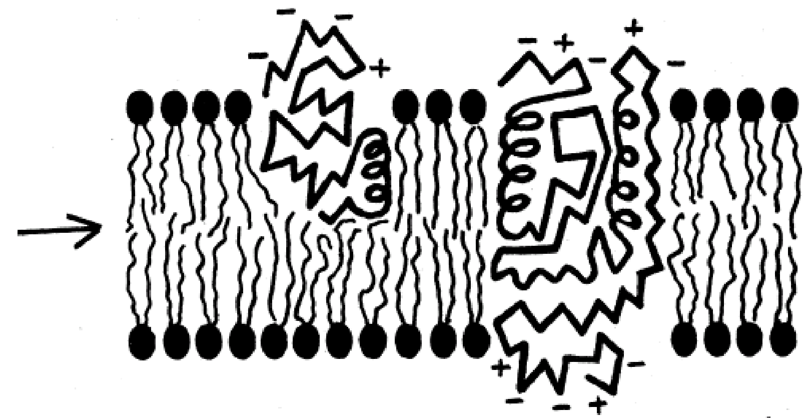
Life at Low D

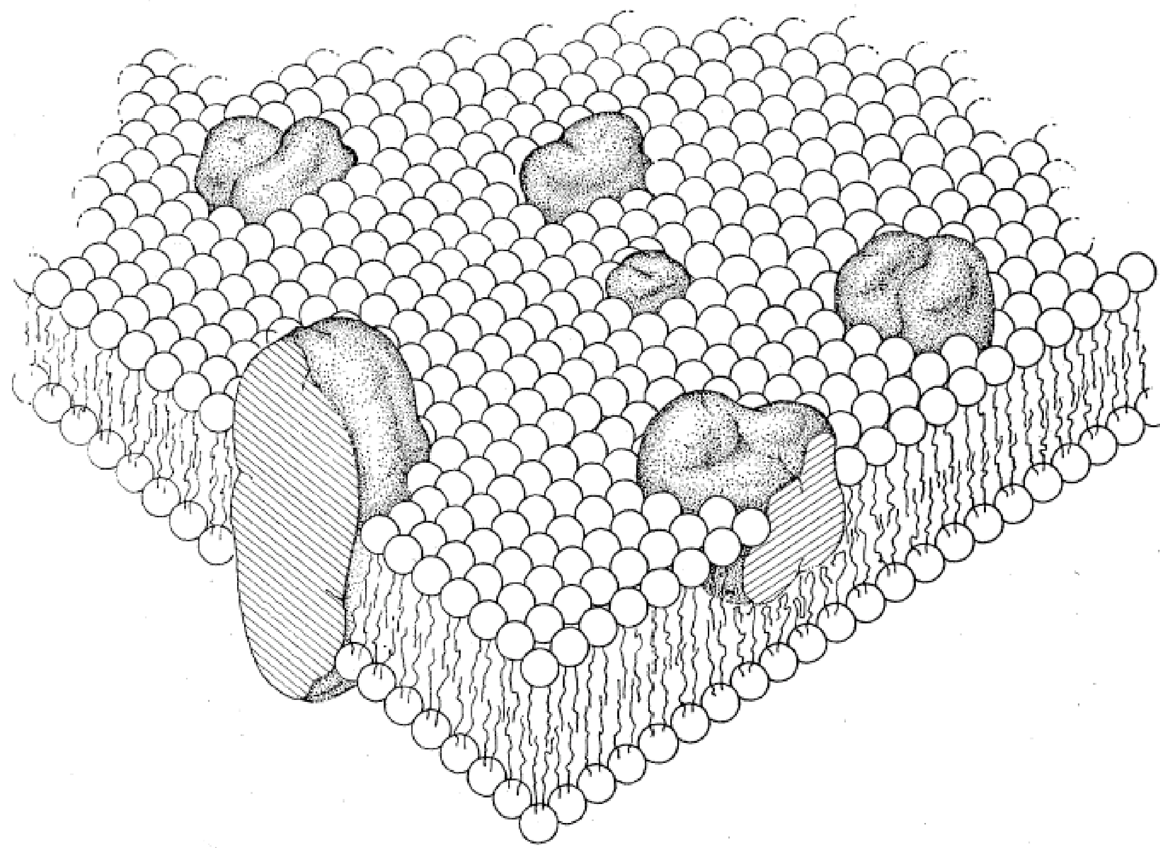
Lecture III: Monolayers and Membranes

The Fluid Mosaic Model of the Structure of Cell Membranes



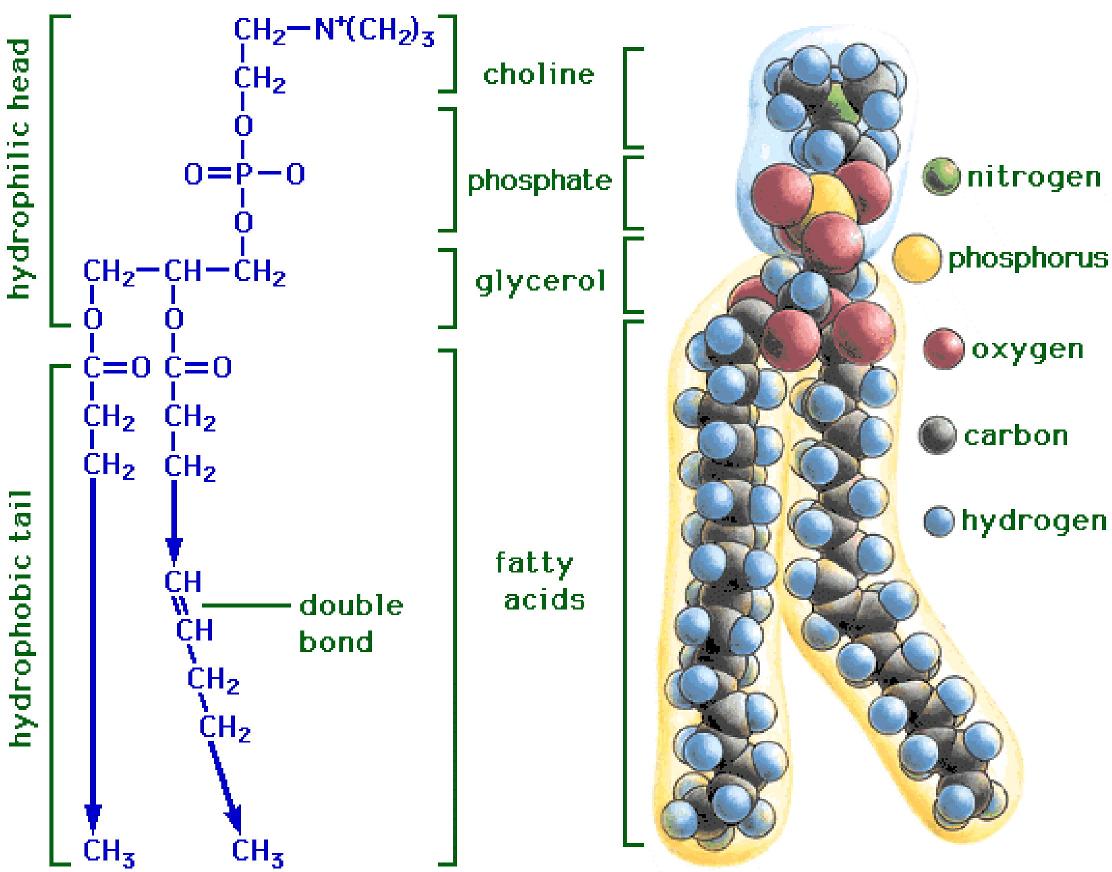
Cell membranes are viewed as two-dimensional solutions of oriented globular proteins and lipids.

S. J. Singer and Garth L. Nicolson



Biological membranes play a crucial role in almost all cellular phenomena, yet our understanding of the molecular organization of membranes is still rudimentary. Experience has taught us, however, that in order to achieve a satisfactory understanding of how any biological system functions, the detailed molecular composition and structure of that system must be known. While we are still a long way from such knowledge about membranes in general, progress at both the theoretical and experimental levels in recent years has brought us to a stage where at least the gross aspects of the organization of the proteins and lipids of membranes can be discerned. There are some investigators, however, who, impressed with the great diversity of membrane compositions and functions, do not think there are any useful generalizations to be made even about the gross structure of cell membranes. We do not share that view.

