

Chemical Origins of Life

Sudha Rajamani

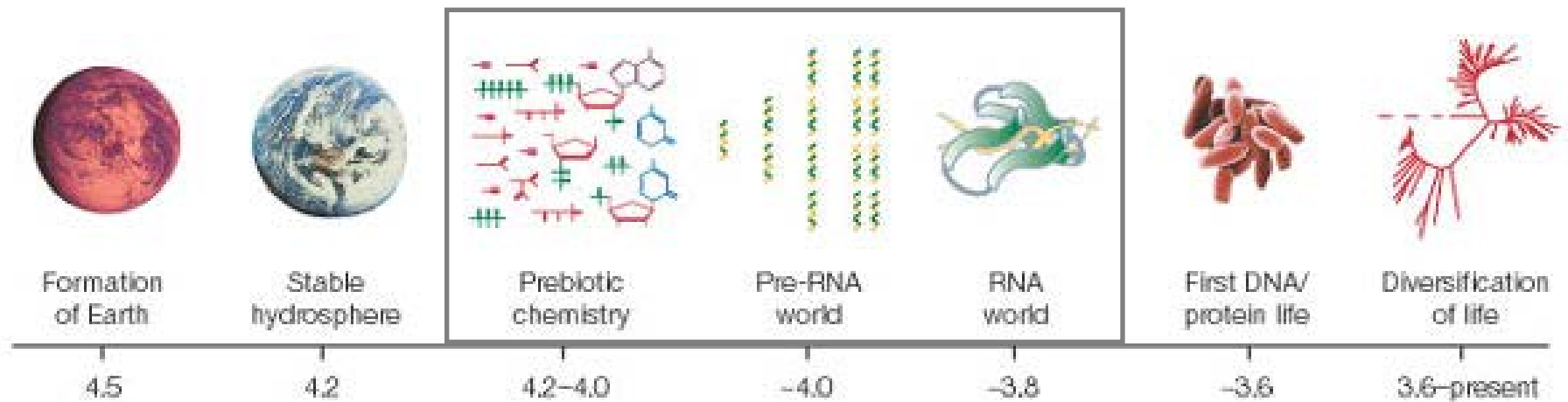
INSA Meeting 2017

Indian Institute of Science Education and Research

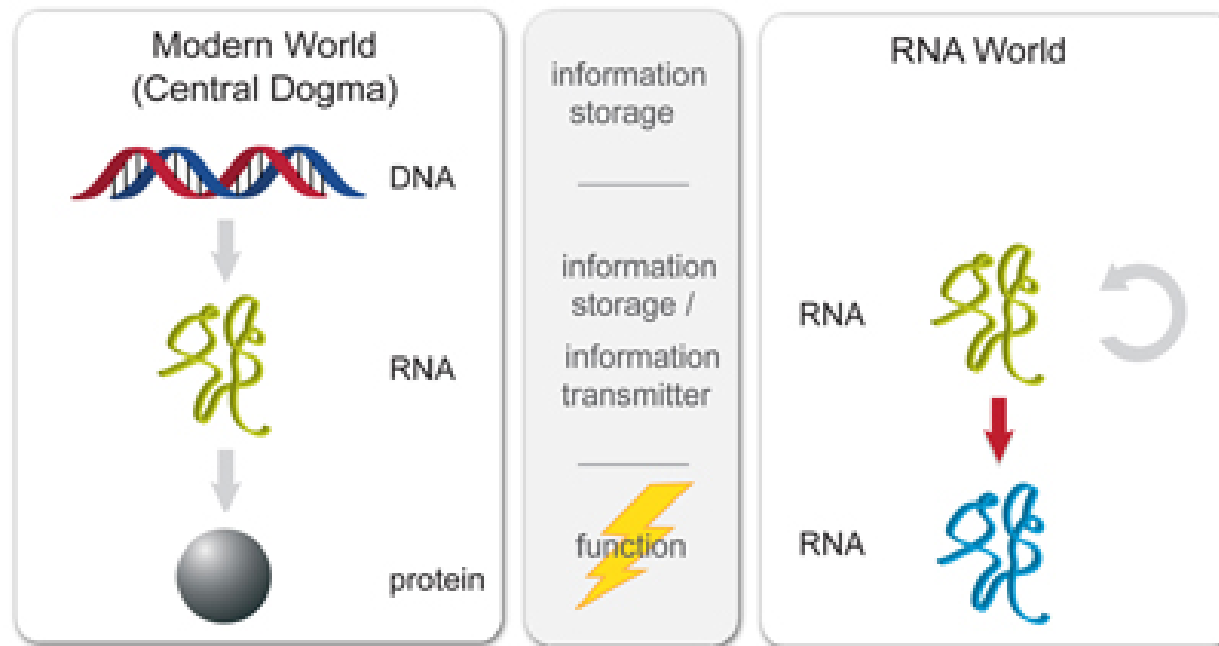
Pune, India



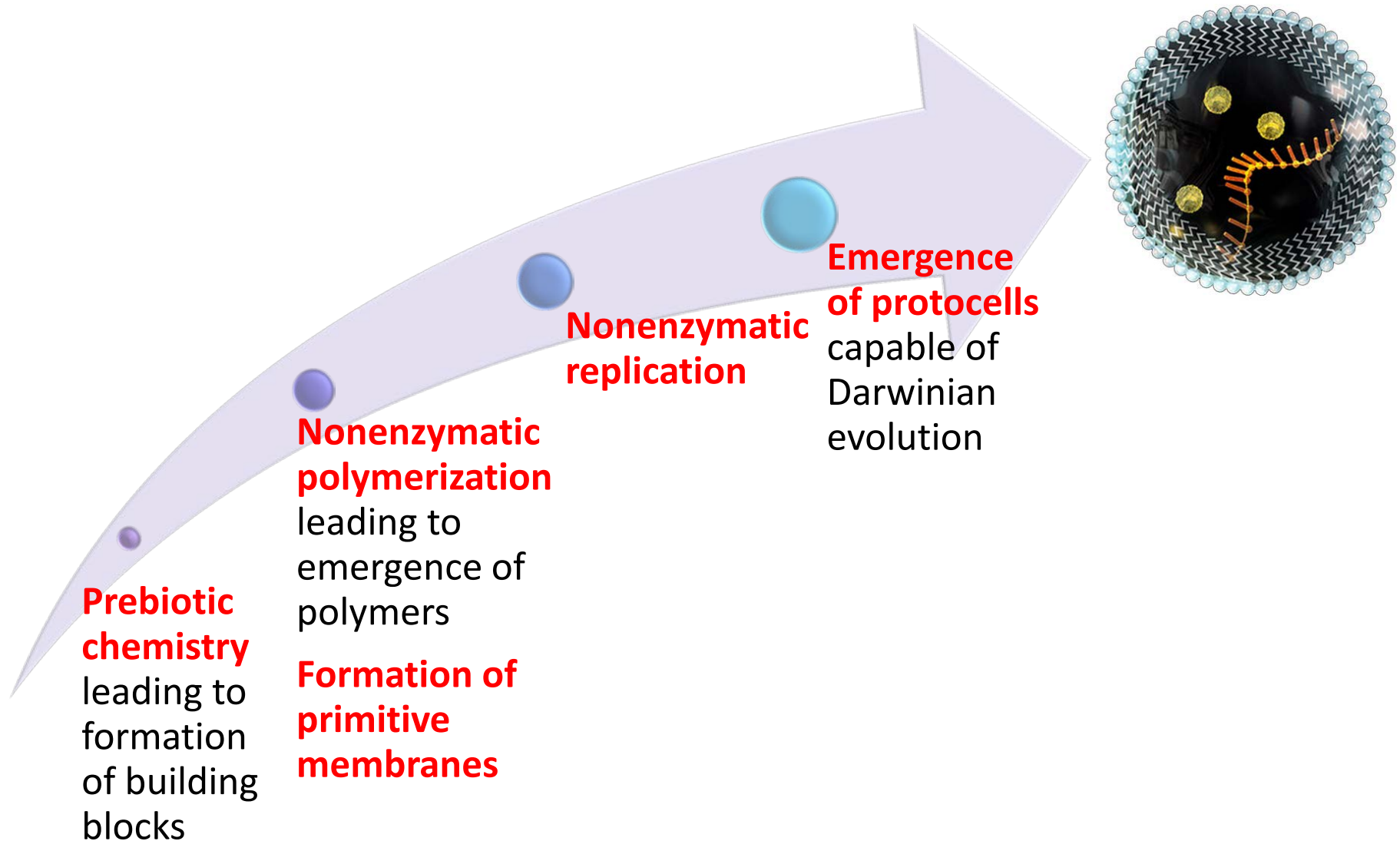
Early history of life on Earth



Joyce, G. *Nature*, 2002, 418, 214.



Steps leading to the emergence of a primitive cellular entity (protocell)



Oparin-Haldane Theory

The ideas of these two men were simple, elegant, and almost identical!

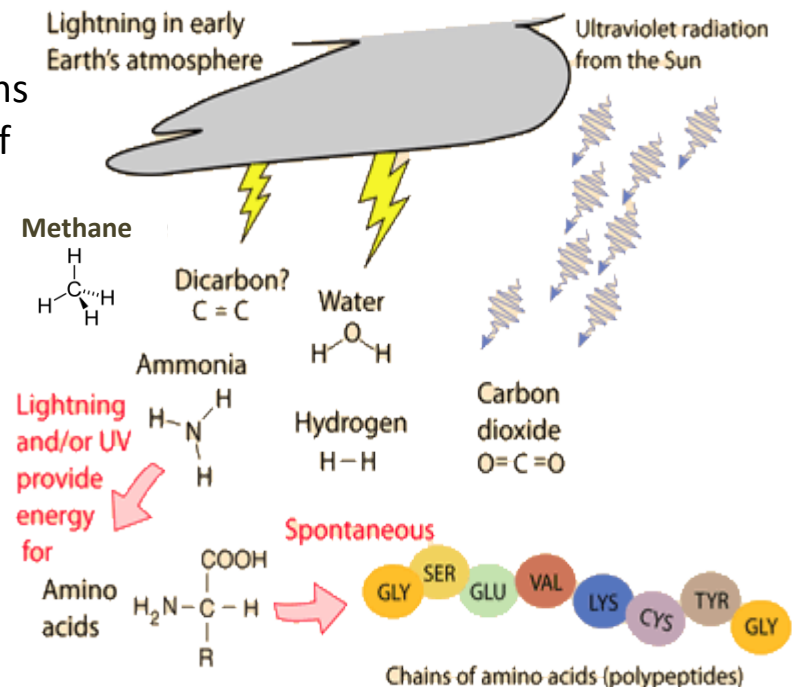
Basic hypothesis: Early Earth's atmosphere was reducing (had an excess of negative charge, could cause reducing reactions by adding electrons to compounds). **Under these conditions, organic molecules could have formed from simple inorganic molecules.**

Haldane's "Primordial Soup": The primordial sea served as a vast chemical laboratory powered by solar energy where the atmosphere was oxygen free.

