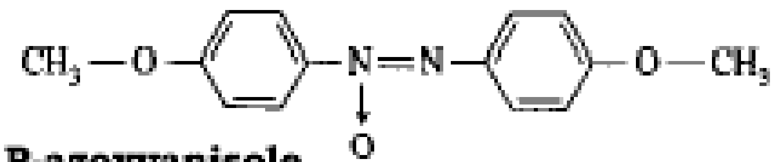
LEGOs of liquid crystals

Small organic molecules

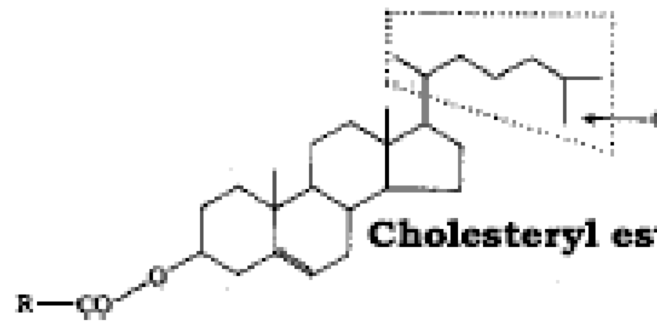
- Anisotropy
- Stiff backbone and flexible tails
- Typically thermotropic

4,4' - dimethyloxyazoxybenzene (p-azoxyanisole)

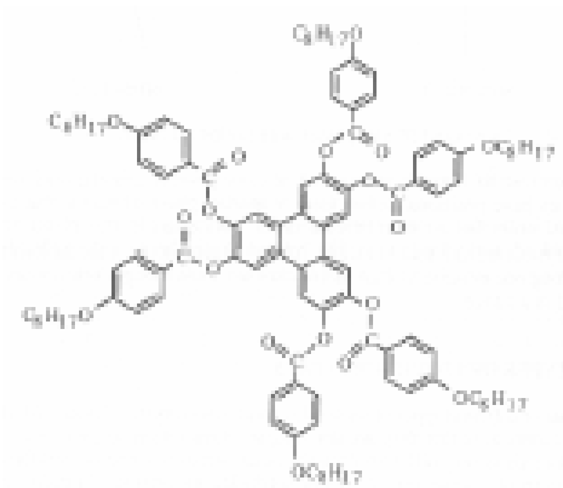




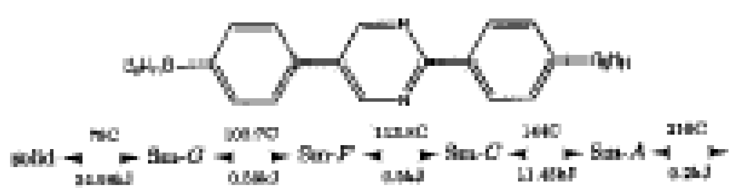
P-azoxyanisole (PAA)