Phospholipids



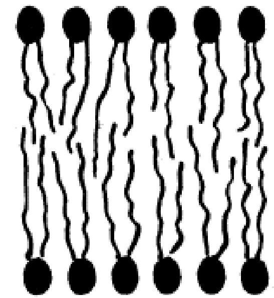
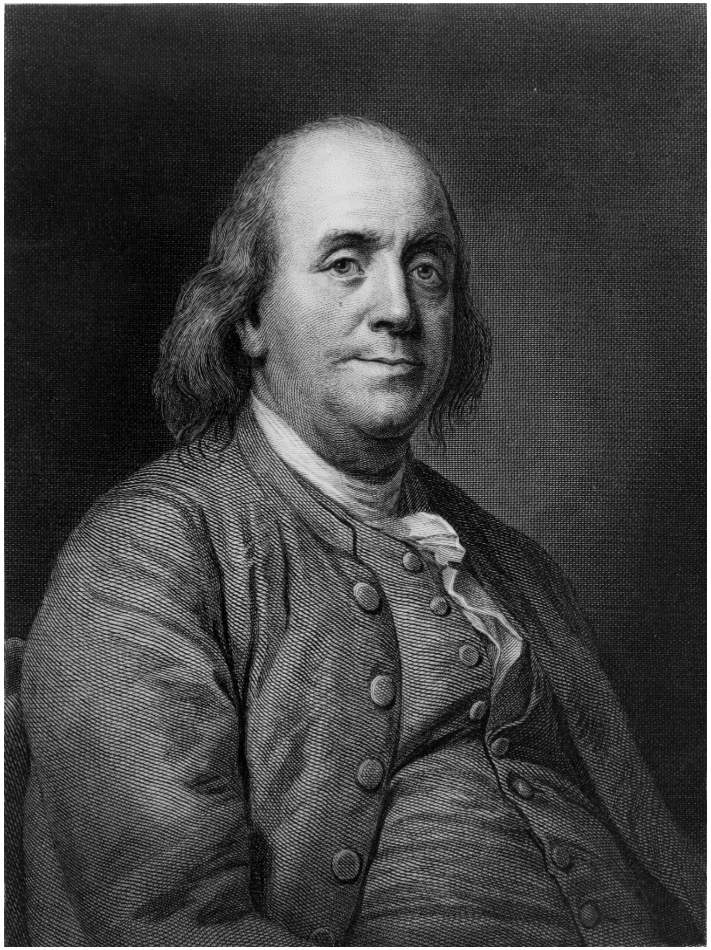


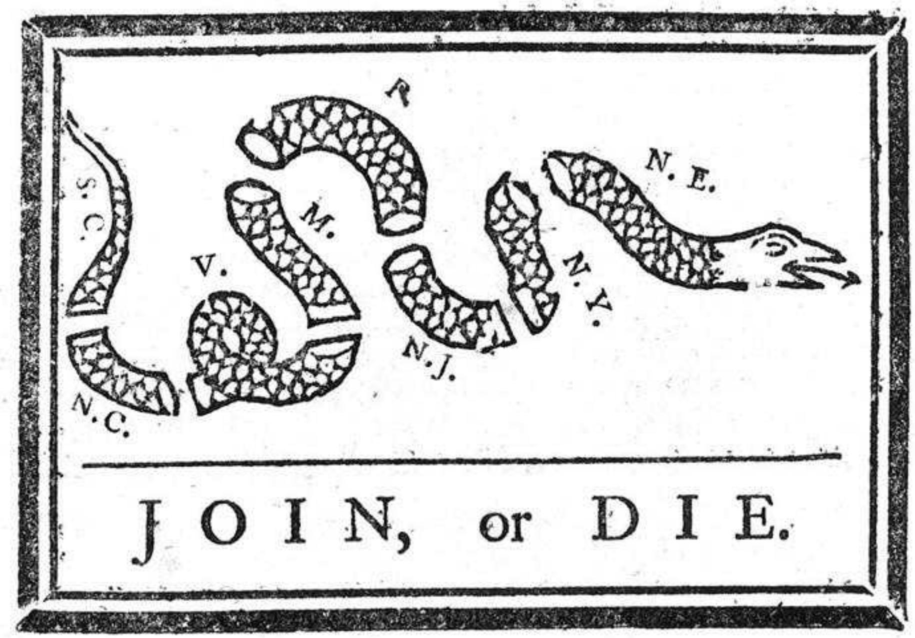
Fig. 1. A phospholipid bilayer: schematic cross-sectional view. The filled circles represent the ionic and polar head groups of the phospholipid molecules, which make contact with water; the wavy lines represent the fatty acid chains.

Amphiphilic Molecules

αμφιζ *φιλια*

Amphi ("both") *philia("love")*



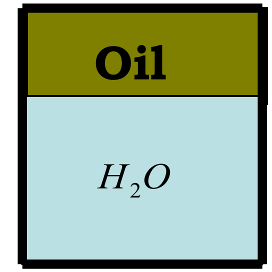


If a drop of oil is put on a highly polished marble table, or on a looking-glass that lies horizontally, the drop remains in its place, spreading very little.

"...the oil, though not more than a teaspoonful, produced an instant calm over a space several yards square which spread amazingly and extended itself..., making all that quarter of the pond, perhaps half an acre as smooth as a looking glass."

