GENESIS: The Scientific Quest for Life's Origin

The Brookings Institution
June 15, 2007
Robert Hazen, Geophysical Laboratory

Chemical Evolution

Life arose by a natural process of "emergent complexity," consistent with natural laws.

This hypothesis predicts that life began as a sequence of chemical steps.

Intelligent Design

Life is "irreducibly complex." Therefore, a supernatural designer must have formed it.

This hypothesis requires a combination of natural and supernatural processes.

Is ID Science?

ON THE ONE HAND:

ID makes predictions, albeit negative ones.

These predictions are falsifiable.

BUT:

ID is based on supernatural processes.

ID is therefore inherently untestable, and is unsupported by observational evidence.

THE “DEBATE”

“Both sides ought to be properly taught ... so people can understand what the debate is about.” G. W. Bush

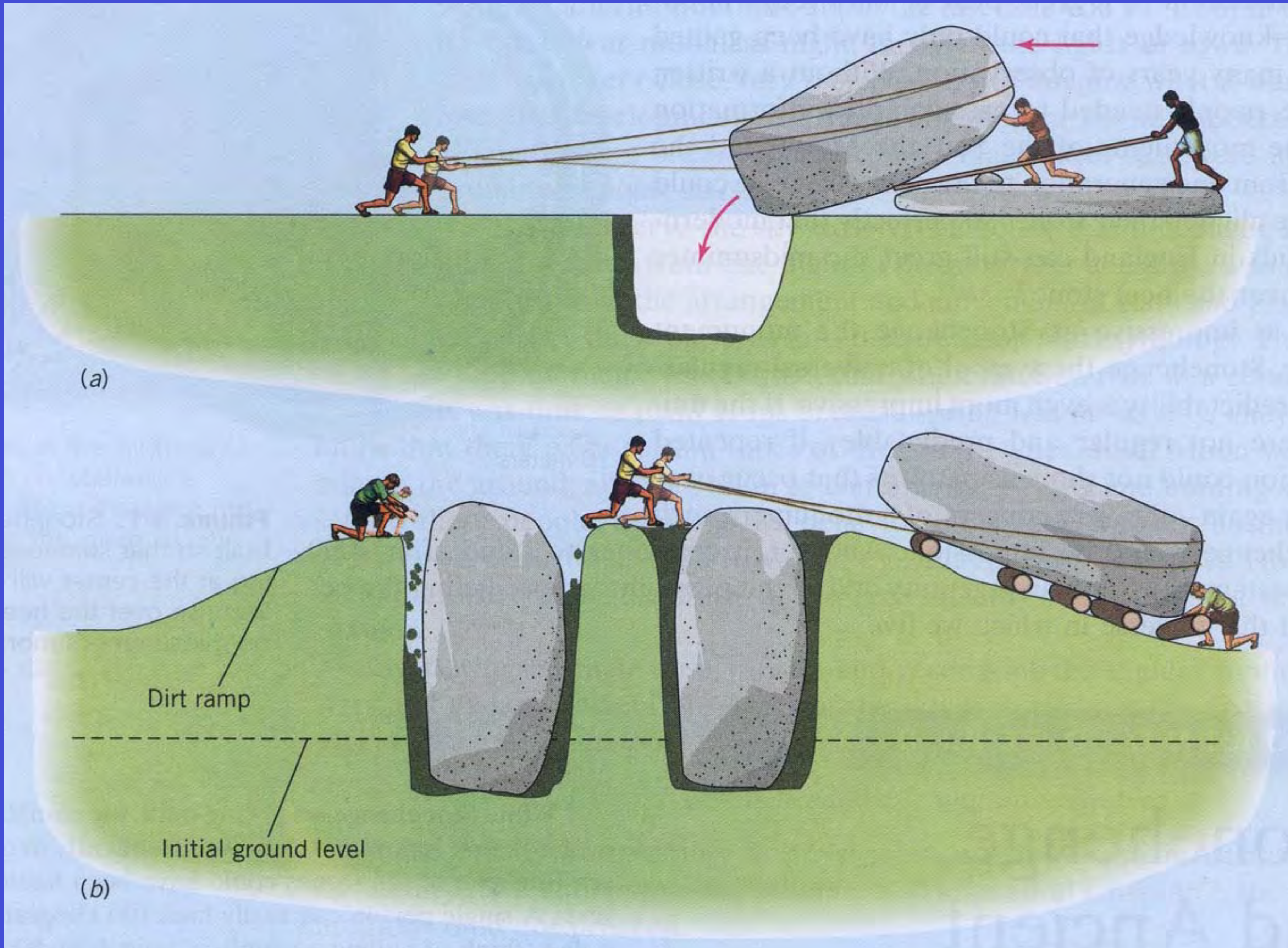
“Intelligent design should not be taught in high school biology classes as an alternative to evolution.”
American Chemical Society