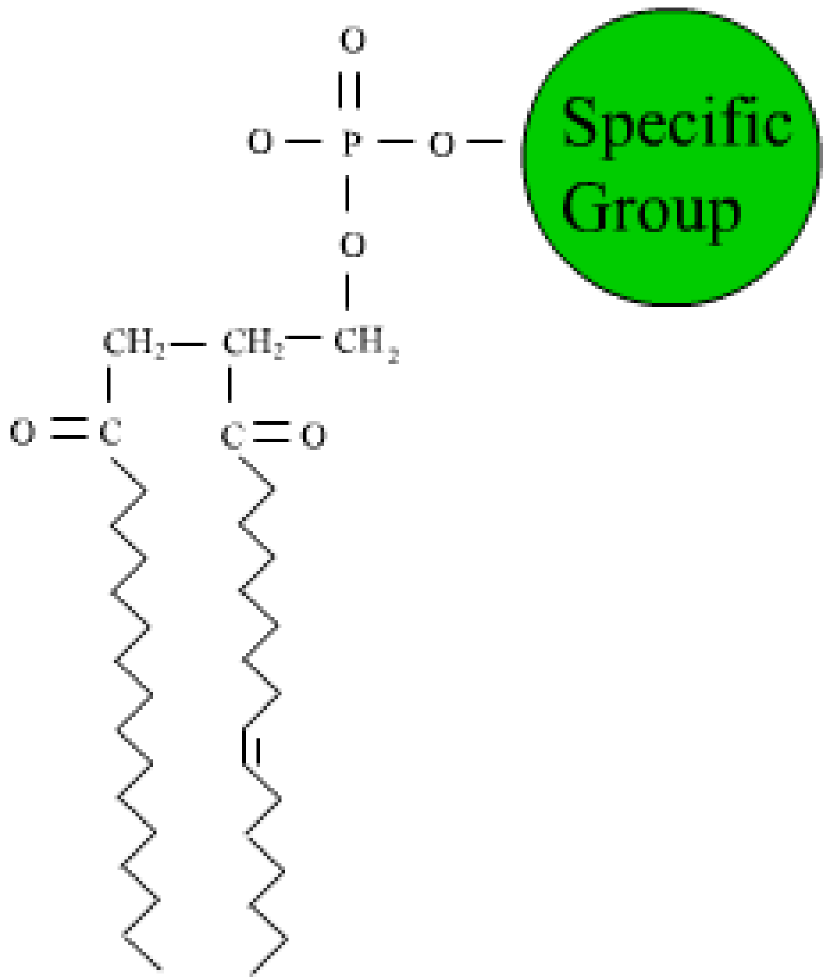
Cholesteryl ester



2-(4-n-pentylphenyl)-5-(4-n-pentyloxyphenyl)-pyrimidine

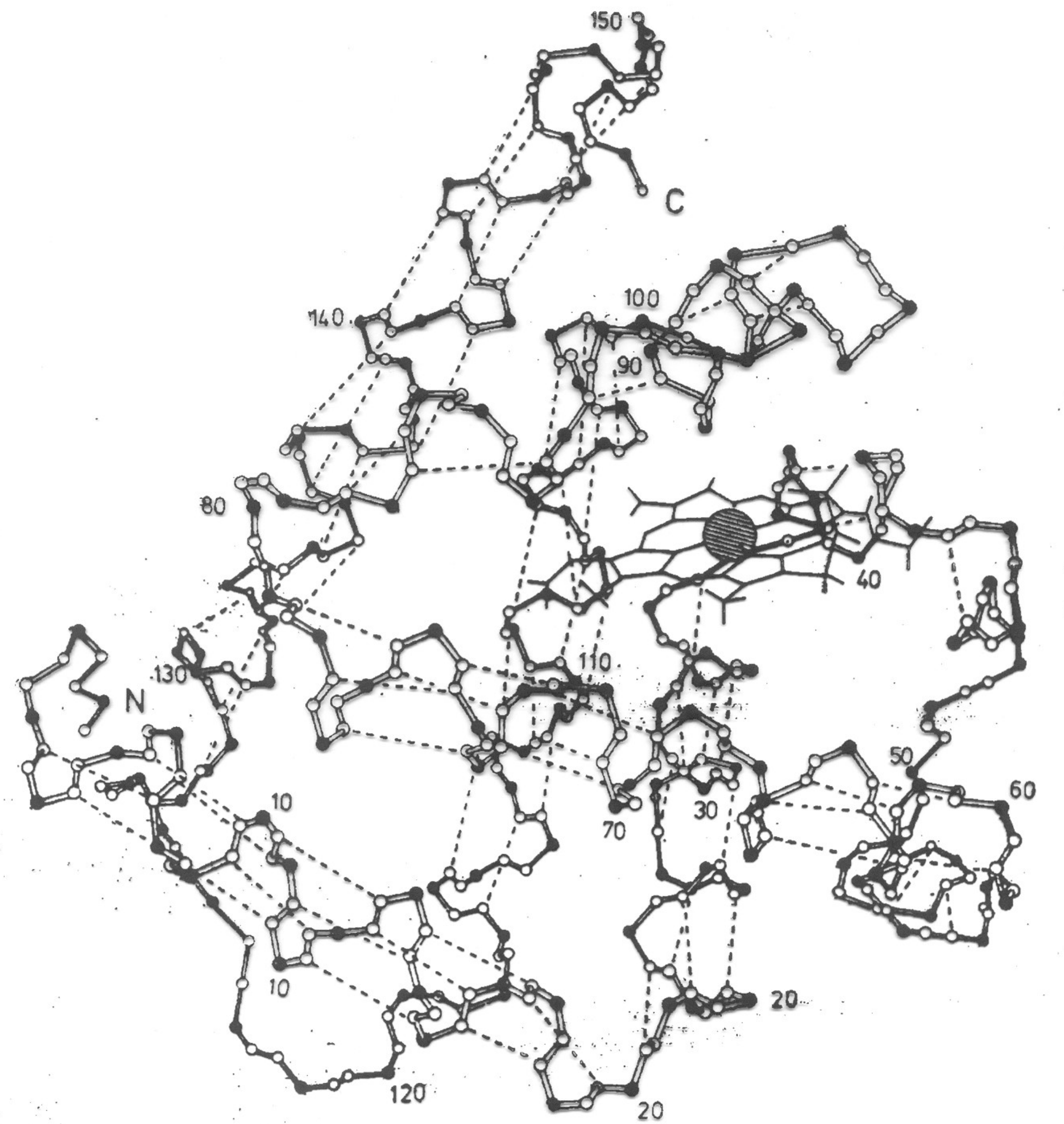


Phospholipid molecules



MYOGLOBIN

MYOGLOBIN



Deoxyribonucleic acid - DNA

DNA

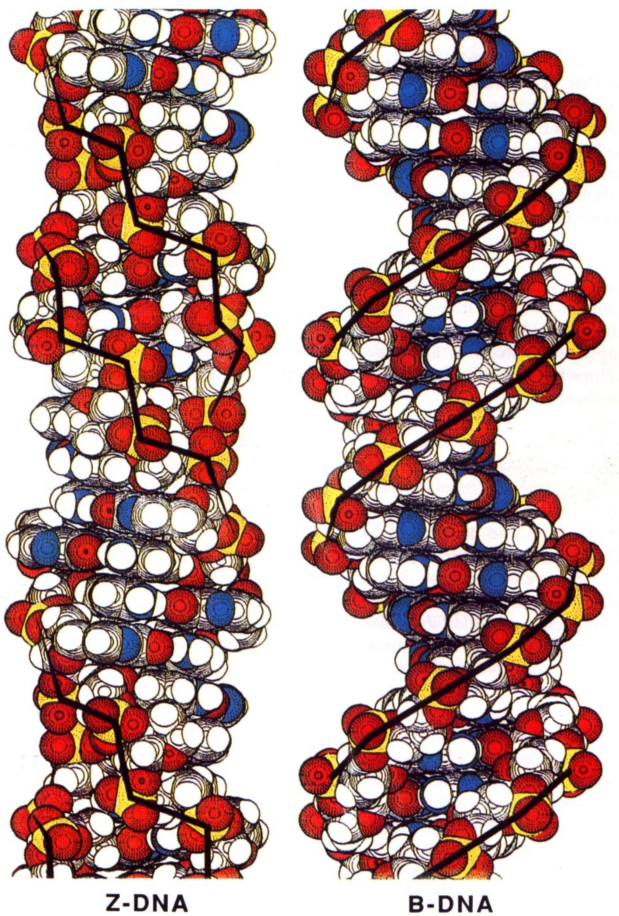
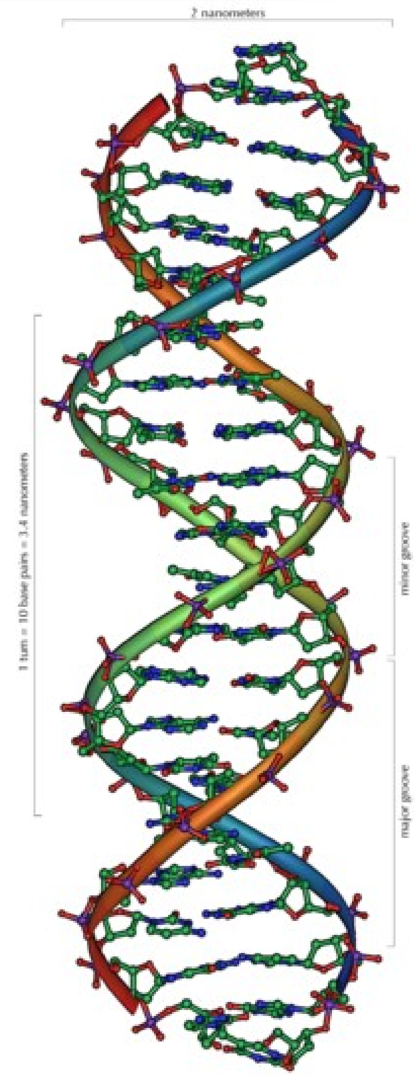


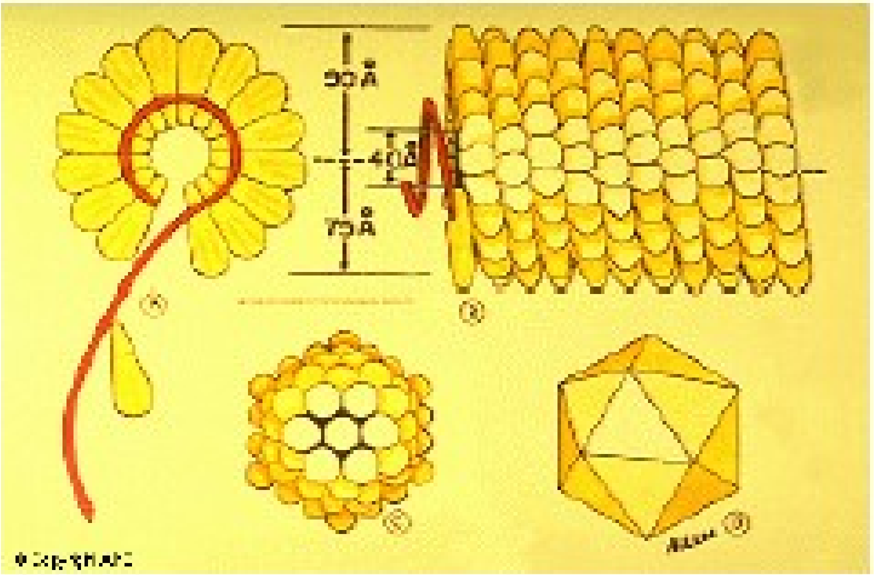
FIGURE 18. Van der Waals diagrams of Z-DNA (*left*) and B-DNA (*right*).[73] The *solid black line* goes from phosphate group to phosphate group along the chain. The zig-zag form of the Z-DNA backbone is evident. Z-DNA has a slightly smaller diameter than B-DNA and it no longer has the wide major groove that is seen in B-DNA. Phosphorus is yellow; oxygen, red; nitrogen, blue; hydrogen, white; and carbon is shown by concentric circles.



LEGOs of liquid crystals

Rodlike molecules in solvent

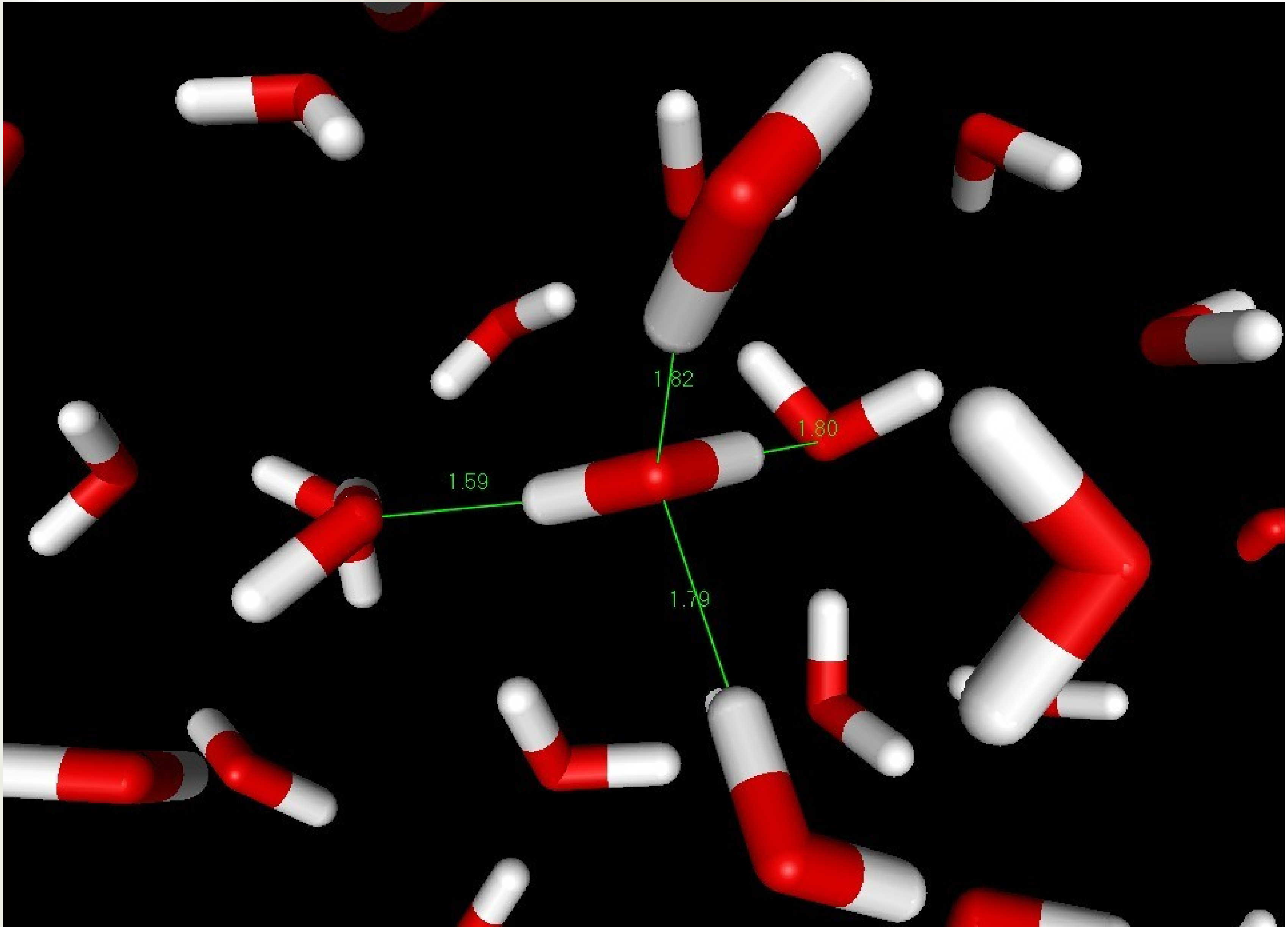
Typically lyotropic



THE HYDROPHOBIC EFFECT

Charles Tanford (1973)