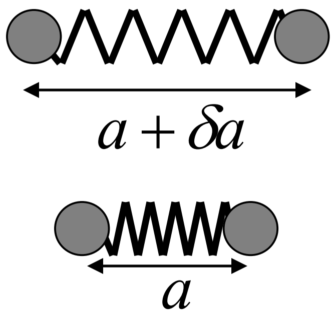
"There seems to be no natural repulsion between water and air such as to keep them from coming into contact with each other." (Franklin, 1773)

Interfacial Energy and Surface Tension

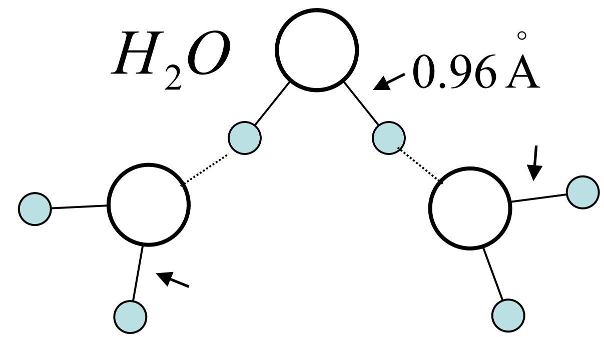


$$F = U - TS$$

<u>GOAL</u>: Minimize Free Energy



Energy	**Entropy**
ΔU	ΔS



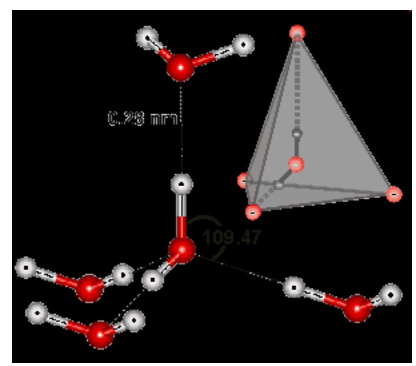
Solids

Covalent $\sim 200 k_B T$

Fluids

VDW $\sim 3 k_B T$

H-Bonding $\sim 10 k_B T$

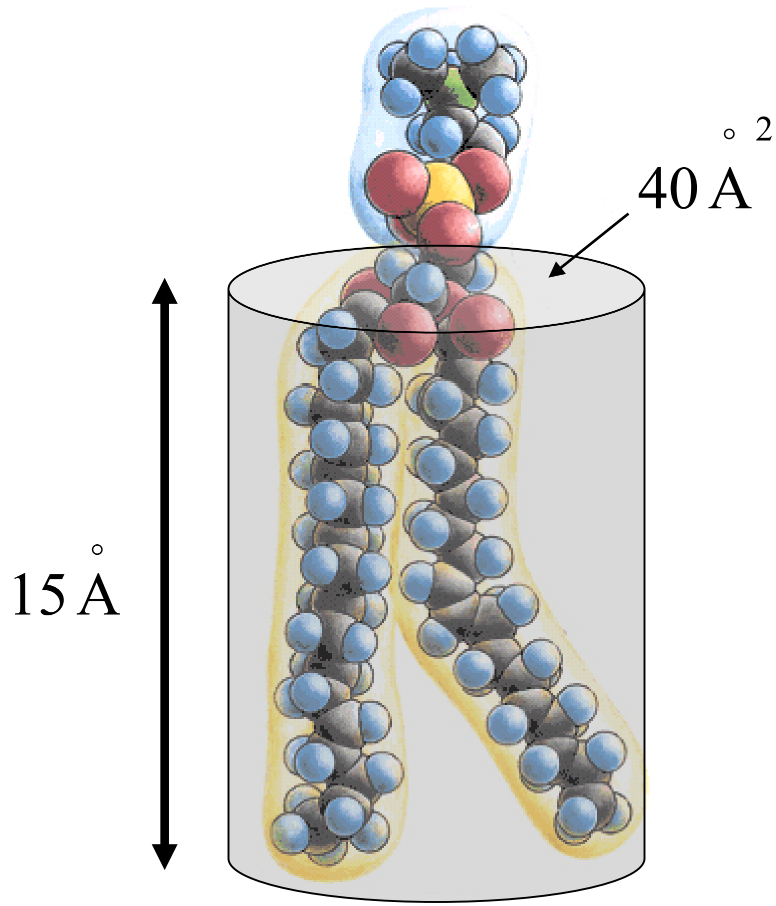


$$a_0 \approx 10\,\mathring{A}^2$$

$$\Delta F = \frac{k_B T \ln[2]}{a_0}$$

$$\sigma_{H_20/Oil} = 0.07 \frac{k_B T}{A^2}$$

Hydrophobic Effect



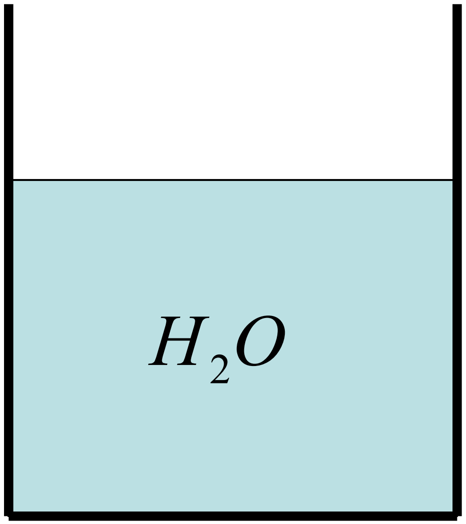
$$\sigma_{H_20/Oil} = 0.07\frac{k_BT}{\mathring{A}^2}$$

Hydrophobic Area/Molecule

$$S_a \approx 300\,\mathring{A}^2$$

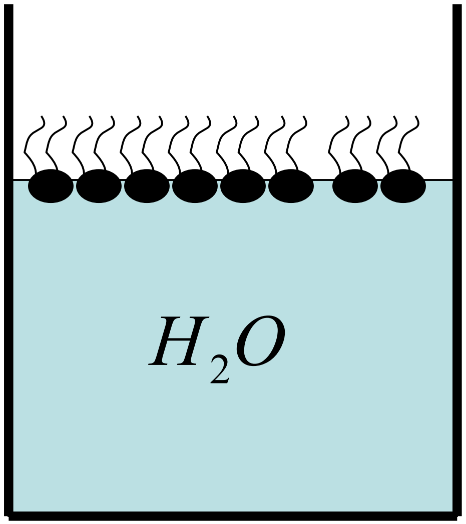
$$\Delta F = S_A\sigma_{H_20/Oil} = \left(0.07\frac{k_BT}{\mathring{A}^2}\right)\left(300\,\mathring{A}^2\right) \approx 25k_BT$$