How Should Science Respond to ID?

Design a research program that demonstrates the natural transition from chemical simplicity to emergent complexity.

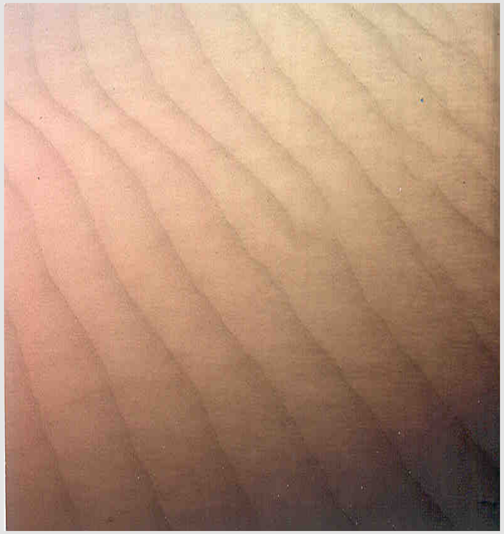
If biological complexity can be shown to arise spontaneously as the result of natural processes, then ID is unnecessary.

STONEHENGE


(a)
Dirt ramp
Initial ground level
(b)

What is Emergent Complexity?

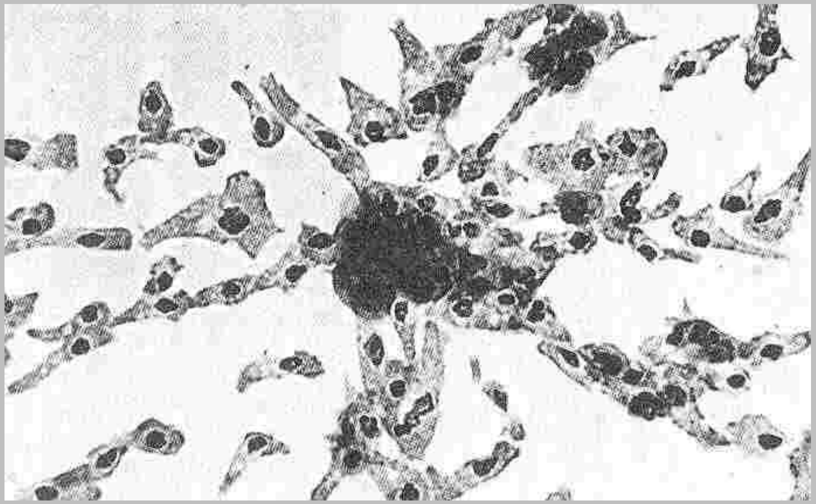
Emergent phenomena arise from interactions among numerous individual particles, or “agents.”