Host of organic compounds formed under these conditions became a 'hot dilute soup' containing large populations of organic monomers and polymers.

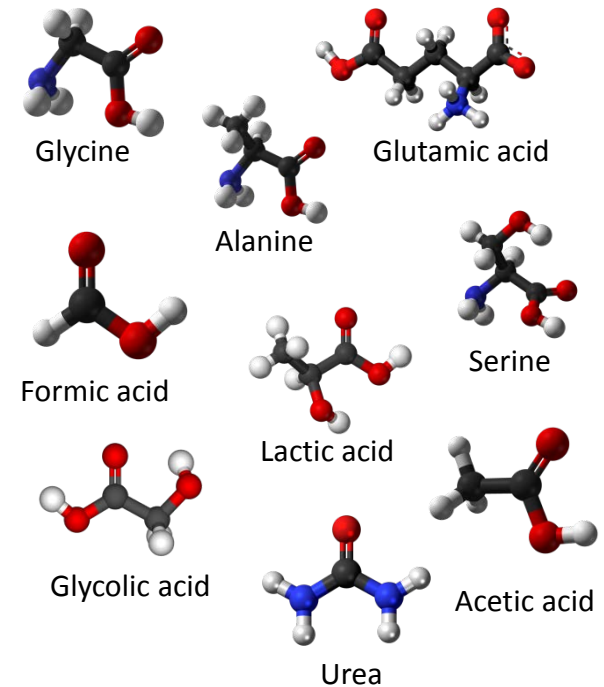
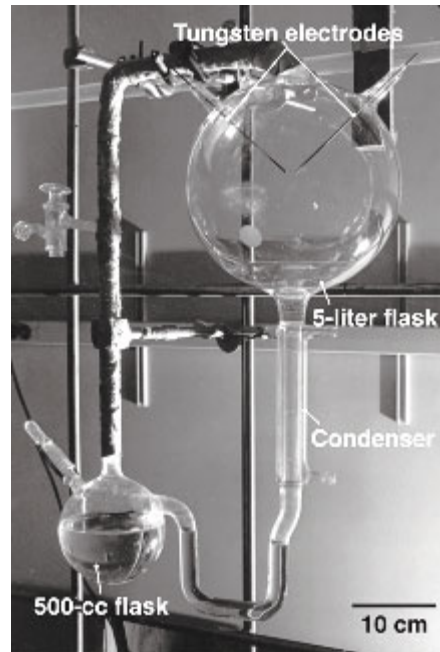
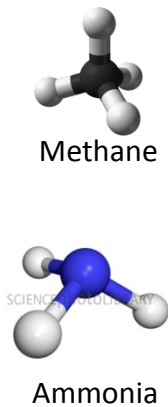
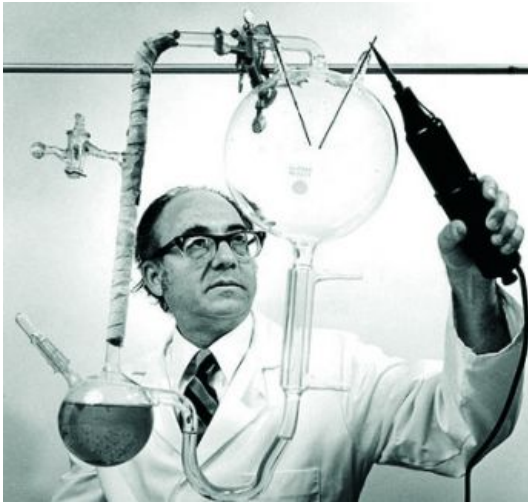


<http://www.cbs.dtu.dk/staff/dave/roanoke/primsoup.jpg>

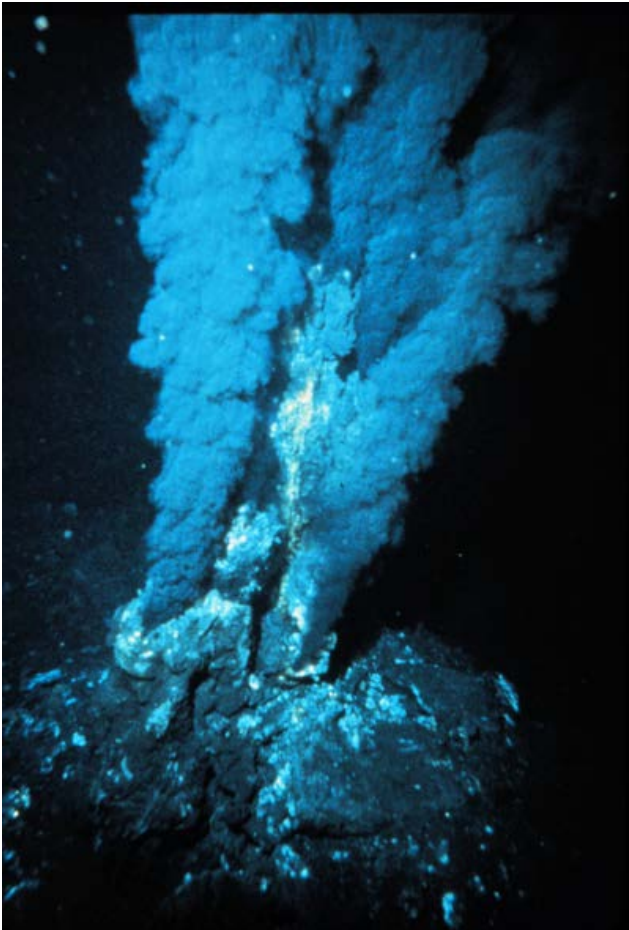


<http://hyperphysics.phy-astr.gsu.edu/nave-html/faithpathh/lifelab.html>

The Miller-Urey Experiment (1953)



Environments that would have supported life-producing chemical reactions

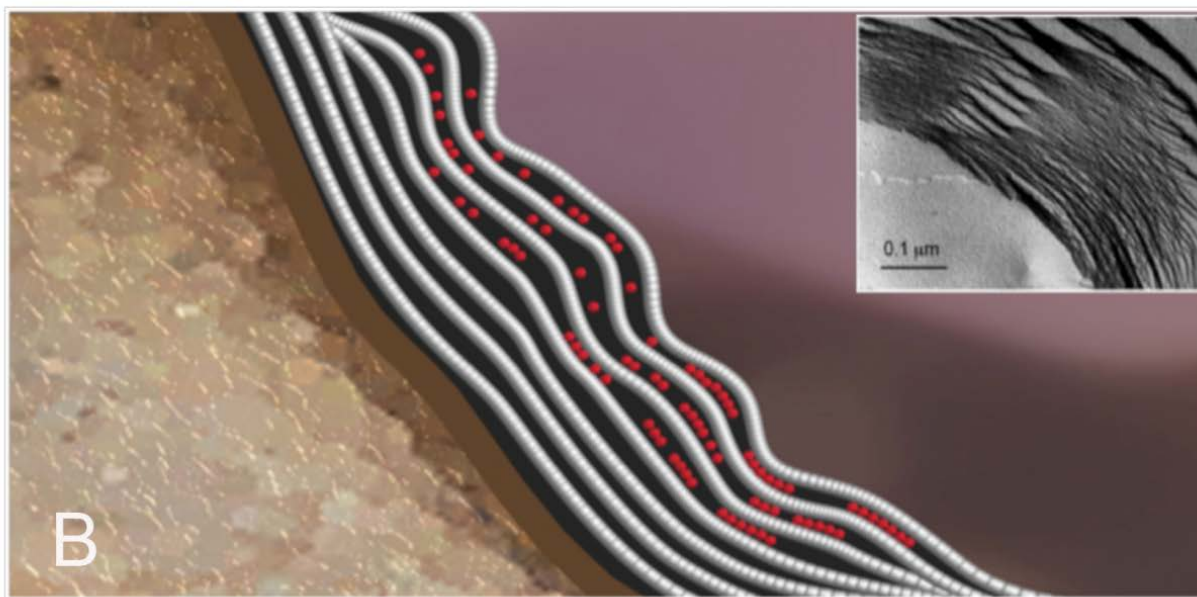
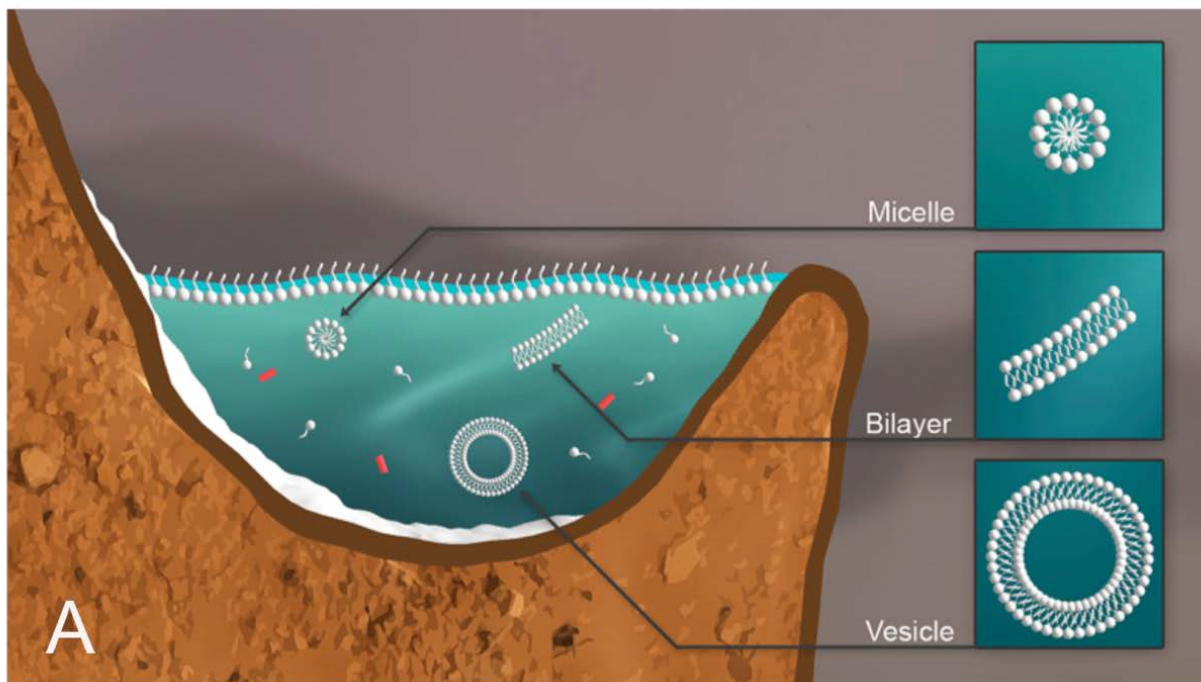