Hydrogen bonding - liquid water simulation



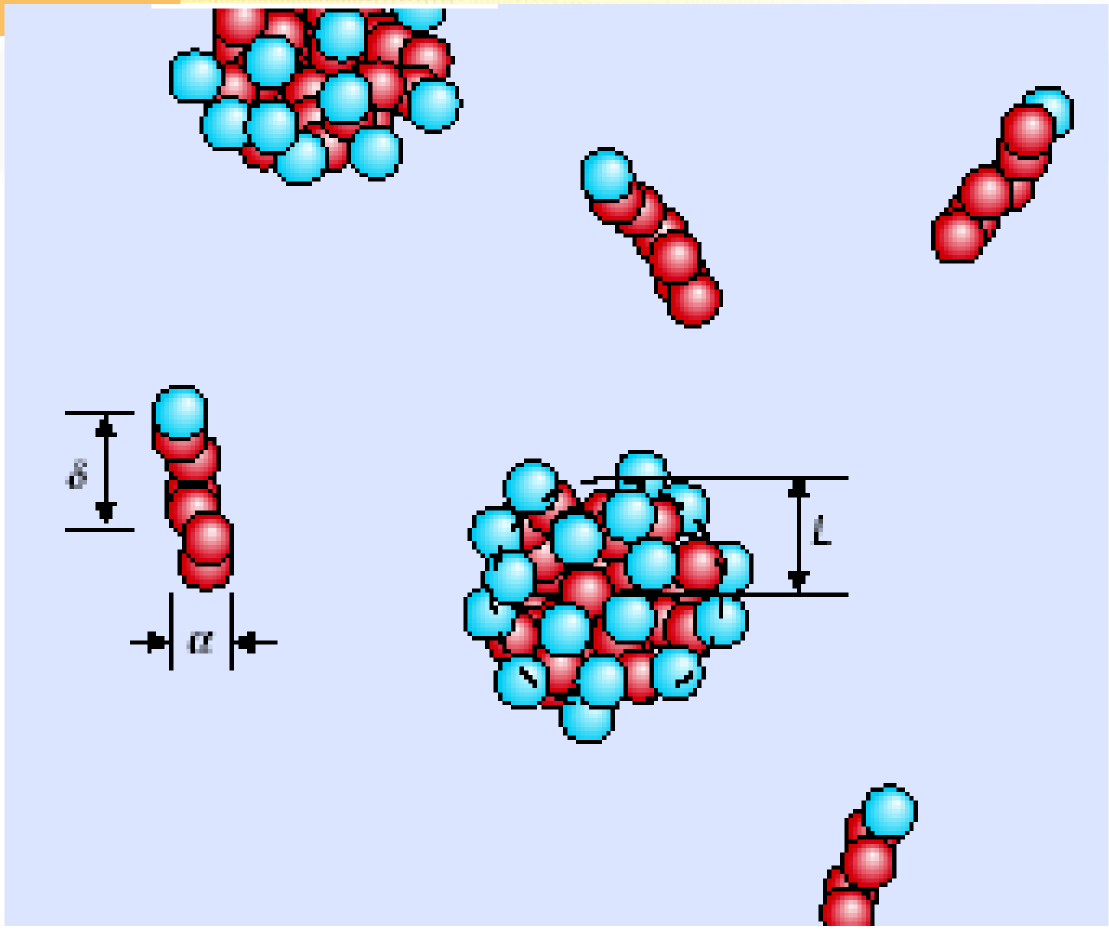
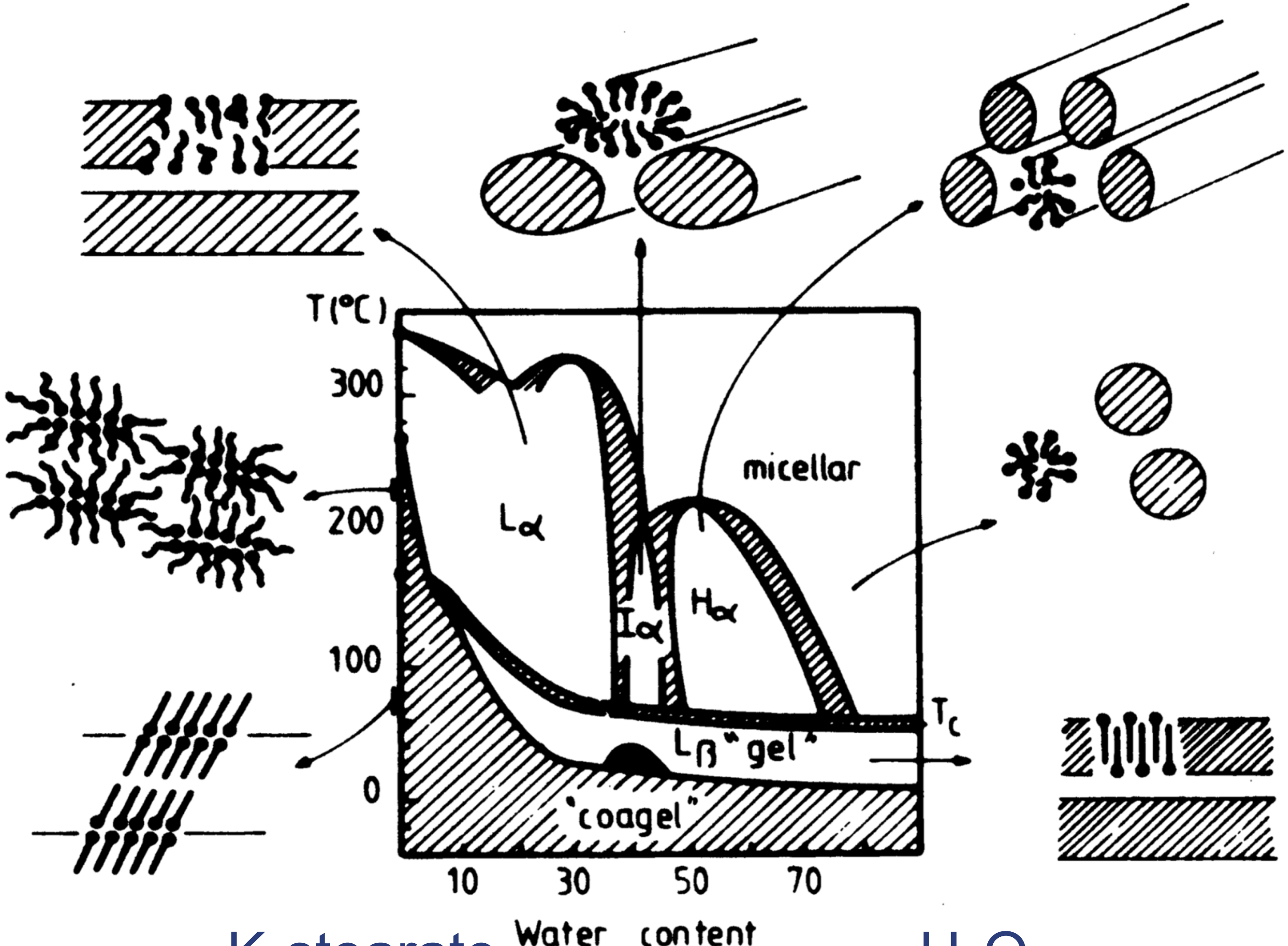