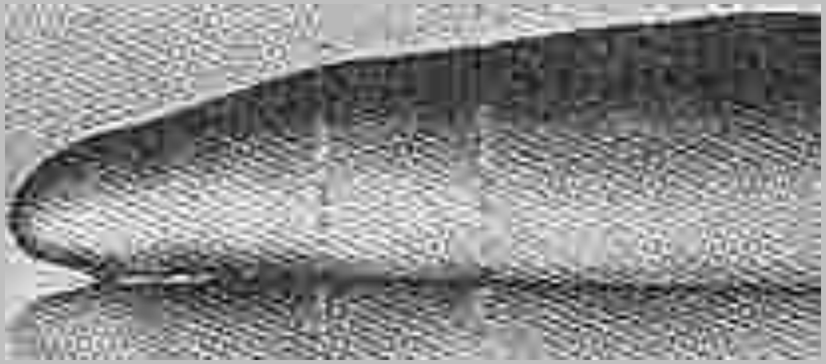


The Emergence of Slime Mold

→

Chemical
Potential
Gradients



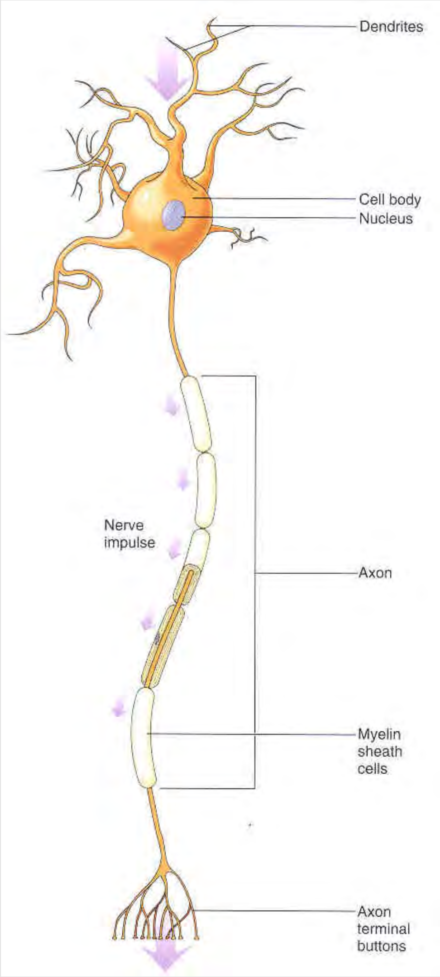


Dictyostelium

The Emergence of Slime Mold

Dictyostelium

The Emergence of Consciousness