David Deamer, Bumpass Hell, Mount Lassen, CA, USA

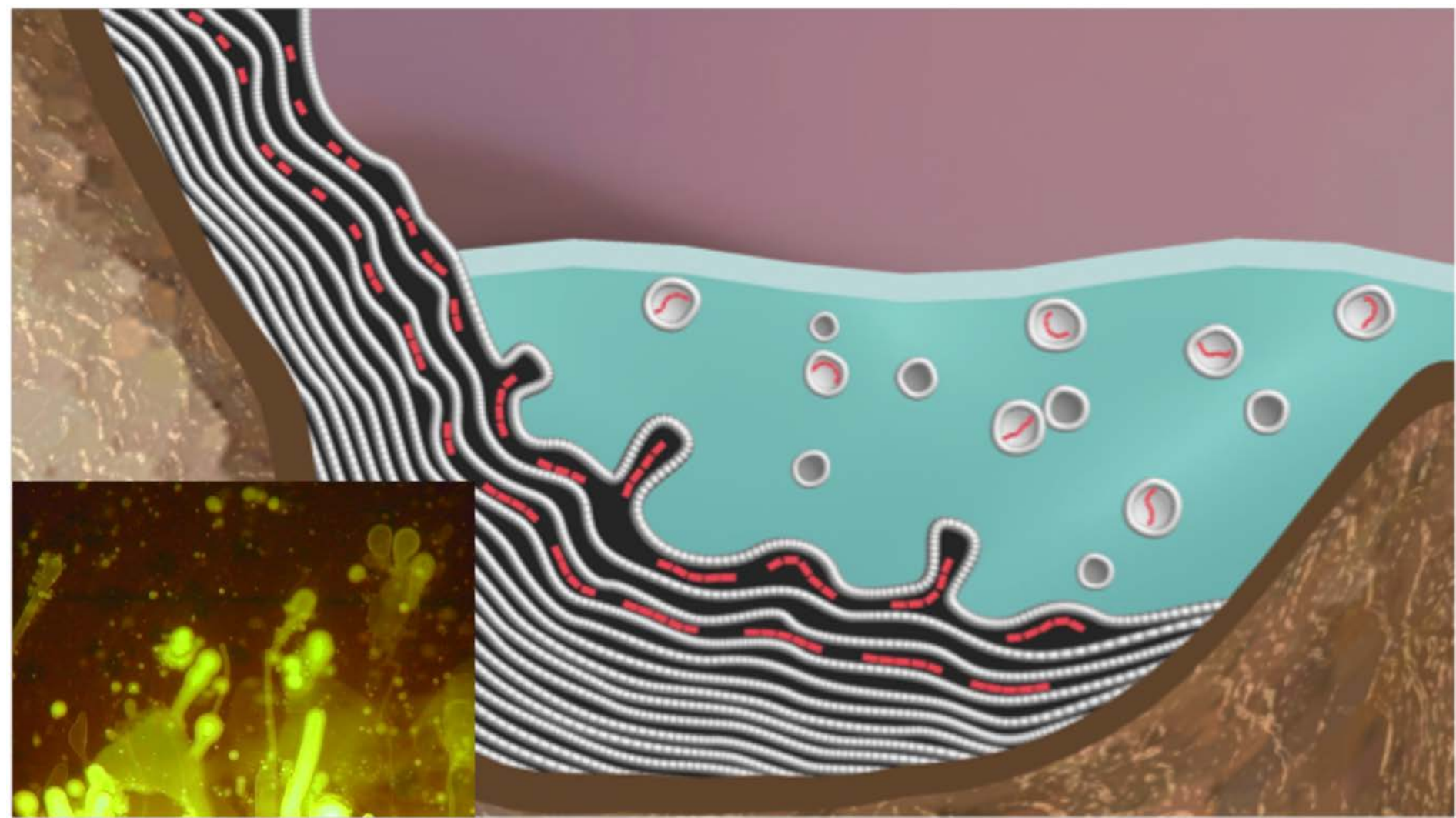
<http://www.photolib.noaa.gov/htmls/nur04506.htm>



Damer and Deamer, <http://www.mdpi.com/2075-1729/5/1/872>



Damer and Deamer, <http://www.mdpi.com/2075-1729/5/1/872>

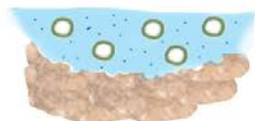


Damer and Deamer, <http://www.mdpi.com/2075-1729/5/1/872>

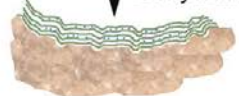
Inland hydrothermal site subject to cycling



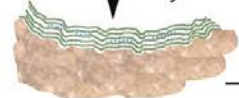
Dehydration and deposition of protocell contents into surface matrix