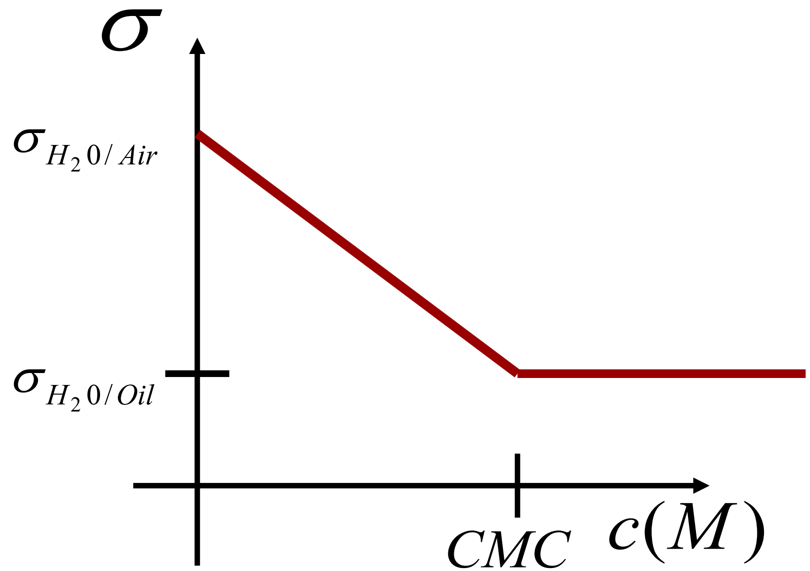
Surface Tension



$$\sigma_{H_2 0/Air} = 0.2 \frac{k_B T}{\mathrm{A}^2}$$

Surface Tension

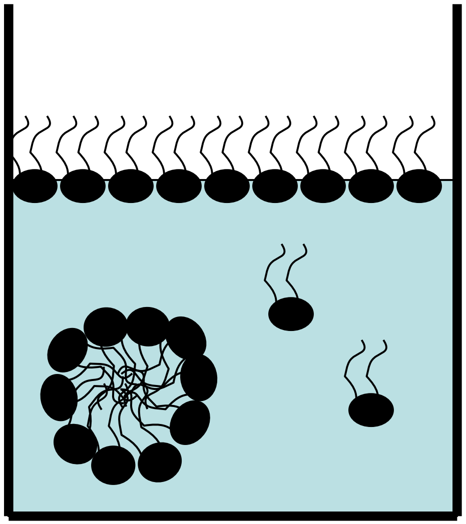


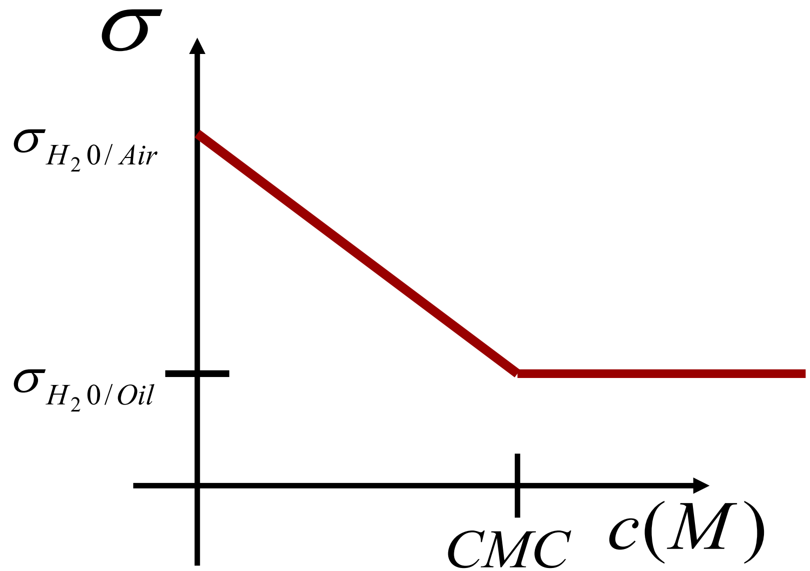


Monolayer reduces Surface Tension

$$\sigma_{H_20/Air} = 0.2\frac{k_BT}{\text{A}^2} \Rightarrow \sigma_{H_20/Oil} = 0.07\frac{k_BT}{\text{A}^2}$$

Surface Tension

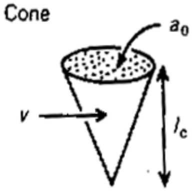
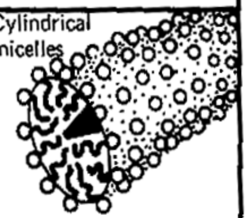
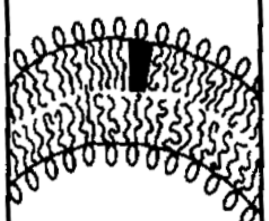


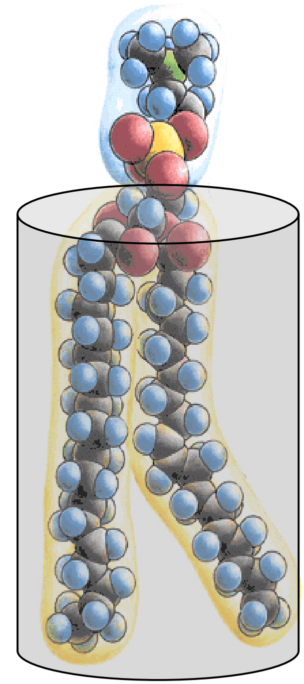


Monolayer reduces Surface Tension

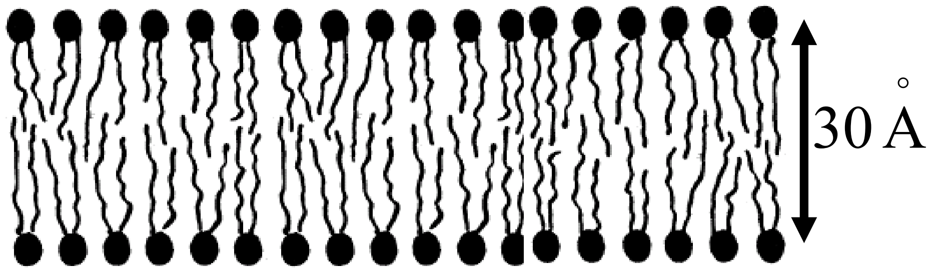
$$\sigma_{H_2 0/Air} = 0.2\frac{k_B T}{\text{A}^2} \quad \Rightarrow \quad \sigma_{H_2 0/Oil} = 0.07\frac{k_B T}{\text{A}^2}$$