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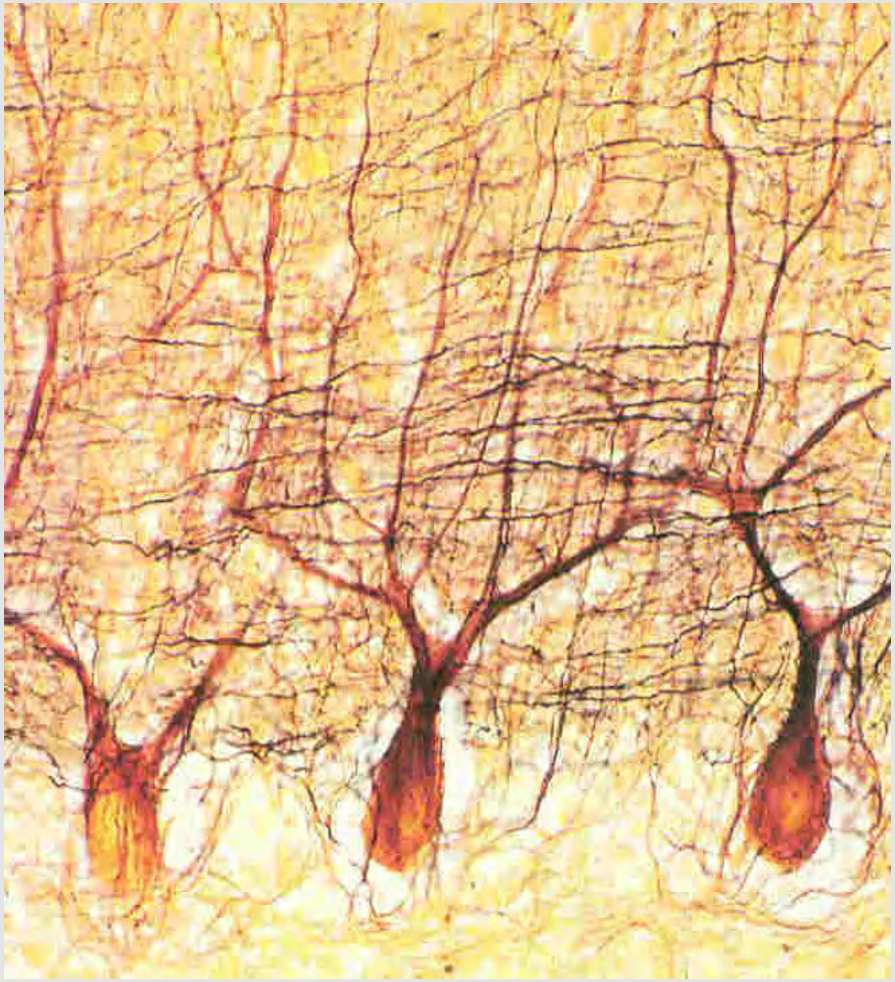
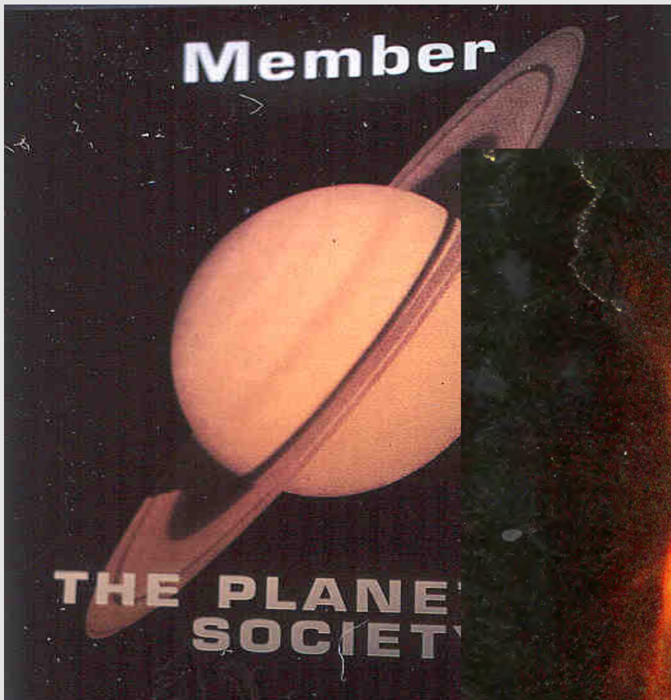
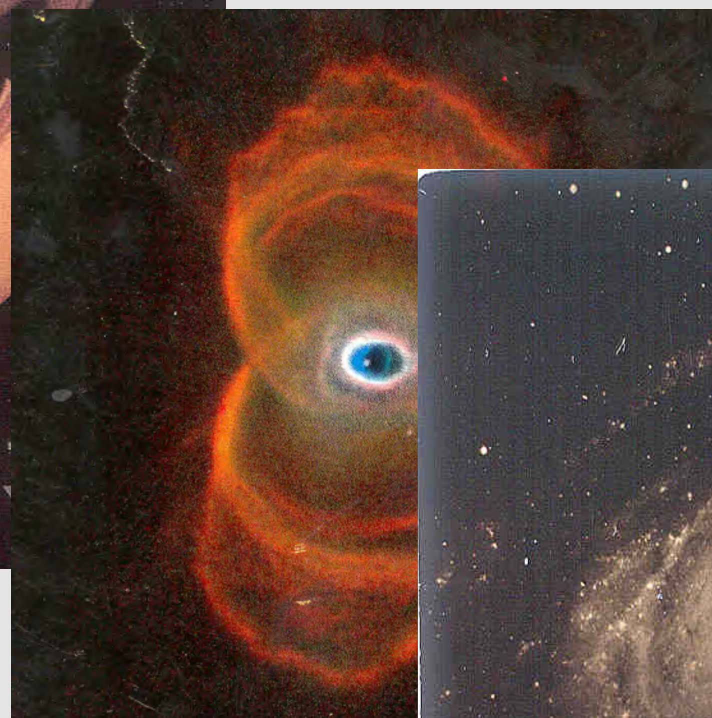
Neural connections and electrical impulses