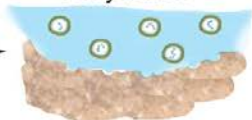
Dehydration



Polymerization



Rehydration

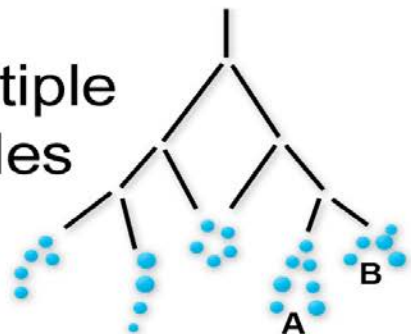


Anhydrous surface phase

Hydrated bulk phase

Stepwise evolution of systems of functional polymers

Multiple cycles

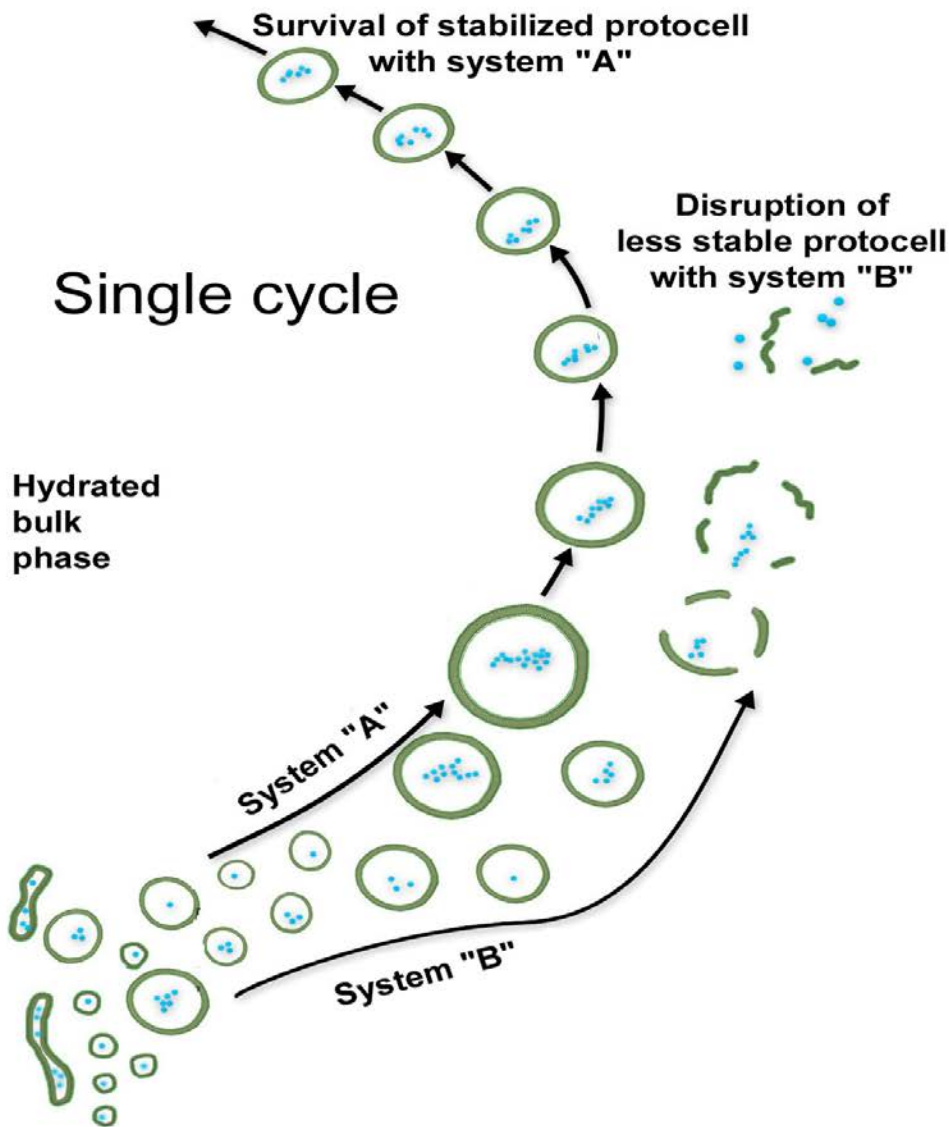


Mutated molecular systems

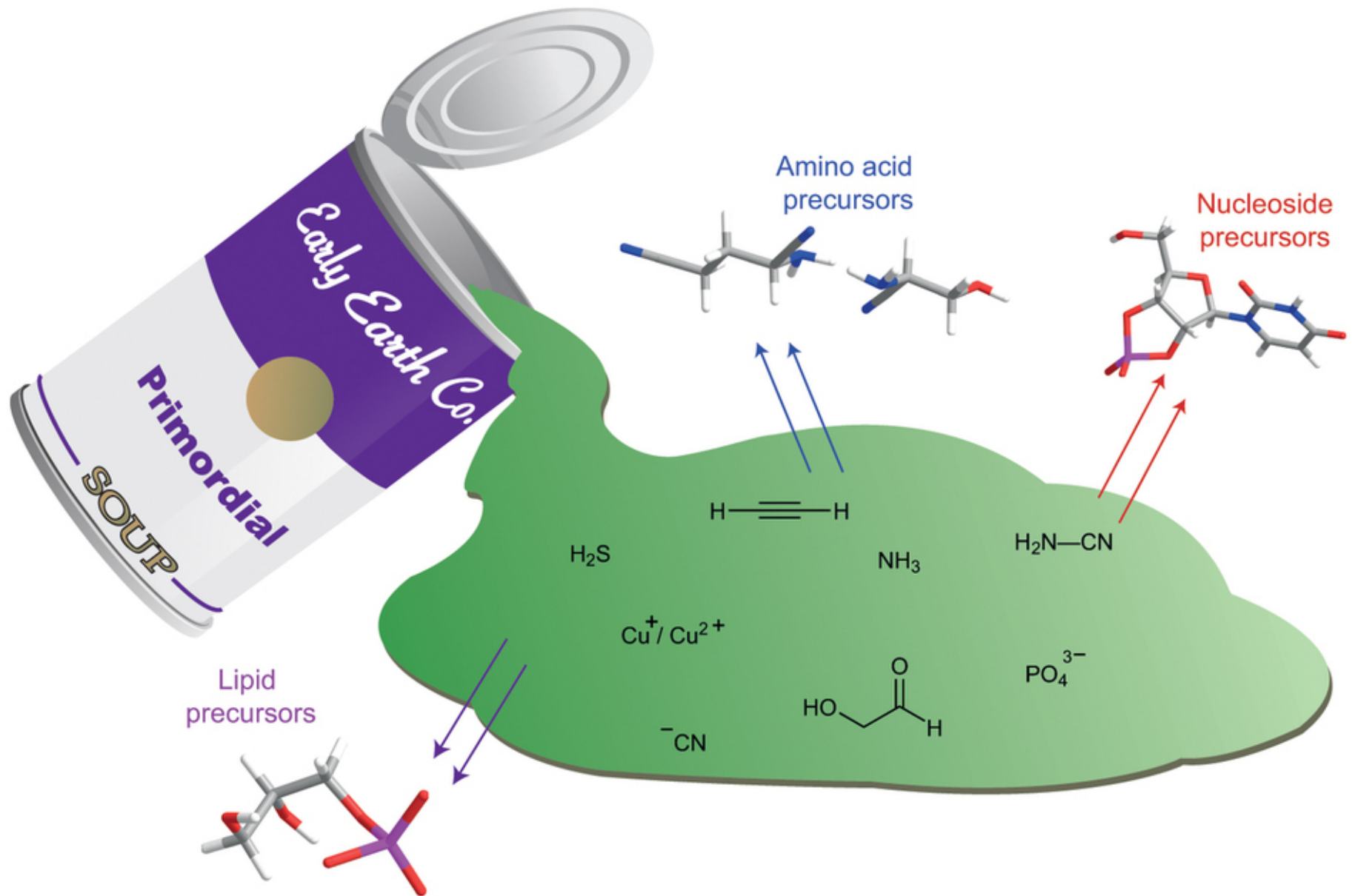
Single cycle

Survival of stabilized protocell with system "A"

Disruption of less stable protocell with system "B"



Hydration and encapsulation of molecular systems in protocells

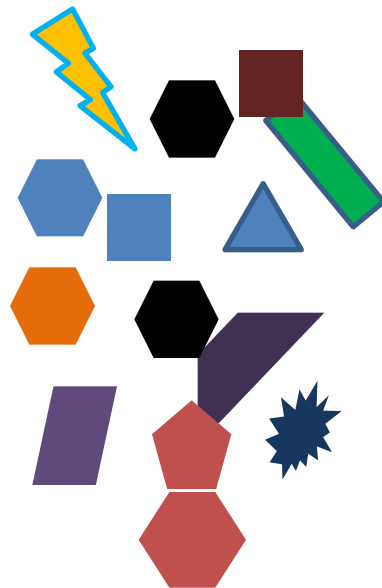
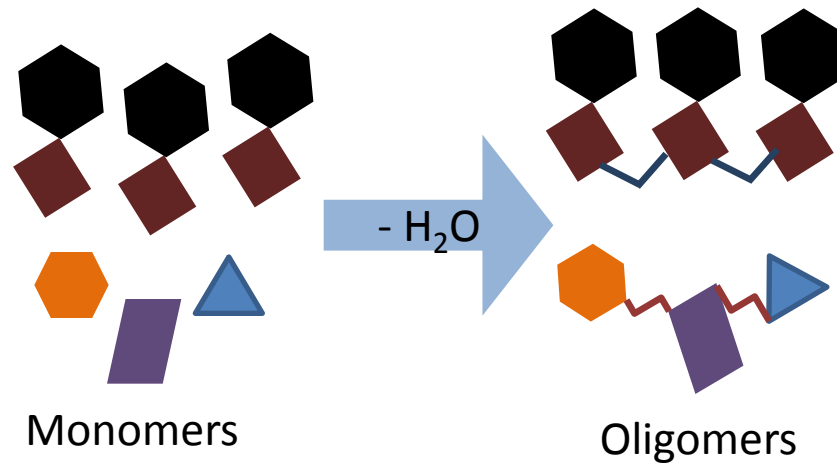


“A recipe for life itself? Precursors to amino acids, nucleosides and lipids can all be obtained from the same simple starting materials.” - Paul J. Bracher, in News and Views of Nature Chemistry , 7, 273–274 (2015)

Formation of RNA by nonenzymatic oligomerization

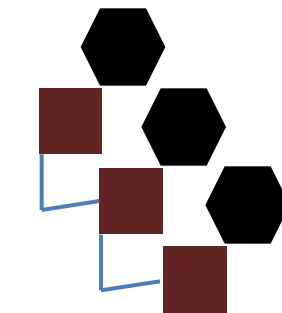
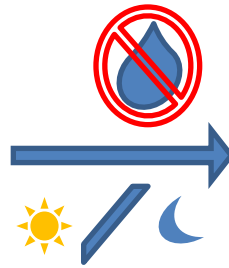
- ☐ Polymerization in biology is achieved by use of high energy monomers and enzymes
- ☐ Early oligomerization had to be nonenzymatic & by chemical means
- ☐ Chemical polymerization is predominantly condensation reaction, driven by fluctuating dehydration-rehydration cycles, a common theme on prebiotic Earth
- ☐ Not favorable in bulk solution due to excess of water
- ☐ Polymerization is an uphill reaction
- ☐ Most studies use activated nucleotides

Condensation reactions result in polymerization



Mixture of
Biomolecules

Originate?



Oligomers

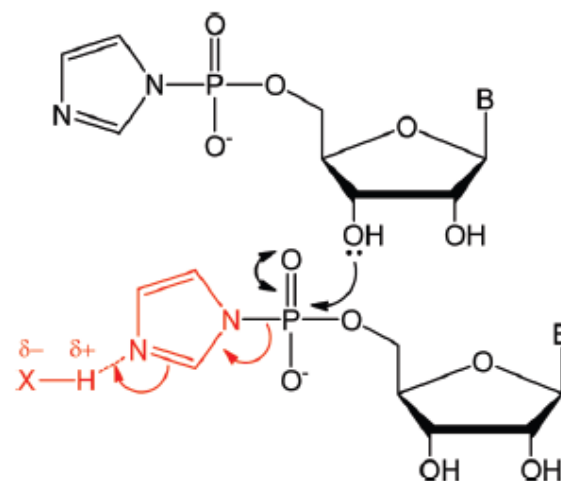
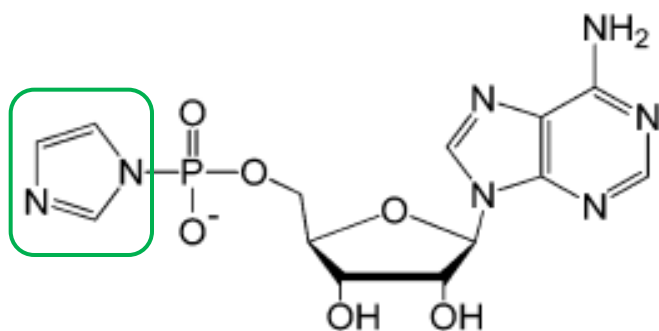
Evolve?



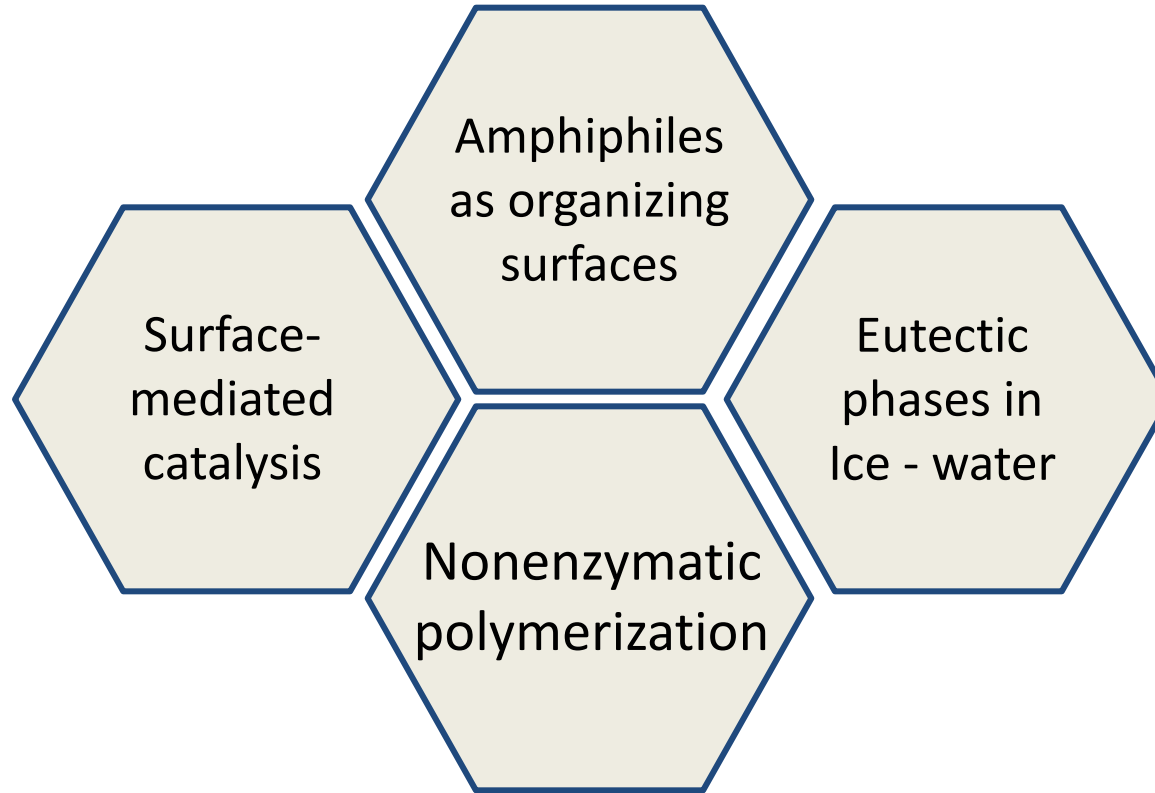
Polymers with complex
functions

Use of activated nucleotides for oligomerization

- ❑ Polymerization favorable if monomers are high energy molecules
- ❑ Modern biology uses activated monomers such as triphosphates, aminoacyl-tRNAs etc
- ❑ For chemical polymerization, monomers are activated using better leaving groups
- ❑ Several studies have used imidazole activated nucleotides
- ❑ Activated nucleotides polymerize faster giving better yields