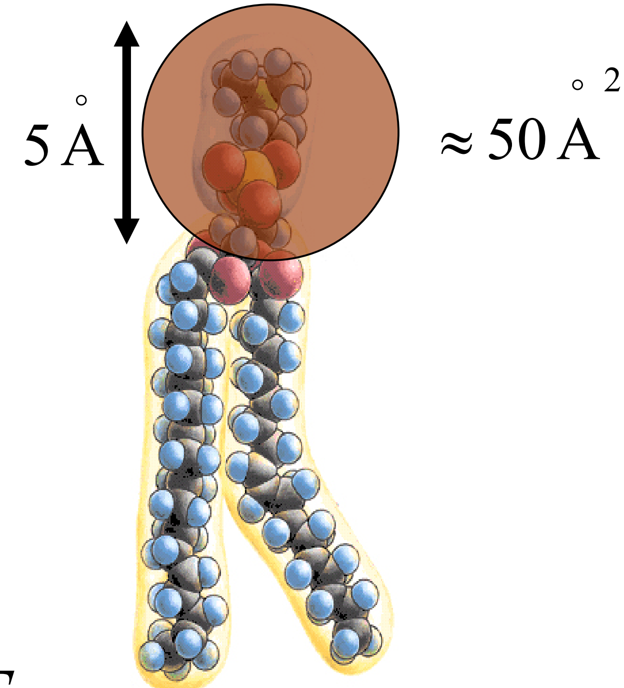
Self-Assembly

Lipid	Critical packing parameter $v/a_0 l_c$	Critical packing shape	Structures formed
Single-chained lipids (surfactants) with large head-group areas: *SDS in low salt*	$< 1/3$	Cone 	Spherical micelles 
Single-chained lipids with small head-group areas: *SDS and CTAB in high salt, nonionic lipids*	1/3-1/2	Truncated cone 	Cylindrical micelles 
Double-chained lipids with large head-group areas, fluid chains: *Phosphatidyl choline (lecithin), phosphatidyl serine, phosphatidyl glycerol, phosphatidyl inositol, phosphatidic acid, sphingomyelin, DGDG[a], dihexadecyl phosphate, dialkyl dimethyl ammonium salts*	1/2-1	Truncated cone 	Flexible bilayers, vesicles 



Bilayer Properties





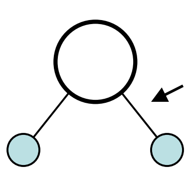
Flip-Flop
(exposing hydrophilic head to hydrocarbon chain)

$$\sigma_{H_20/Oil} = 0.07 \frac{k_B T}{\mathring{A}^2}$$

$$S_A \approx 50 \mathring{A}^2$$

$$\Rightarrow \quad \Delta E \approx 12 k_B T$$

Water Permeable
(cost of water passing through)