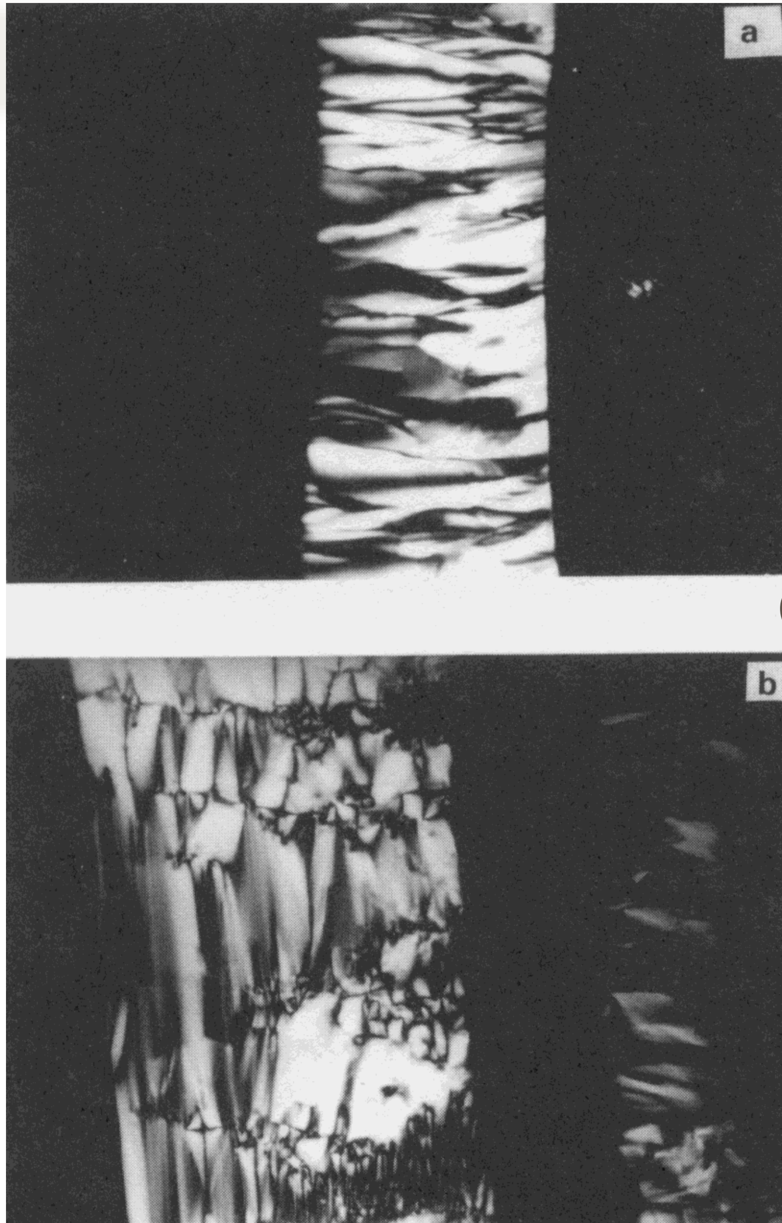
Figure 5 | Length scales of amphiphiles in dynamic equilibrium with micelles. The blue and red spheres depict the hydrophilic heads and the hydrophobic tails, respectively, of the amphiphiles. The typical length over which hydrophobic and hydrophilic components are separated within a single molecule is given by δ. Assuming a roughly spherical structure and tightly packed oily components in the centre, the micelle radius is $L \approx (\alpha^2\delta)^{1/3}\, n^{1/3}$, where n is the number of surfactants in the micelle.

LYOTROPIC LC PHASES



K-stearate H_2O

TRITON X-100 H_2O



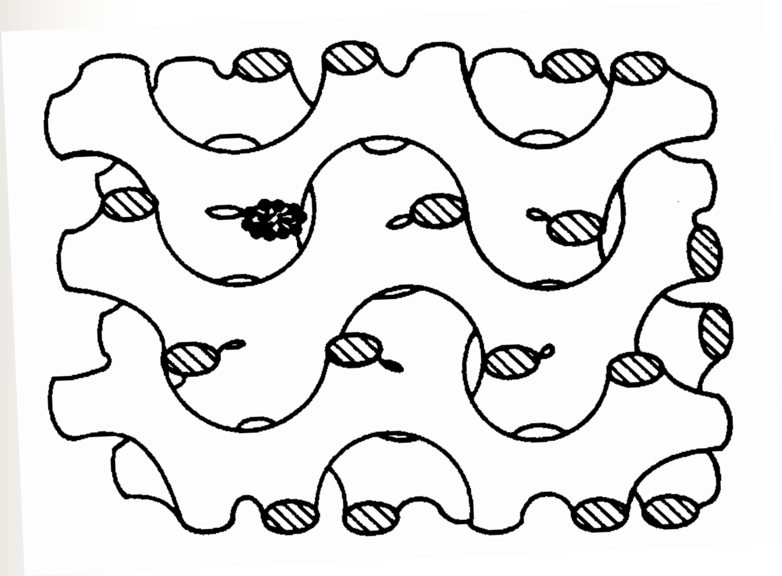
Contact preparation

NP10EO H_2O

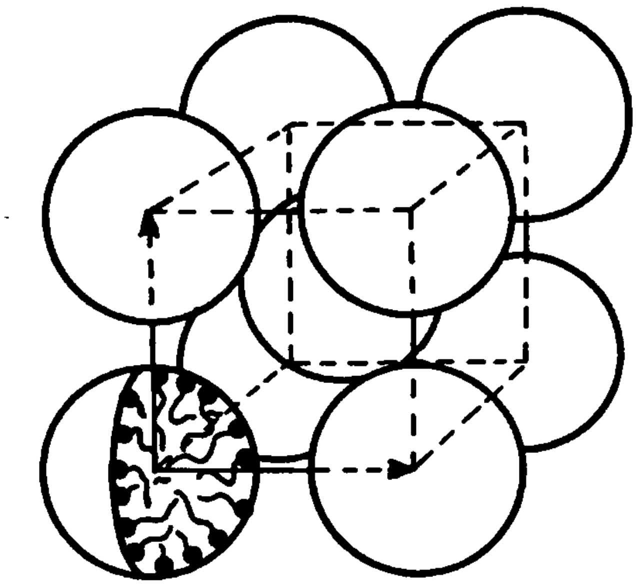
Lyotropic liquid crystal. Temperature wedge