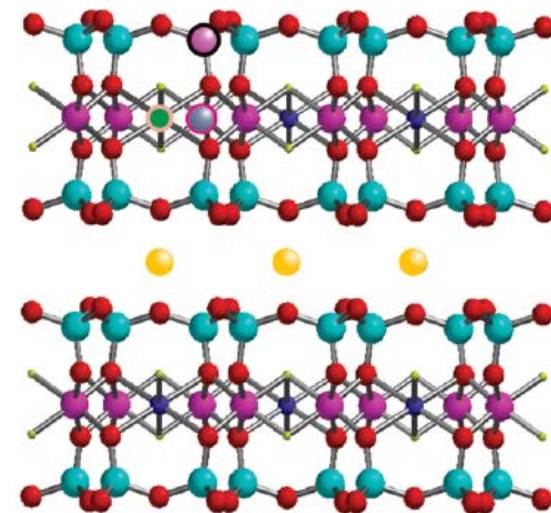
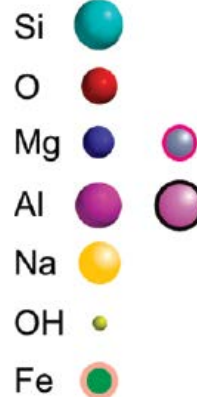
Polymerization mechanisms



Surface-mediated catalysis

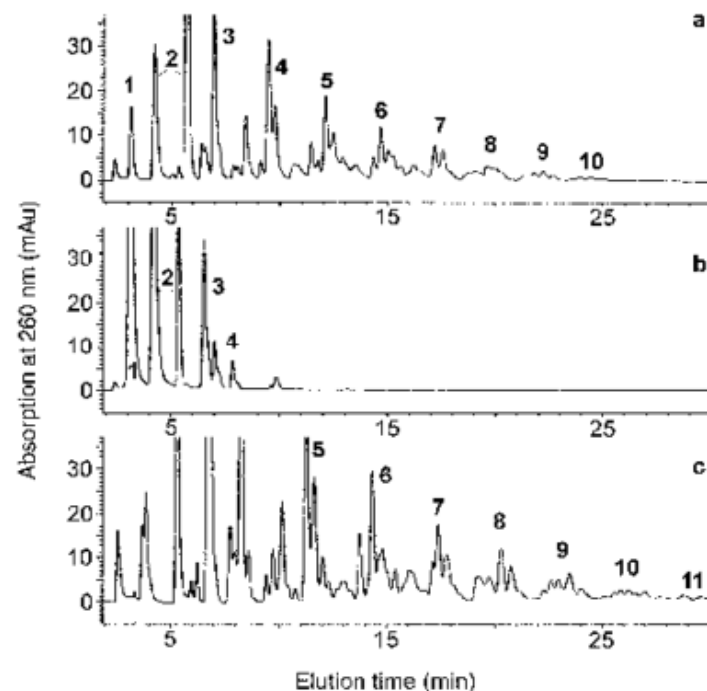
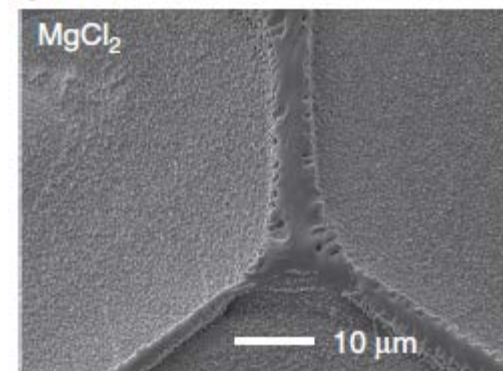
- ☐ Polymerization in aqueous solutions is a chance event due to diffusional mobility
- ☐ Adsorption onto surfaces bring monomers closer and also increases their local concentration
- ☐ Studies on surface-mediated catalysis use clay as catalyzing agents
- ☐ Clay thought to be abundant on prebiotic Earth
- ☐ Clay has large surface area to volume ratio
- ☐ Internal structure is lattice-like with several ions present in interlayers, spaces where polymerization is favoured

Key



Eutectic phases in Ice-Water

- ☐ Dilute solutions of salt show eutectic freezing
- ☐ Eutectic phases result in selective exclusion of solute molecules from ice crystals thus increasing the effective concentration
- ☐ Formation of nucleobases from HCN & cyanoacetylene at low temp.
- ☐ Polymerization of imidazole activated nucleotides under eutectic conditions is observed
- ☐ Freezing is required for efficient polymerization & not just low temp.
- ☐ Unfavorable back reactions (hydrolysis) prevented



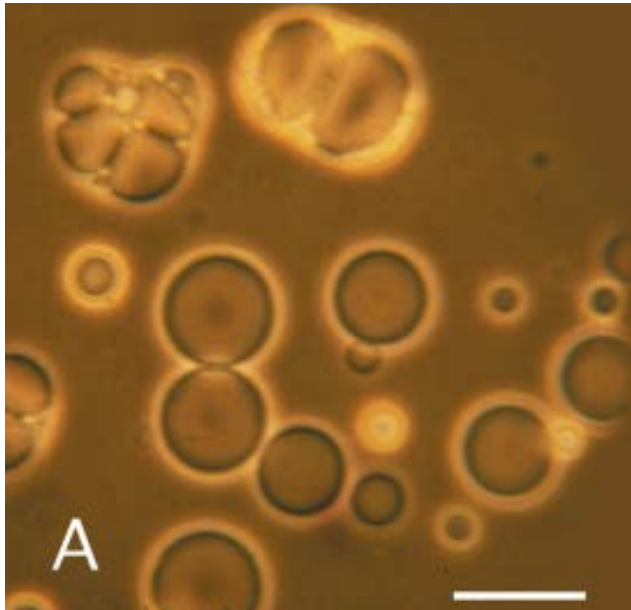
Amphiphiles on prebiotic Earth

- ☐ Biomolecules such as phospholipids, fatty acids are amphiphiles and are components of cell membranes
- ☐ Fatty acids as candidate for primitive membranes
- ☐ Fatty acids have shown to be synthesized by Fisher-Tropsch-Type reactions
- ☐ Mixed fatty acids form vesicles in high ionic strength solutions and at very low & high pH regimes
- ☐ Stabilized by addition of various polycyclic aromatic compounds
- ☐ Some compositions selectively permeable for biomolecules seen in extant biology (ribose over other sugars)



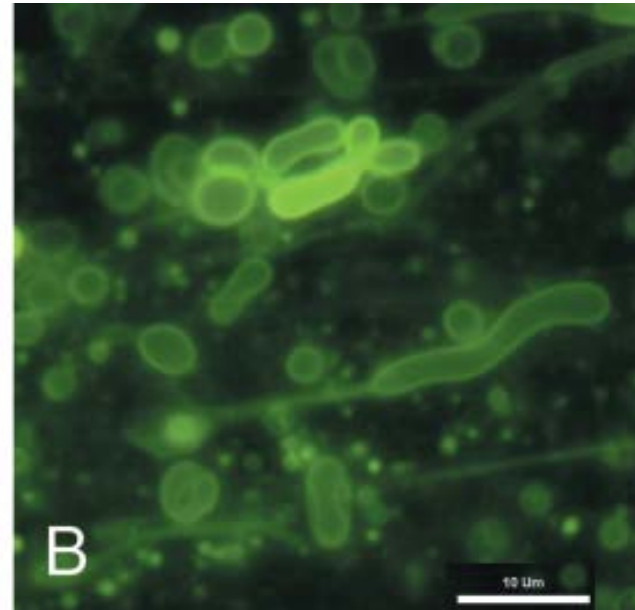
Primitive FA membrane structures visualized by light microscopy

**Amphiphilic compounds
extracted from the
Murchison meteorite**



**Monocarboxylic acids with admixtures of
PAH derivatives form vesicles when
exposed to dilute aqueous salt solutions at
pH 7.0**

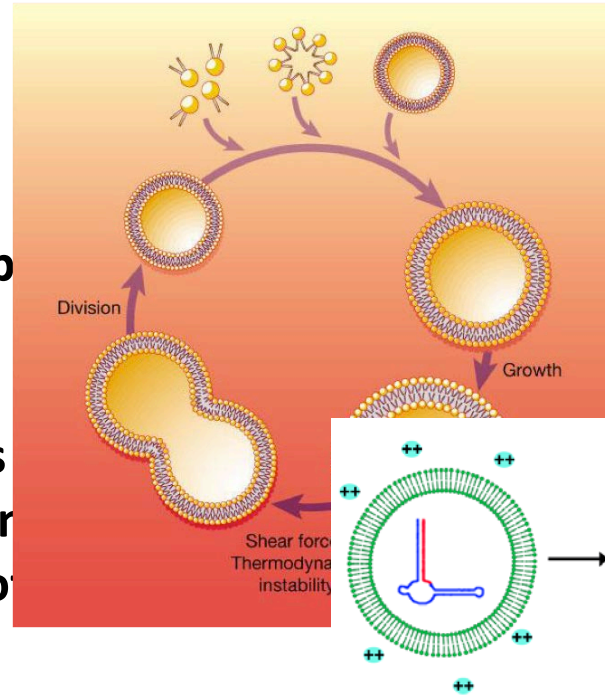
**Vesicles formed from
pure monocarboxylic
acids**