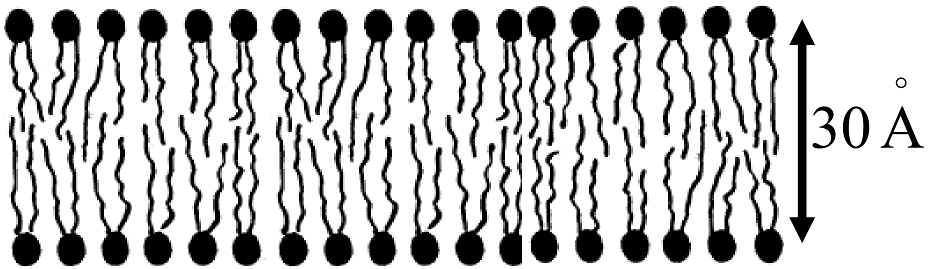


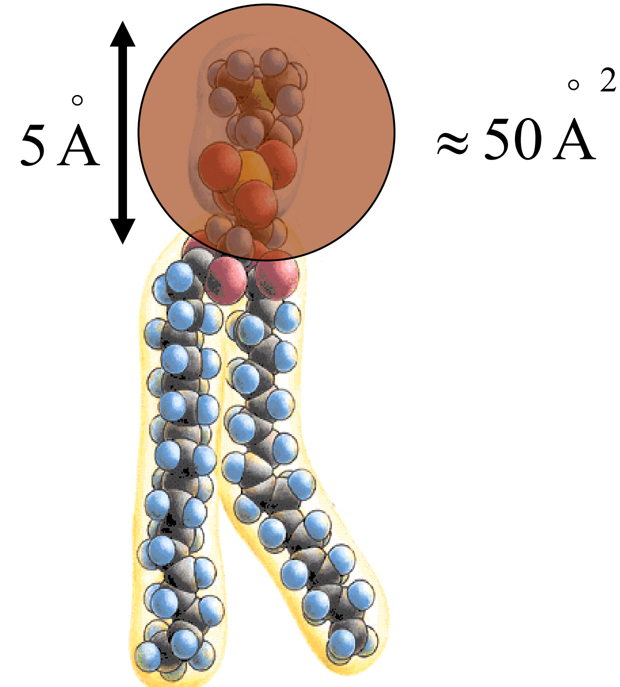
$$S_A \approx 12 \mathring{A}^2$$

$$\sigma_{H_20/Oil} = 0.07 \frac{k_B T}{\mathring{A}^2}$$

$$\Rightarrow \quad \Delta E \approx k_B T$$

Bilayer Properties

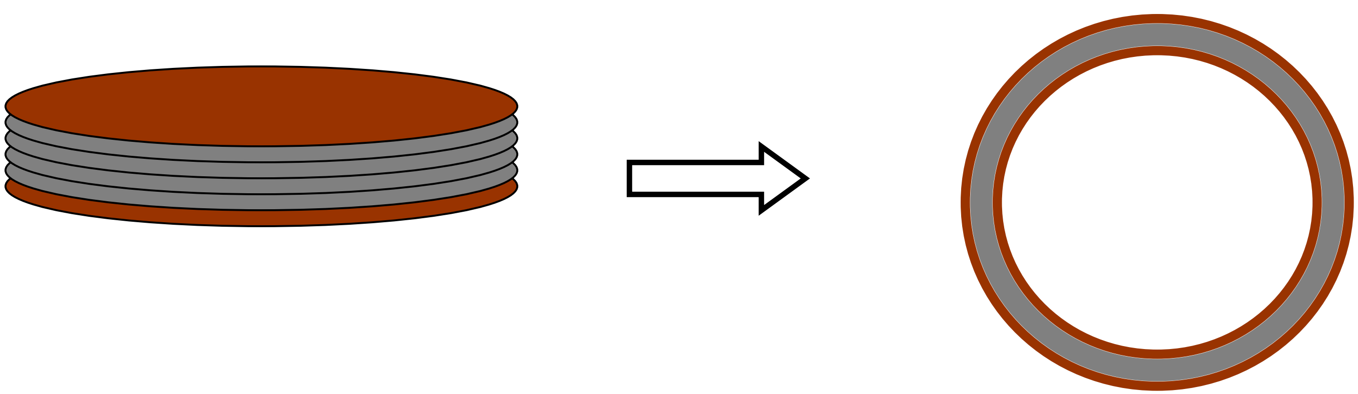




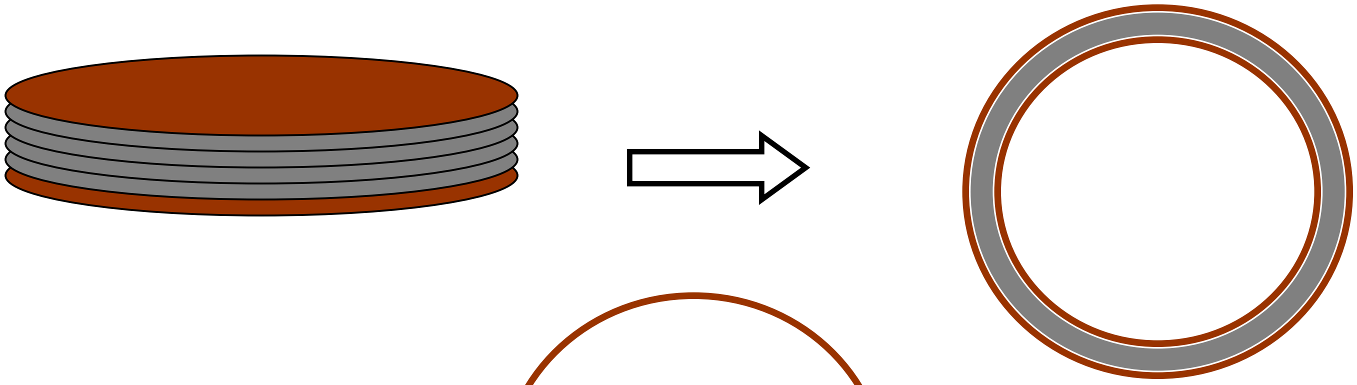
Edge Energy/Length

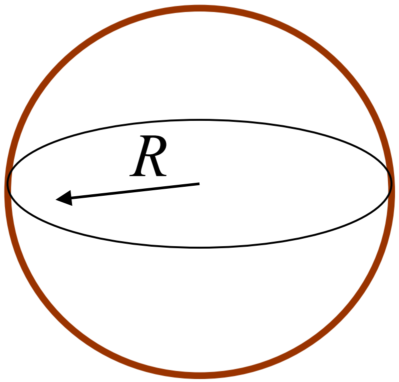
$$E / L \approx \left(0.07 \frac{k_B T}{\mathring{A}^2}\right)\left(30\,\mathring{A}\right) = 2 \frac{k_B T}{\mathring{A}}$$

Driving "Force" for the Formation of closed Structures



Bending Energy





$$E_{Bend} = \frac{\kappa_B}{2}\int\left(\frac{2}{R}\right)^2 dA = \frac{\kappa_B}{2}\left(\frac{4}{R^2}\right)4\pi R^2 = 8\pi\kappa_B$$

$$\kappa_B \approx 10 k_B T \quad \Longrightarrow \quad \boxed{E_{Bend} \approx 240 k_B T}$$