Hexagonal – Isotropic phase transition

CUBIC LYOTROPIC PHASES

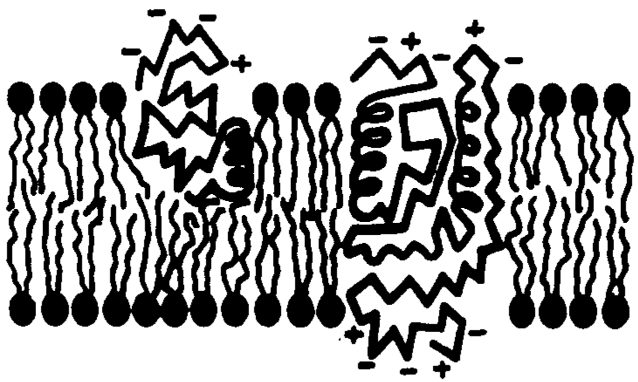


BICONTINUAL CUBIC

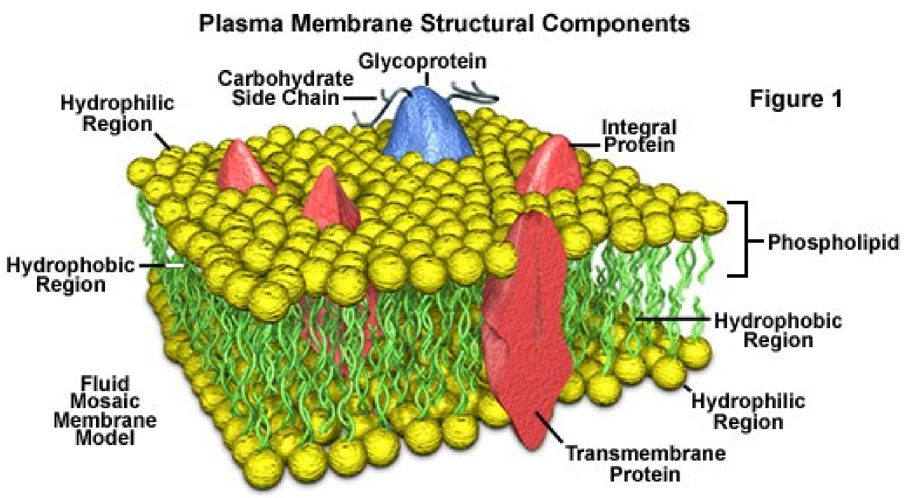


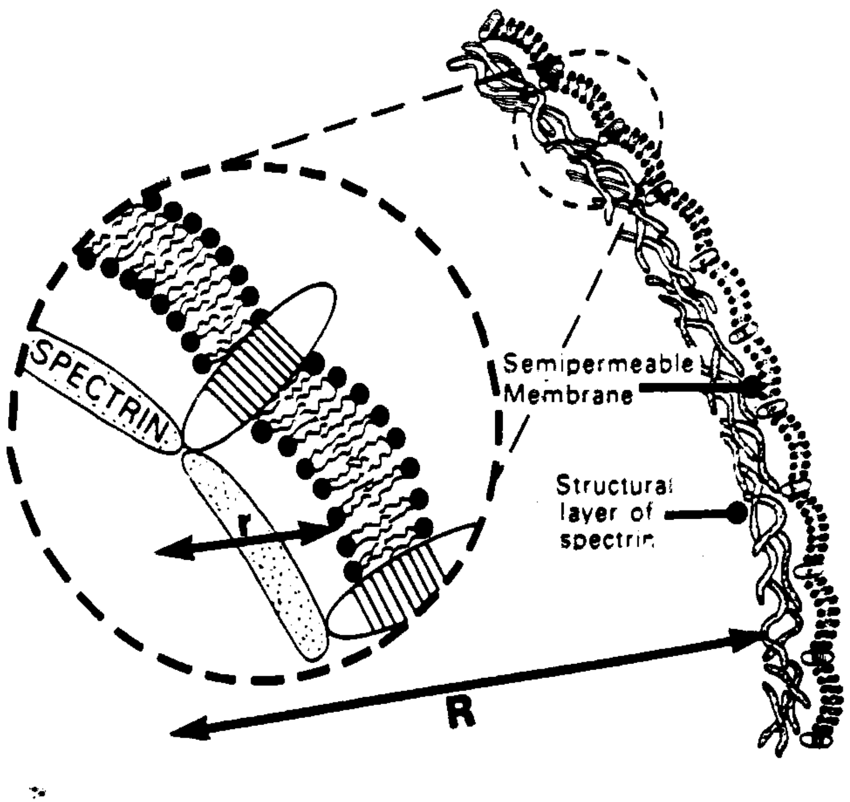
MICELLAR CUBIC

SOFT LIVING MATTER

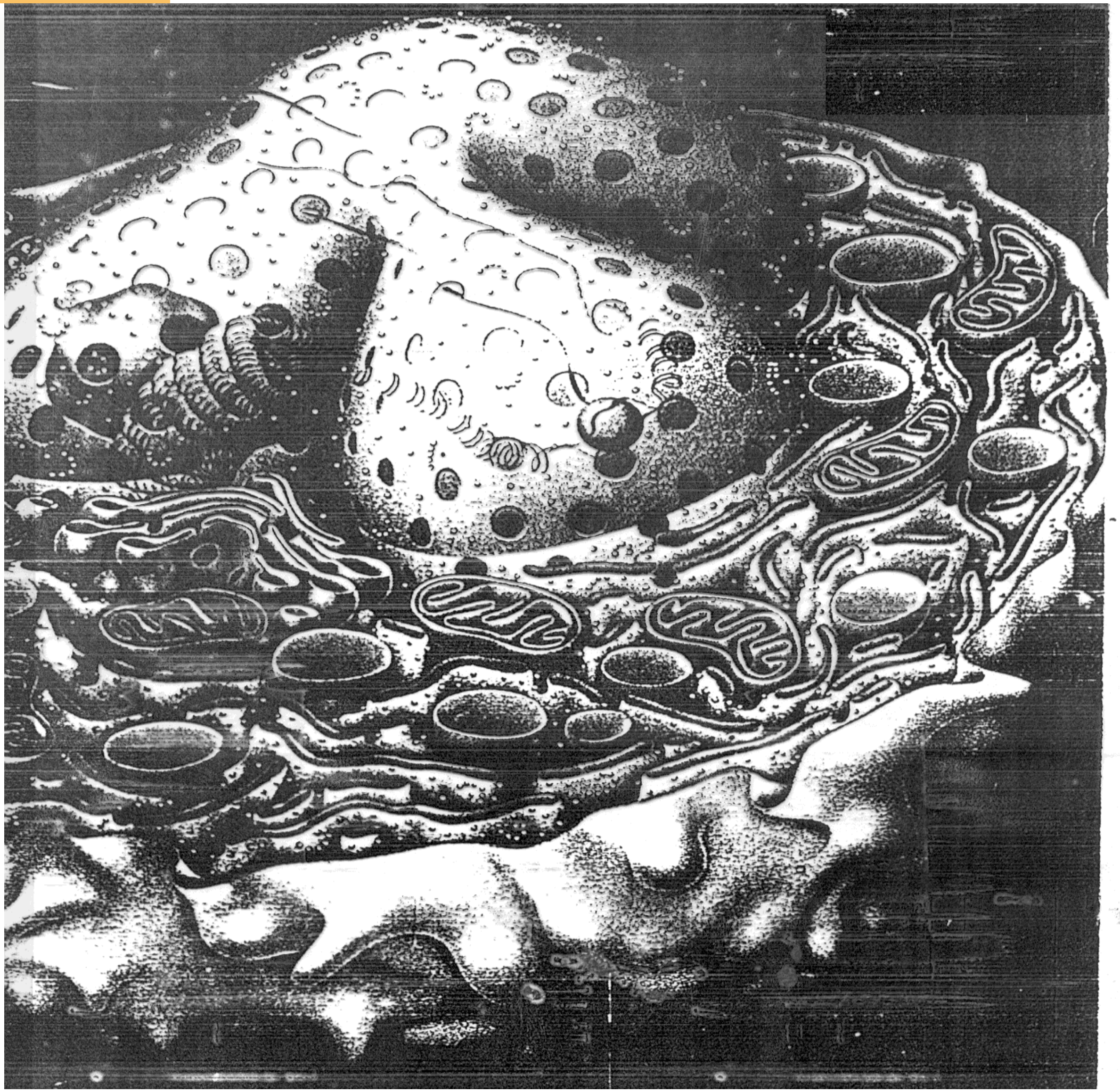


Singer and Nicolson (1972):
Fluid Lipid Globular Protein
Mosaic Model of Membranes