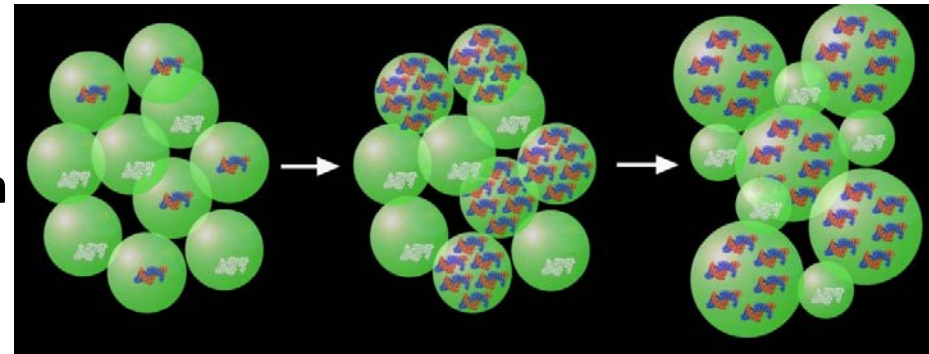
**Decanoic acid:decanol (37mM: 3mM,
C10, pH 7.4)**

Amphiphiles as compartments

- ❑ Fatty acid vesicles show growth and division without external catalyst
- ❑ Ribozymes have been shown to be functional inside vesicles
- ❑ Competition is shown by vesicles containing active ribozymes. Vesicles containing active ribozymes can grow at the expense of other vesicles

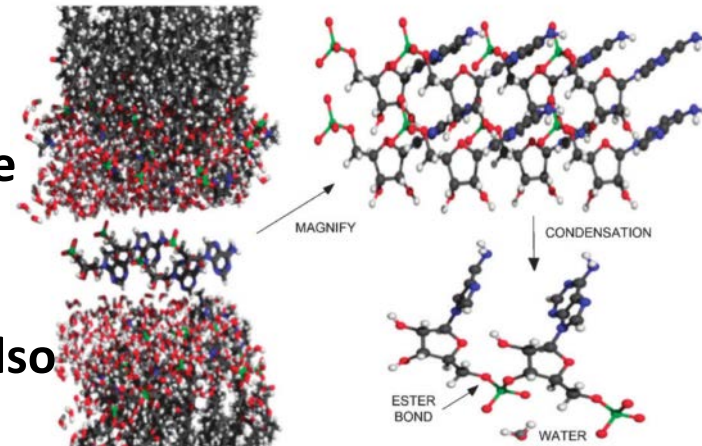
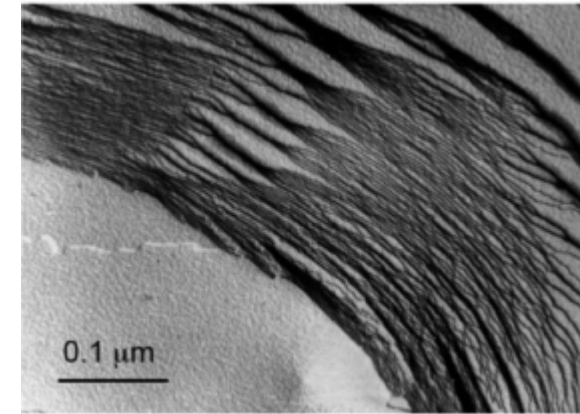


Compartmentalization enhances functionality, facilitates prebiotic evolution and would have provided selective advantage in an “RNA World”

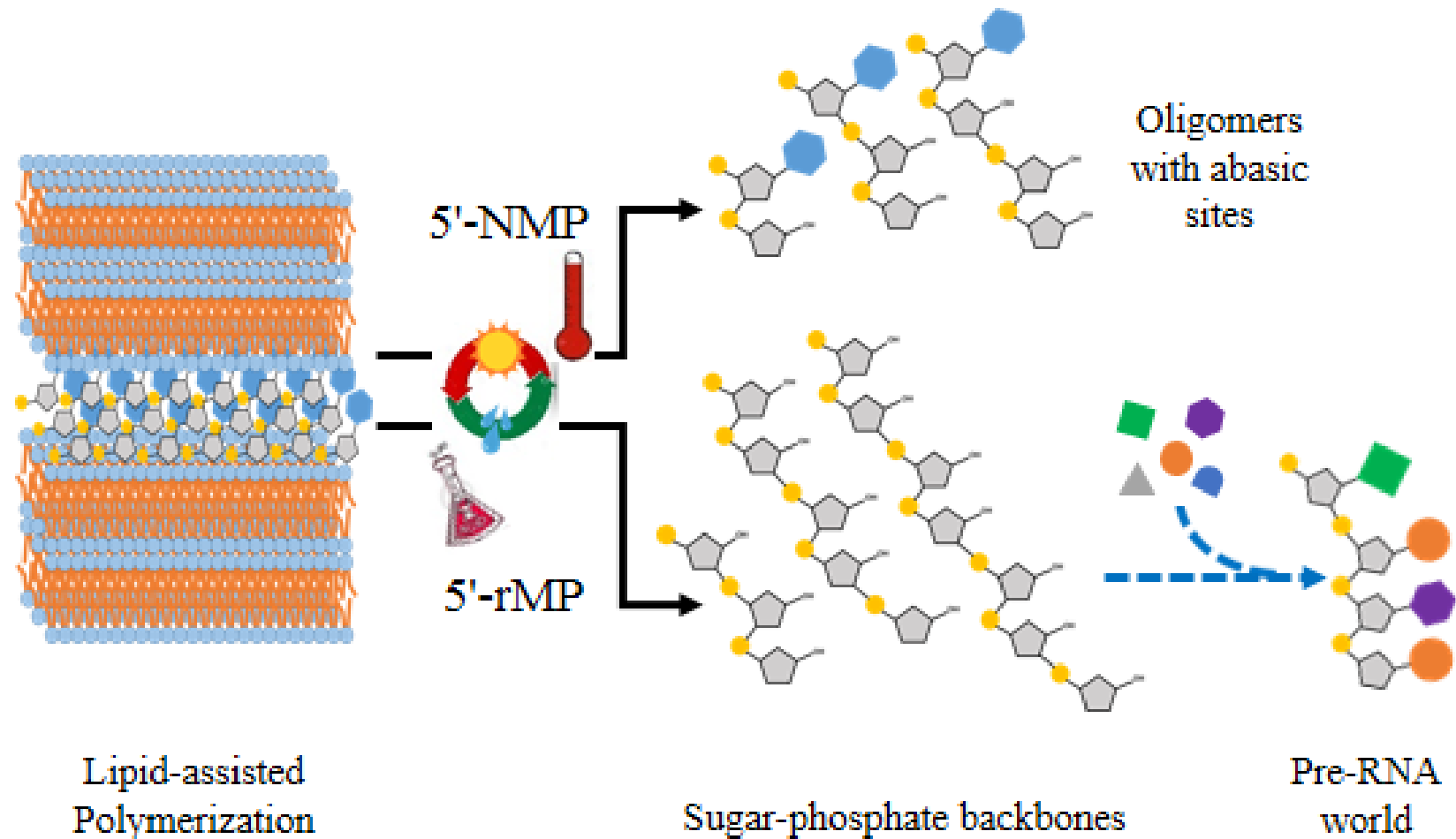


Amphiphiles as organizing matrix

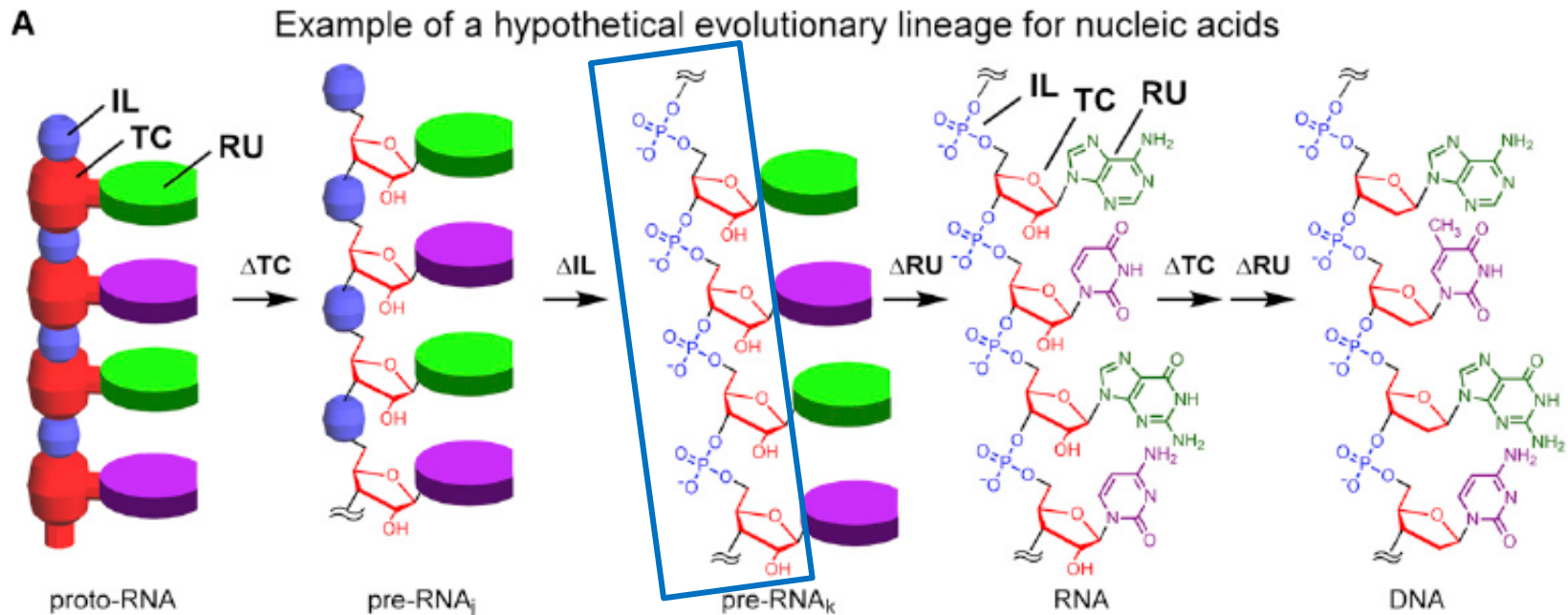
- ❑ Amphiphiles form higher order structures depending on concentration
- ❑ Fluctuating environments common on early Earth which allow for formation of alternating hydrophobic & hydrophilic environments in multilamellar sandwiches
- ❑ Monomers are ordered in these 2D spaces with diffusional mobility. Structural analysis reveals arrangement of monomers in patterns that can favor bond formation
- ❑ Non-activated RNA monomers and simpler sugar-phosphate monomers are shown to polymerize in presence of amphiphiles at low pH & high temp
- ❑ Transfer of information by templated- replication also possible



Lipid-assisted oligomerization of non-activated nucleotides and sugar-phosphate monomers



Chemical evolution: Primitive Genetic Polymers



Chemistry & Biology
Perspective

The Origin of RNA and “My Grandfather’s Axe”

Nicholas V. Hud,^{1,*} Brian J. Cafferty,¹ Ramanarayanan Krishnamurthy,² and Loren Dean Williams¹

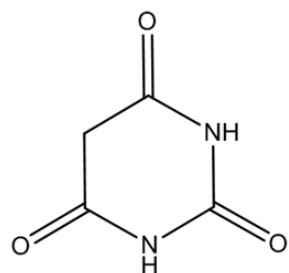
¹School of Chemistry and Biochemistry and Parker H. Pett Institute for Bioengineering and Bioscience, Georgia Institute of Technology, Atlanta, GA 30332, USA

²Department of Chemistry, The Scripps Research Institute, La Jolla, CA 92037, USA

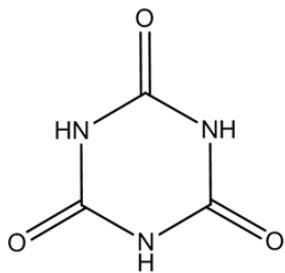
*Correspondence: hud@gatech.edu

<http://dx.doi.org/10.1016/j.chembiol.2013.03.012>

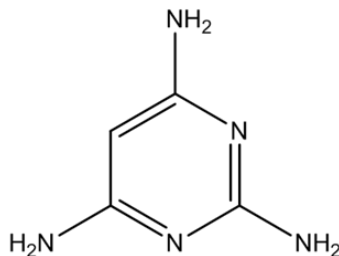
Other heterocycles as information carrying units



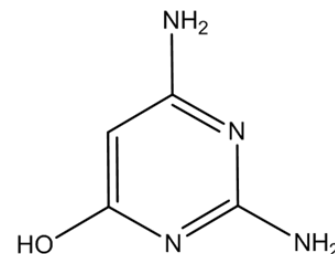
Barbeturic acid
(BA)



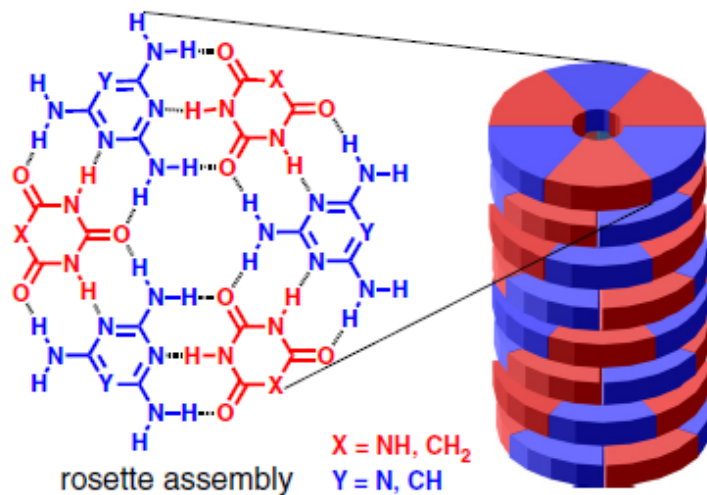
Cyanuric acid
(CA)



2,4,6-Triamino Pyrimidine
(TAP)

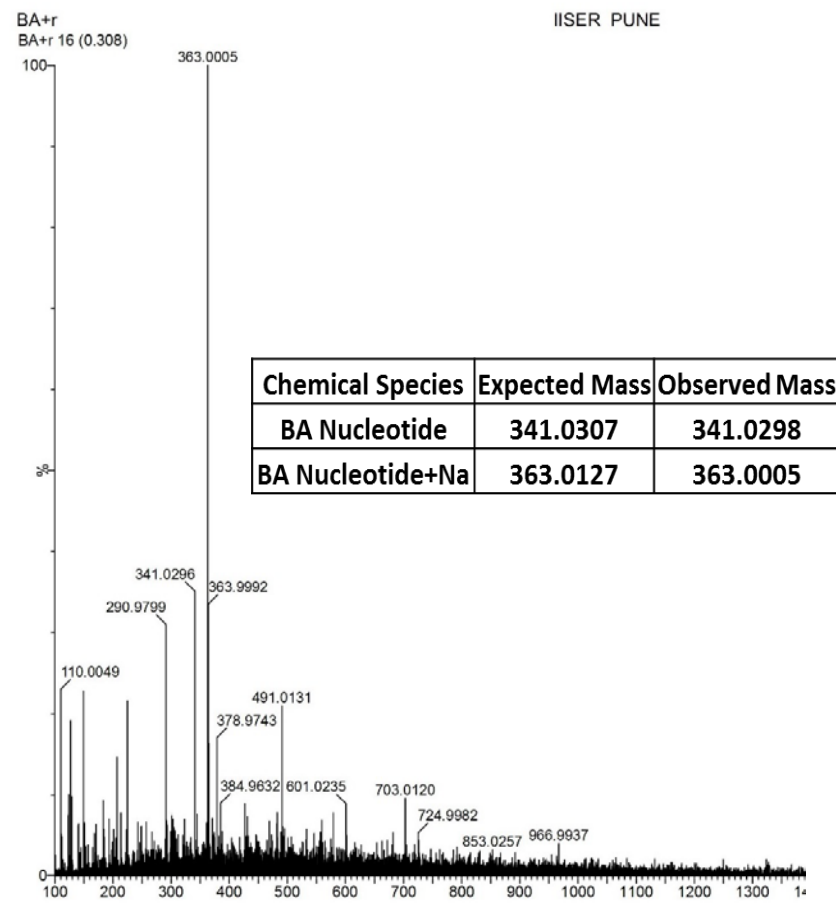
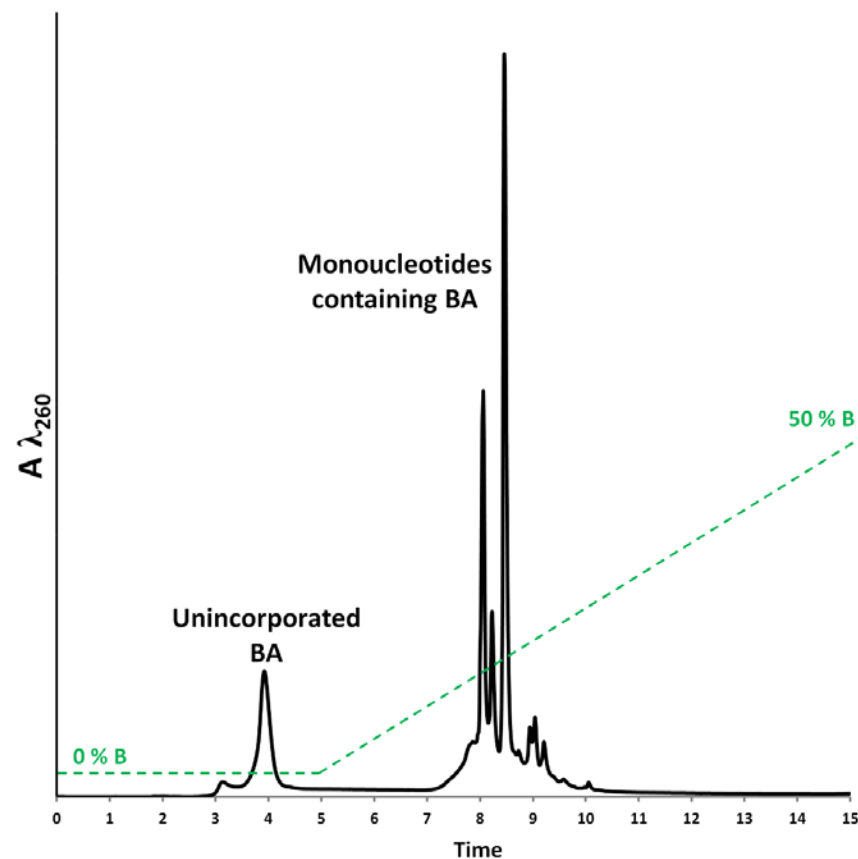
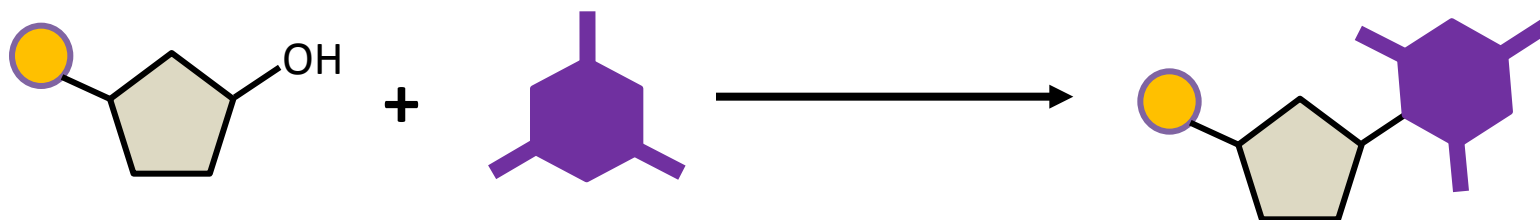


2,4-Diamino 6-Hydroxy Pyrimidine
(DAHP)