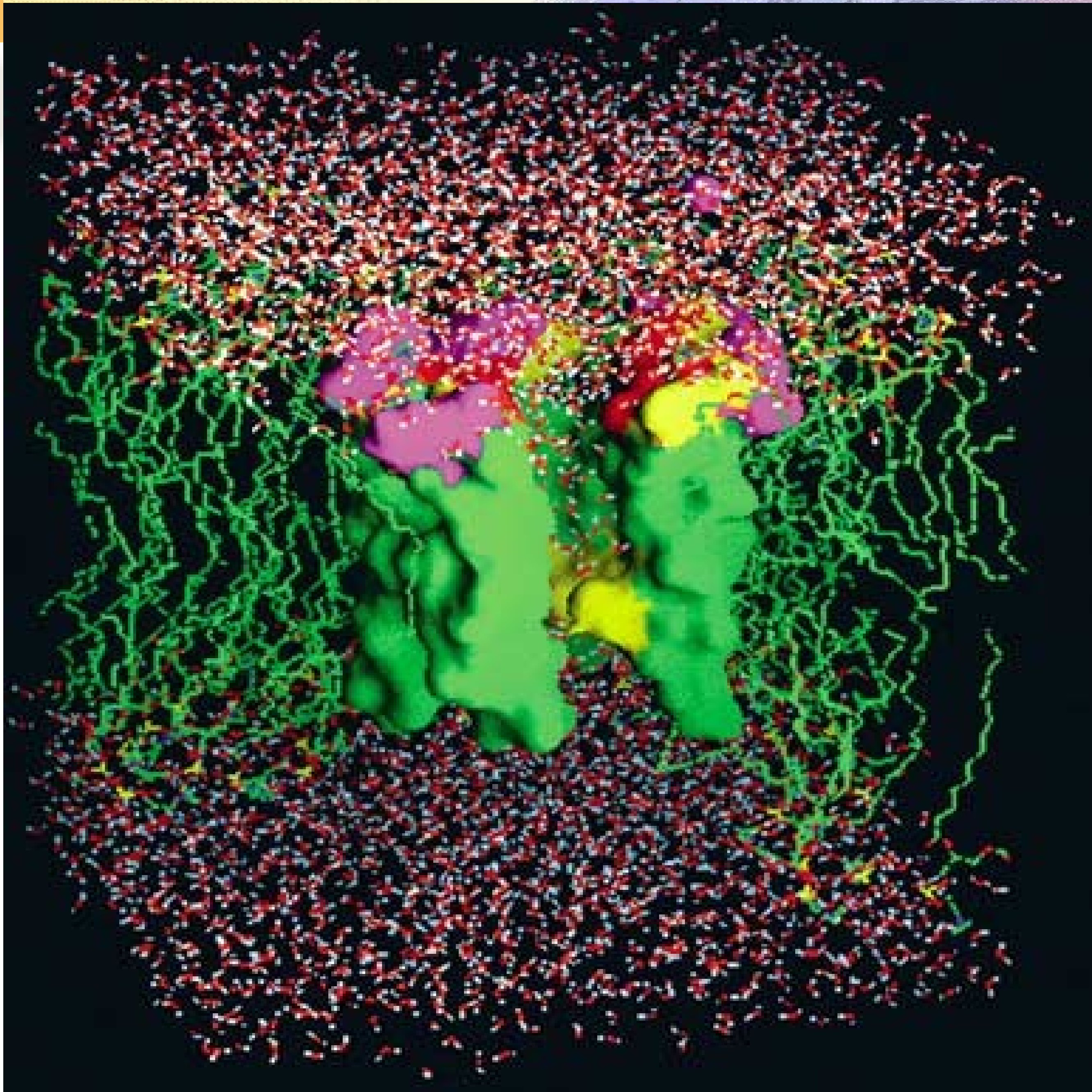
Membrane and cytoskeleton

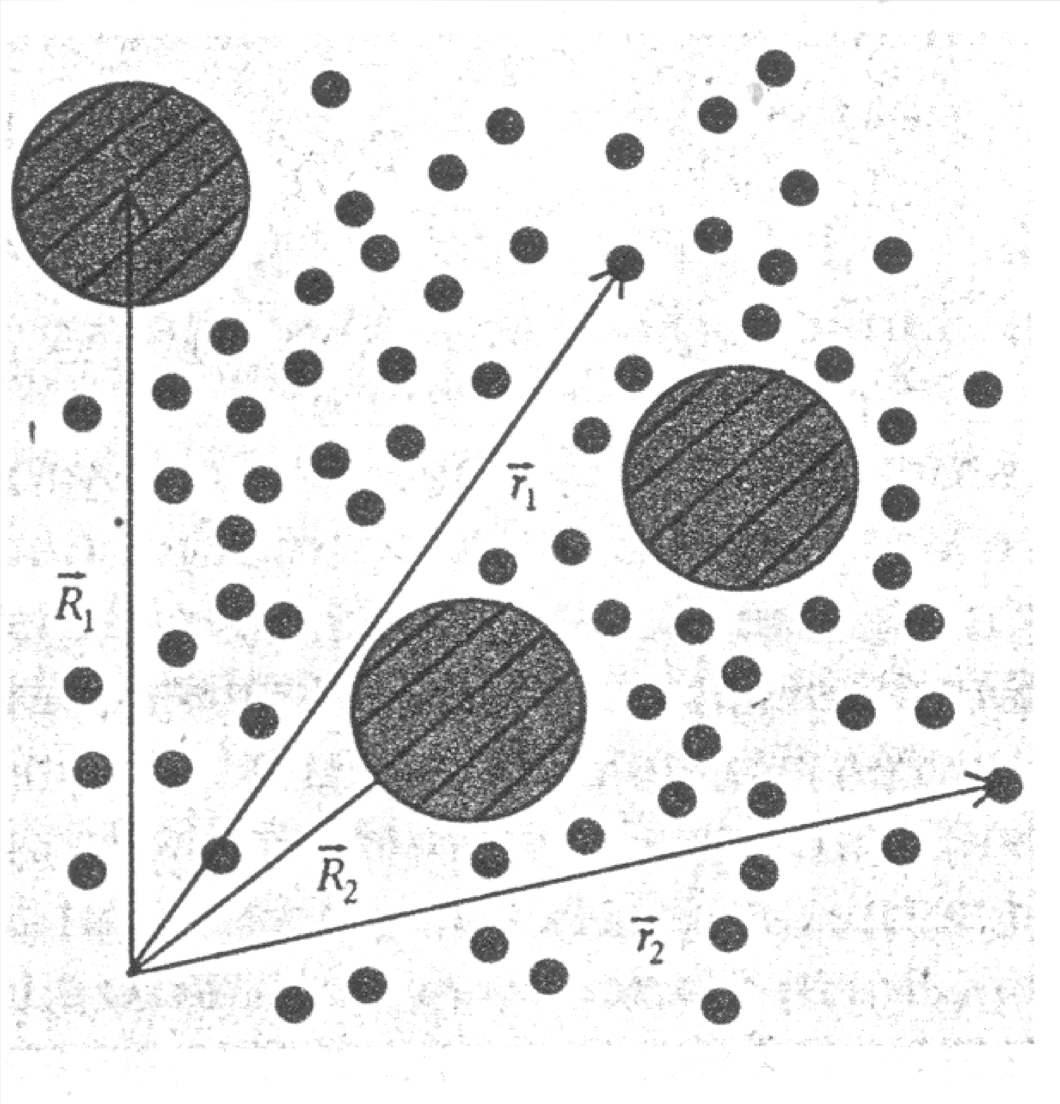


Soft membrane structures in a living cell

RAT CEREBELLUM

Alamethicin ion channel in a lipid bilayer membrane (computer simulation)





Theoretical description of soft matter:

Integrating out of external degrees of freedom

Coarse-graining

Integrating out external degrees of freedom (“coarse graining”)

H. Loewen, Physik Journal 2 (2003) 51

Das Konzept der effektiven Wechselwirkung

Man betrachte eine zweikomponentige Mischung aus N_1 großen und N_2 kleinen klassischen Teilchen im Volumen V bei vorgegebener Temperatur T.

Wenn $\{\vec{R}_i\},(i=1,\ldots,N_1)$ bzw. $\{\vec{r}_j\},(j=1,\ldots,N_2)$ die Orte der großen bzw. kleinen Teilchen bezeichnet (siehe Abbildung), dann sei die potentielle Gesamtenergie des Systems gegeben durch

$$U(\{\vec{R}_i\},\{\vec{r}_j\}) = U_{11}(\{\vec{R}_i\}) + U_{12}(\{\vec{R}_i\},\{\vec{r}_j\}) + U_{22}(\{\vec{r}_j\}). \qquad (1)$$

Aufgabe der Gleichgewichtsstatistik ist es, einen Konfigurationsmittelwert zu berechnen. Mit $\beta = 1/k_B T$ erhält man somit für die Helmholtzsche freie Energie F

$$\exp(-\beta F) = \mathrm{Sp}_1 \mathrm{Sp}_2 \exp(-\beta U), \qquad (2)$$

mit folgenden Abkürzungen für die klassische Spur
$\mathrm{Sp}_1 = 1/N_1! \int d^3R_1 \ldots \int d^3R_{N_1}$ und
$\mathrm{Sp}_2 = 1/N_2! \int d^3r_1 \ldots \int d^3r_{N_2}$.
Einsetzen von (1) in (2) ergibt

$$\begin{aligned}\exp(-\beta F) &= \mathrm{Sp}_1\big[\exp(-\beta U_{11}) \\ &\quad \mathrm{Sp}_2 \exp(-\beta(U_{12}+U_{22}))\big] \\ &=: \mathrm{Sp}_1 \exp(-\beta V_{11}(\{\vec{R}_i\}))\end{aligned}$$

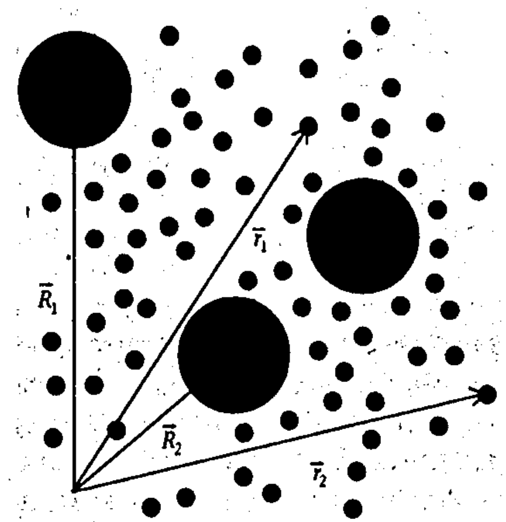
Deswegen gelingt eine *exakte* Abbildung von zweikomponenten Systemen auf ein effektiv einkomponentiges System, welches durch die *effektive Wechselwirkung*

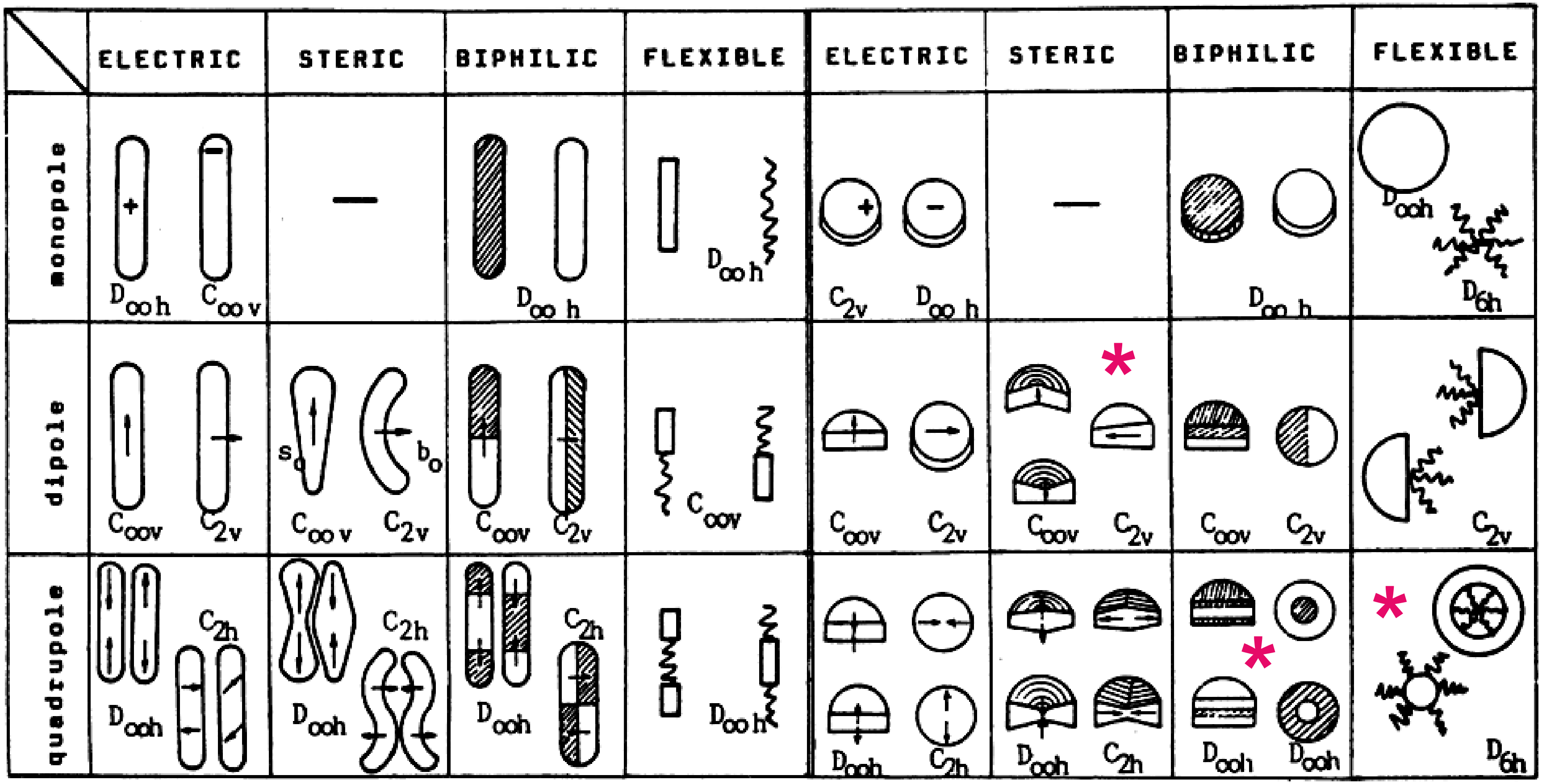
$$V_{11}(\{\vec{R}_i\}) = U_{11}(\{\vec{R}_i\}) - k_B T \ln[\mathrm{Sp}_2 \exp(-\beta(U_{12}+U_{11}))]$$