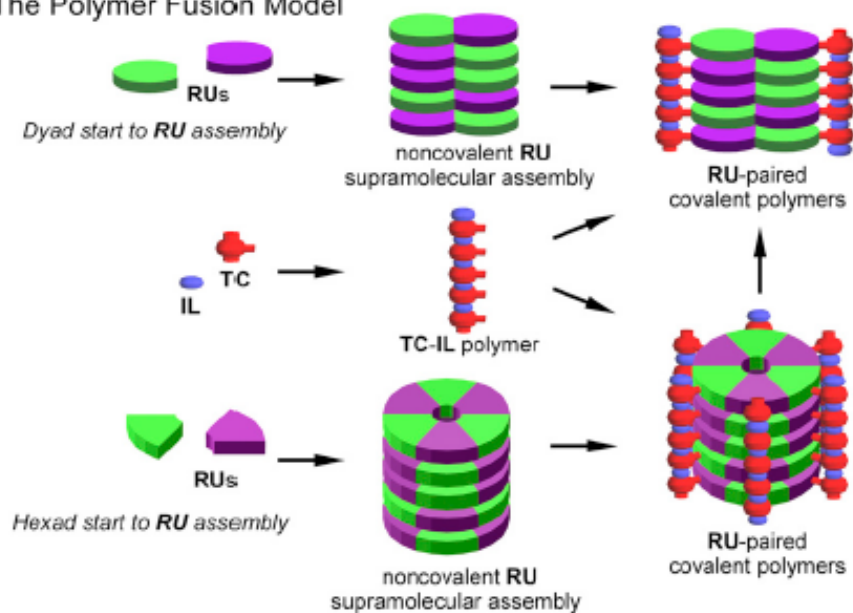
Adapted from Cafferty and Hud 2014

Nucleotide formation with alternate bases

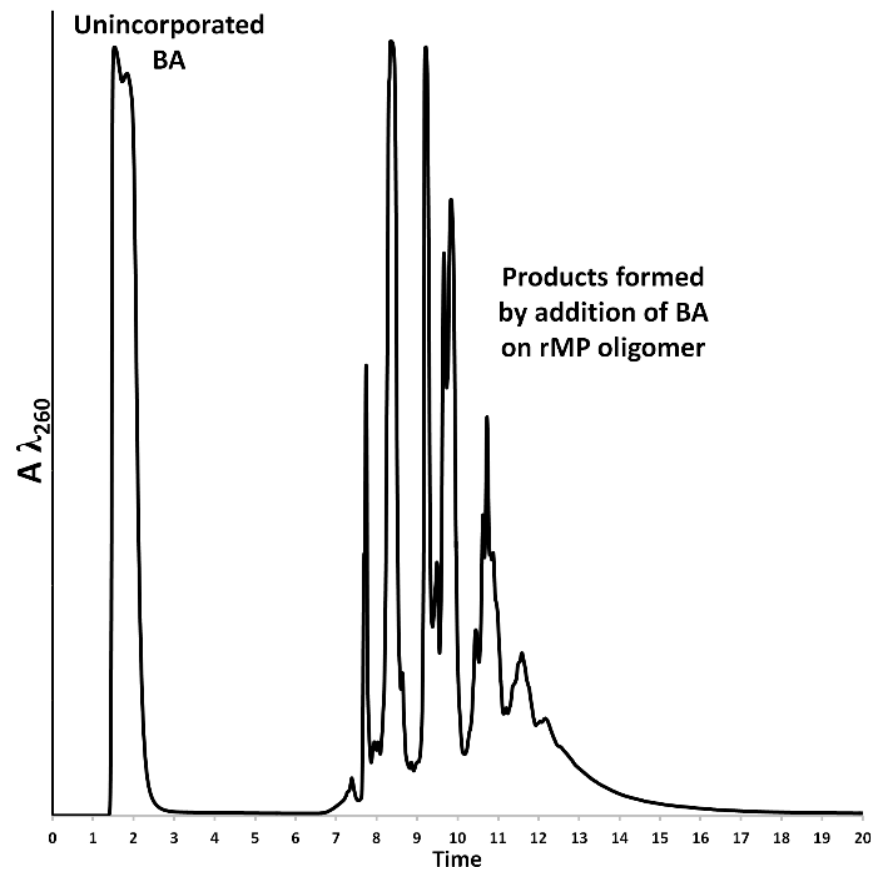


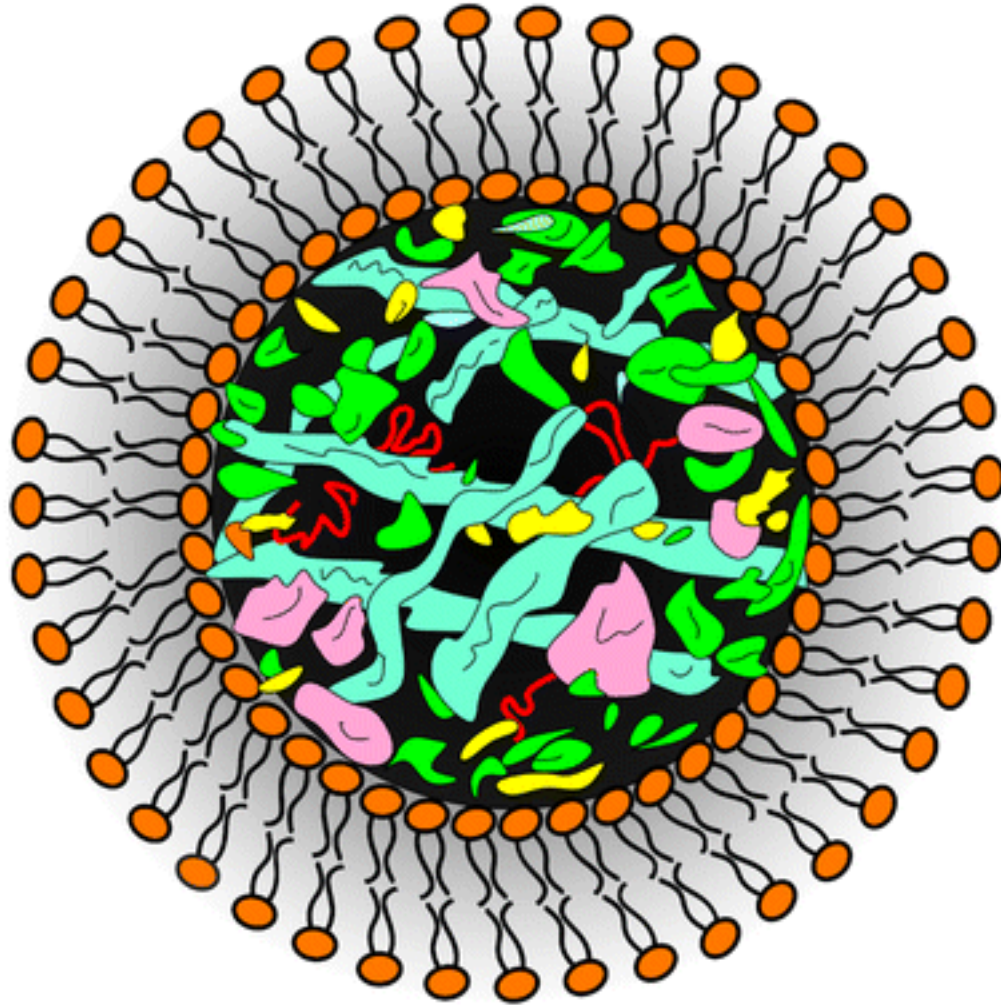
Polymer fusion model

C The Polymer Fusion Model



Hud *et. al.* Chemistry & Biology, 2013





“The best we can ever do is to draw up a story that is consistent with all the evidence: with experiments in chemistry, with what we know about the early Earth, and with what biology reveals about the oldest forms of life. Finally, after a century of fractious effort, that story is coming into view.”



Da verrry best!!!!



https://www.toonpool.com/cartoons/intelligent%20life_17590

Acknowledgments

Jeet Chugh and Harshad
IISER Pune Chemistry



Dr. Yayoi Hongo,
Dr. Jim Cleaves,
ELSI members

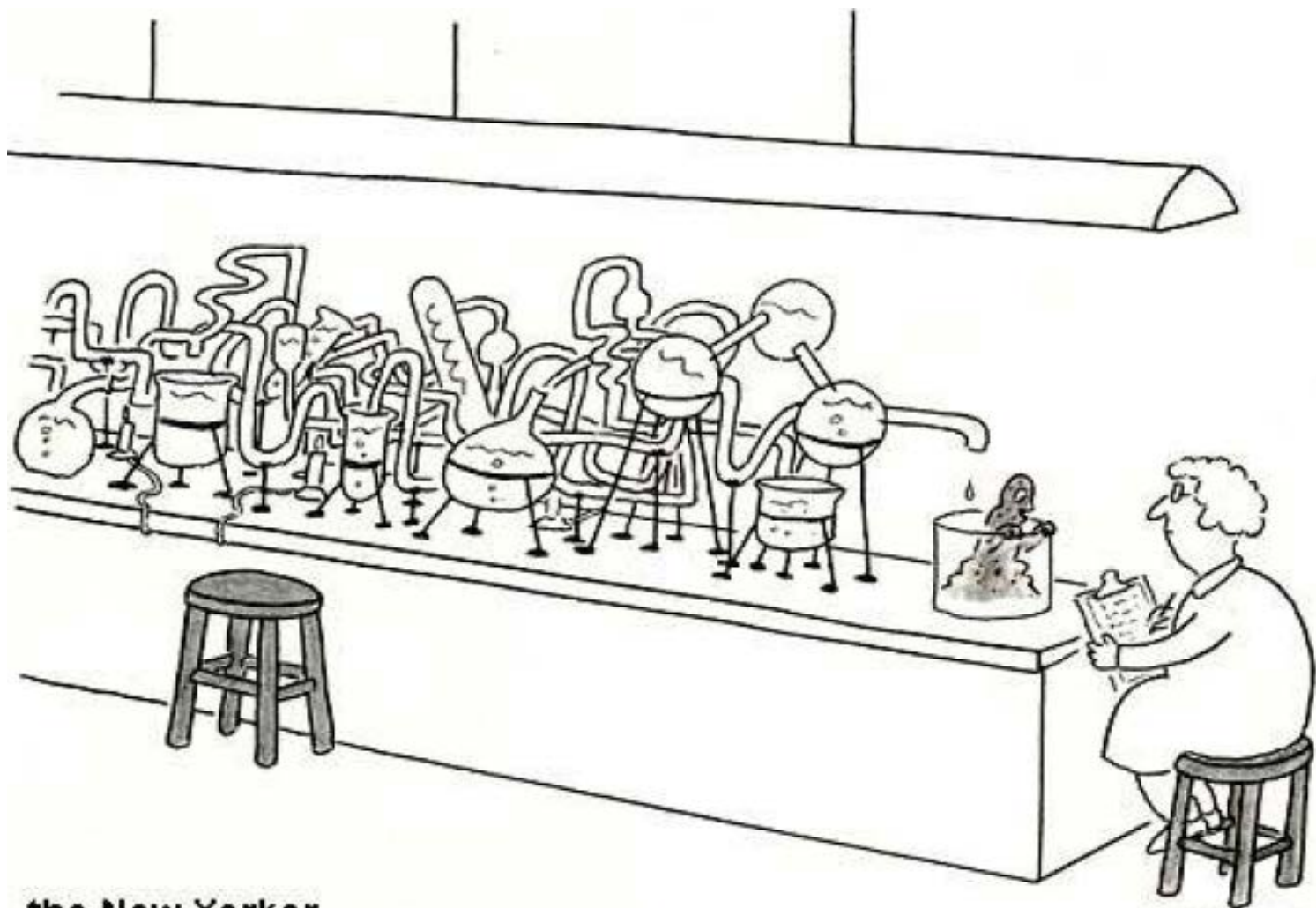


COoL Lab Members and IISER Pune Biology



Thank you!!

Chemical Origins of Life



the New Yorker
Sep 18, 2006
pg 77

"Are you my mommy?"

S. GROSS