beschrieben wird. Die Freiheitsgrade der kleinen Teilchen wurden „herausintegriert“. Die Näherung besteht typischerweise darin, $V_{11}(\{\vec{R}_i\})$ als Summe von *Paar*-Wechselwirkungen anzunehmen:

$$V_{11}(\{\vec{R}_i\}) \cong \sum_{i<j} V_{\text{eff}}(\vec{R}_i, \vec{R}_j)$$

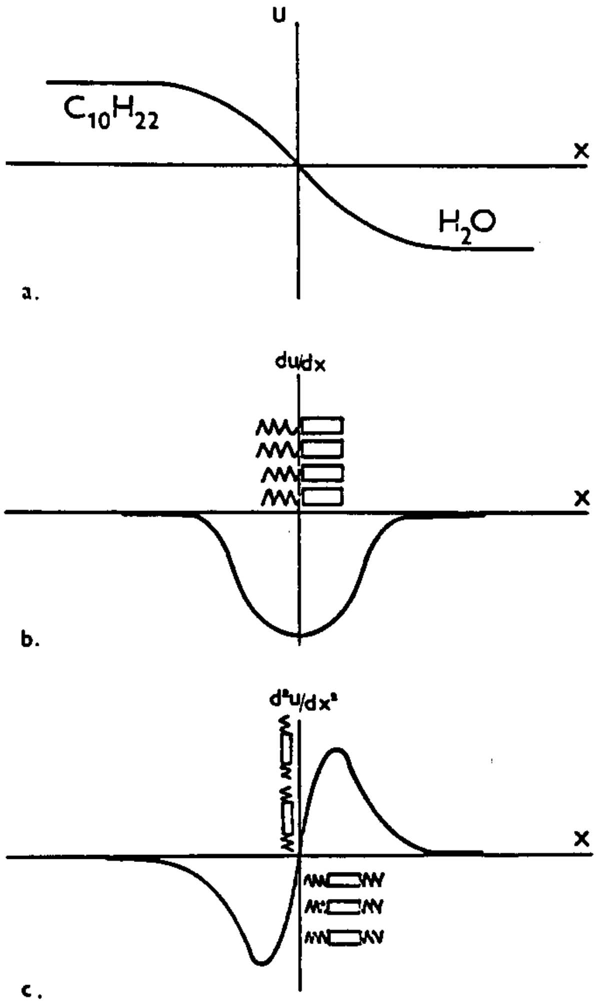
Freiheitsgrade, die sich zum Herausintegrieren bei einem System der Weichen Materie eignen, können vielfältig sein: Lösungsmittelmoleküle, Ionen, Monomere, auch ganze Polymerknäuel oder kleine Kolloidteilchen in binären Dispersionen. Somit ist das Konzept der effektiven Wechselwirkung sehr weitreichend.



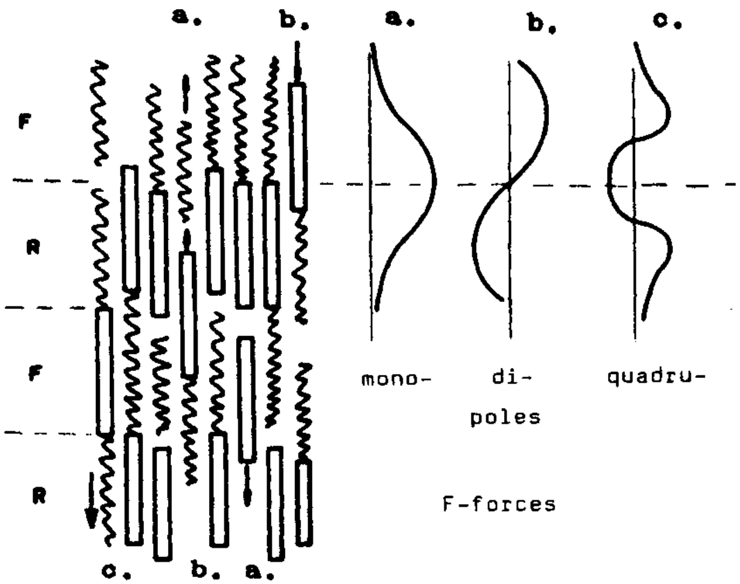


Generalized molecular asymmetry model (GMA model)

GENERALIZED FIELDS

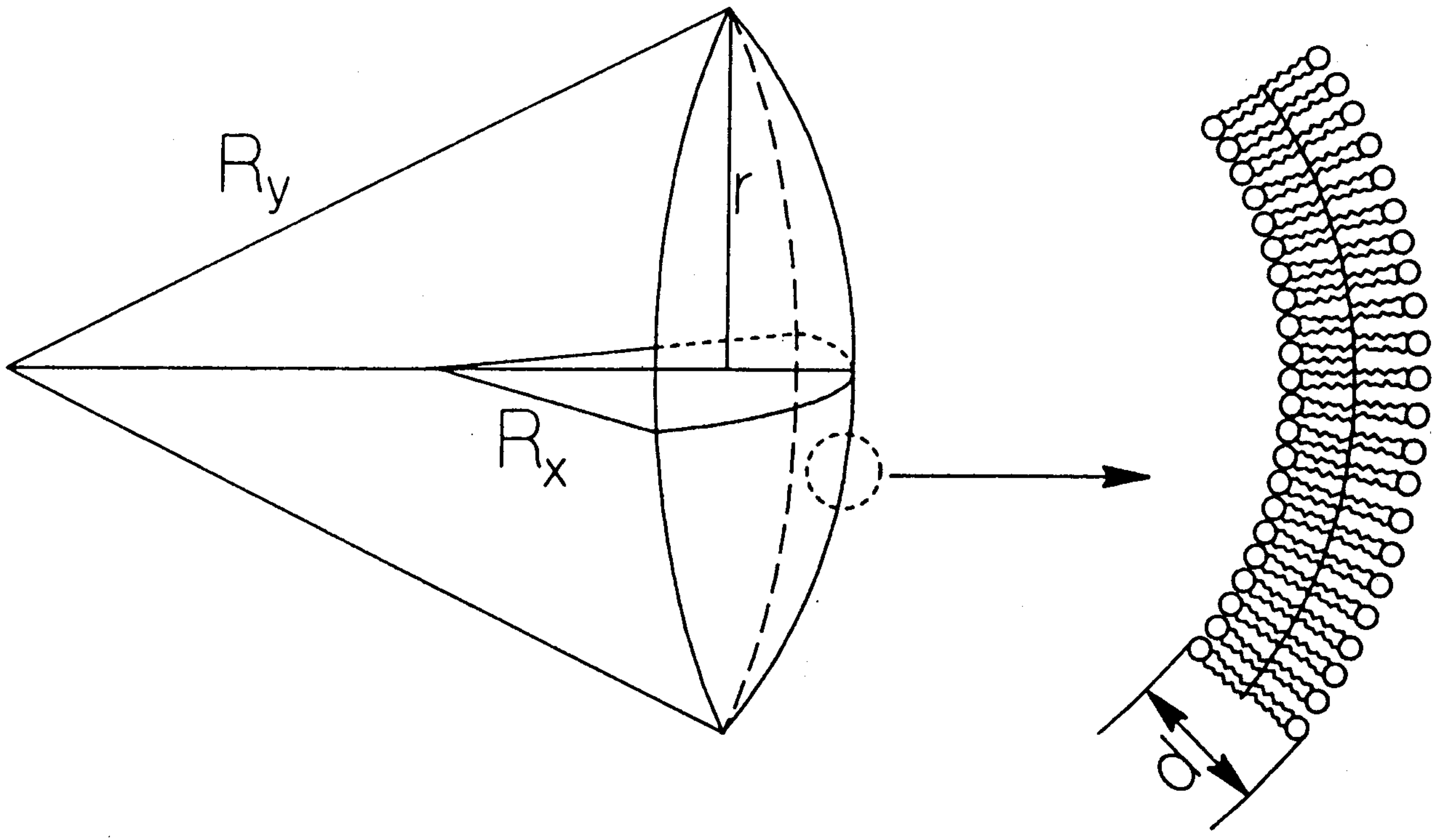


Biphilic field



Flexibility field

FLEXOELECTRICITY

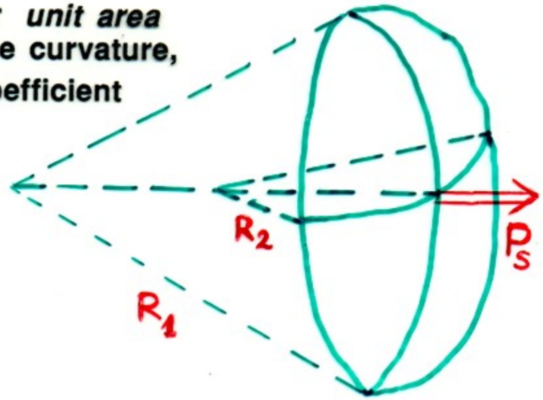


PHENOMENOLOGY (Petrov, 1975) :

$$P_s = f \left(1/R_1 + 1/R_2 \right)$$

cf. R.B.Meyer (1969)

P_s is membrane polarization per *unit area*
R_1, R_2 are the radii of membrane curvature,
f is membrane flexoelectric coefficient



Dimensions:

$$[P_s] = C \cdot m^{-1}$$
$$[f] = C$$

f *ca.* $1 \cdot 10^{-18}$ C

$f \approx e.d$ f = e.d

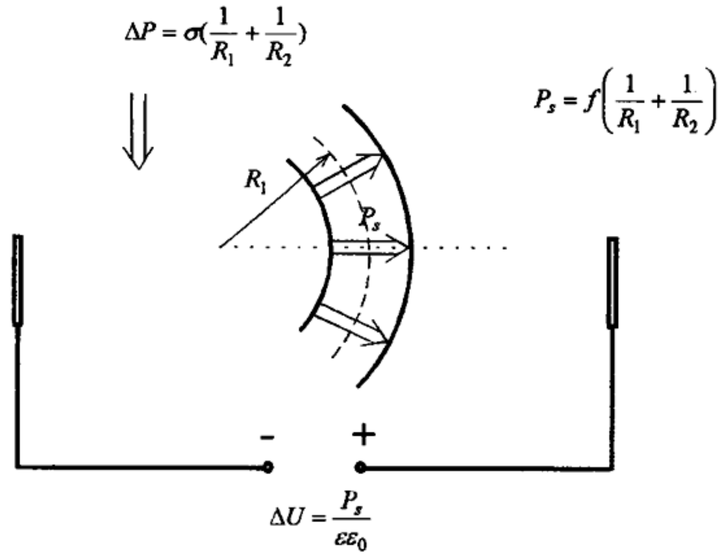
For spherical curvature of radius R the transmembrane flexoelectric voltage is :

$$\Delta U = P_s / \varepsilon_o = (f / \varepsilon_o)(2/R)$$

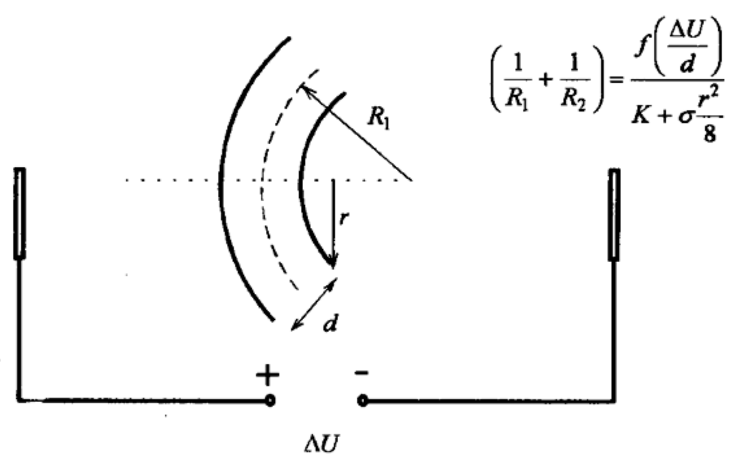
Helmholtz eqn.

ΔU *ca.* 200 μV for R = 1 mm
ΔU *ca.* 20 mV for R = 10 μm

DIRECT FLEXOEFFECT



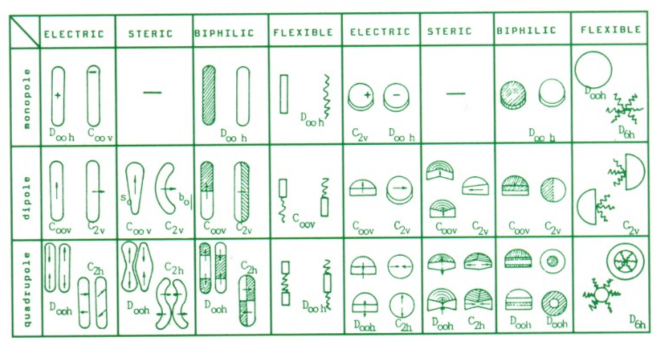
CONVERSE FLEXOEFFECT



The Lyotropic State of Matter

Molecular Physics and Living Matter Physics

Alexander G. Petrov



Gordon and Breach Science Publishers

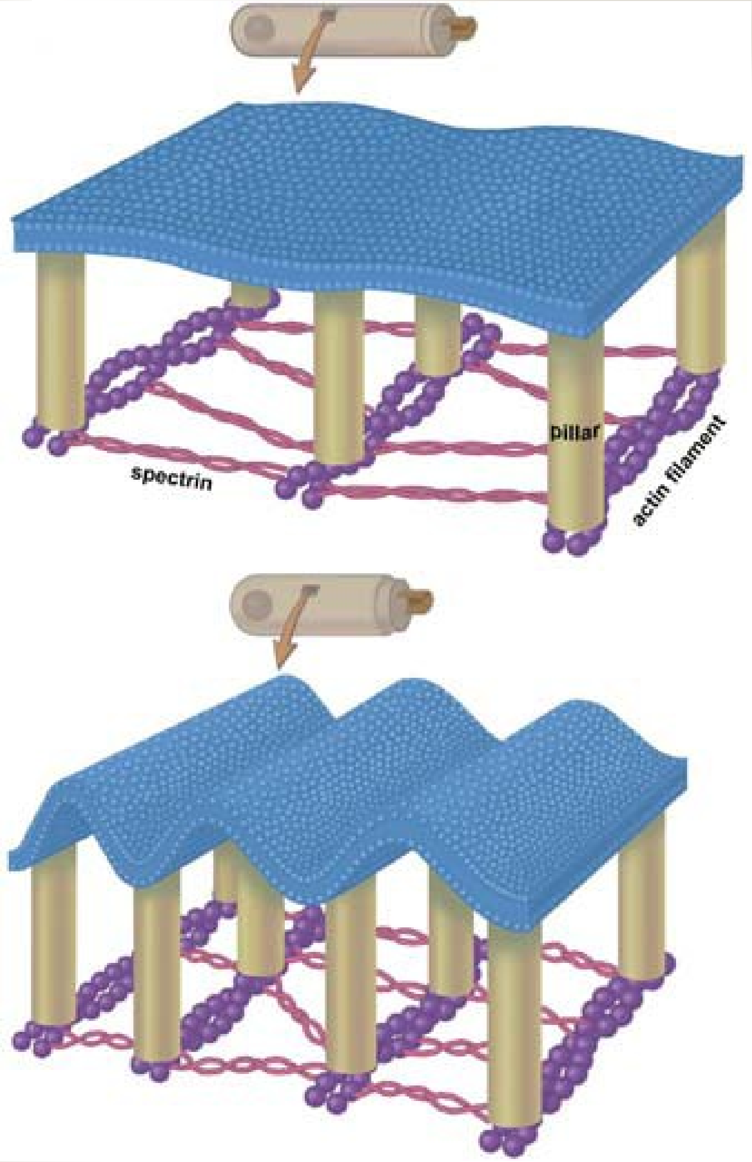
Membrane Electromechanics in Biology, with a Focus on Hearing

F. Sachs, W.E. Brownell, and A.G. Petrov

MRS BULLETIN • VOLUME 34, 665-670, (SEPT 2009) • www.mrs.org/bulletin

Abstract

Cells are ion conductive gels surrounded by a ~5-nm-thick insulating membrane, and molecular ionic pumps in the membrane establish an internal potential of approximately −90 mV. This electrical energy store is used for high-speed communication in nerve and muscle and other cells. Nature also has used this electric field for high-speed motor activity, most notably in the ear, where transduction and detection can function as high as 120 kHz. In the ear, there are two sets of sensory cells: the "inner hair cells" that generate an electrical output to the nervous system and the more numerous "outer hair cells" that use electromotility to counteract viscosity and thus sharpen resonance to improve frequency resolution. Nature, in a remarkable exhibition of nanomechanics, has made out of soft, aqueous materials a microphone and high-speed decoder capable of functioning at 120 kHz, limited only by thermal noise. Both physics and biology are only now becoming aware of the flexoelectric material properties of biomembranes and their ability to perform work and sense the environment. We anticipate new examples of this bioflexoelectricity will be forthcoming.



Postulated nanoscale rippling of the outer hair cell (OHC) lateral wall plasma membrane. OHC is shown at low magnification when hyperpolarized (a) and depolarized (c). A portion of the lateral wall is shown at higher magnification in (b) and (d). These cartoons portray flexoelectric alterations in membrane curvature associated with electromotile length changes. The plasma membrane is attached to cortical lattice pillars (tan), which, in turn, are attached to actin filaments (purple). These are cross linked with the elastic spectrin (thin red) filaments.

- **Basic question of SM physics:** *Why is living matter soft?*

- **Lesson from LC physics:** *Because it is made of large molecules (aggregates) whose strong atom-atom interactions (charges, valent bonds) are saturated within a molecule.*

  Intermolecular interactions are thus weaker and non-specific (dipole-dipole, dipole-induced dipole, double layer forces, dispersion forces, entropic forces, hydrophobic interactions, fluctuation forces, etc. etc.)

  Consequently, molecules are farther apart and only partially ordered.

  Theoretical description by point generalized dipoles is thus rendered possible.

Auguste Rodin

The Thinker

1880
Bronze