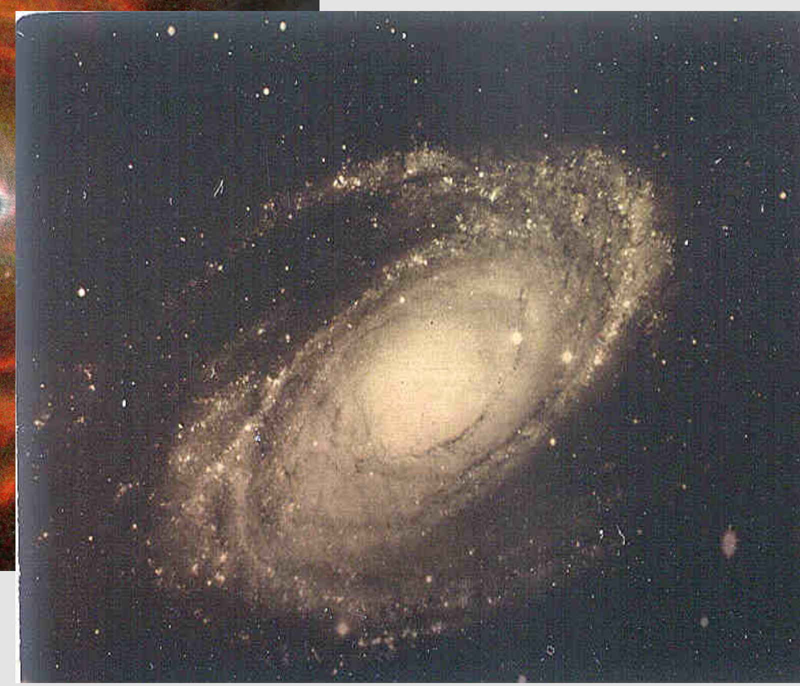


The Emergence of Consciousness

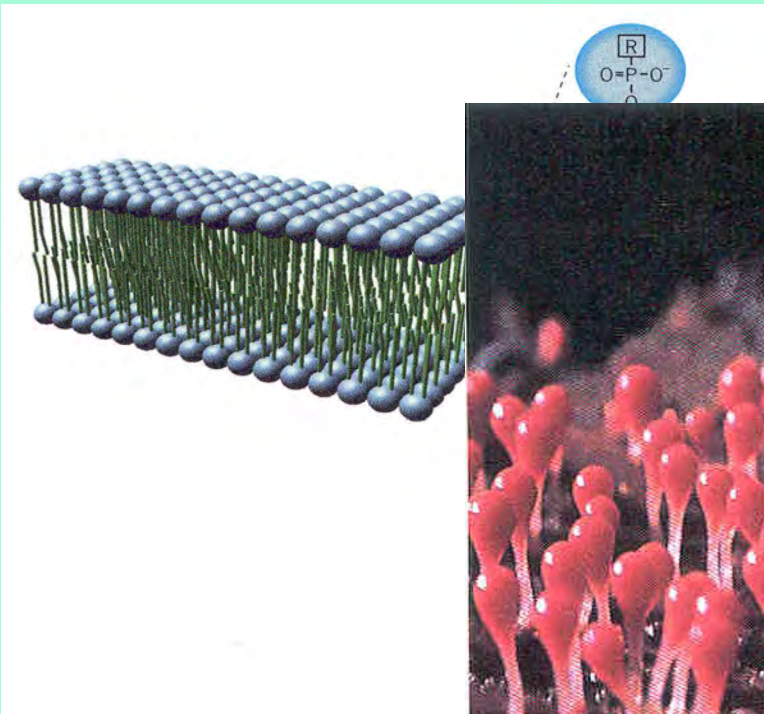
Emergent Phenomena – Space

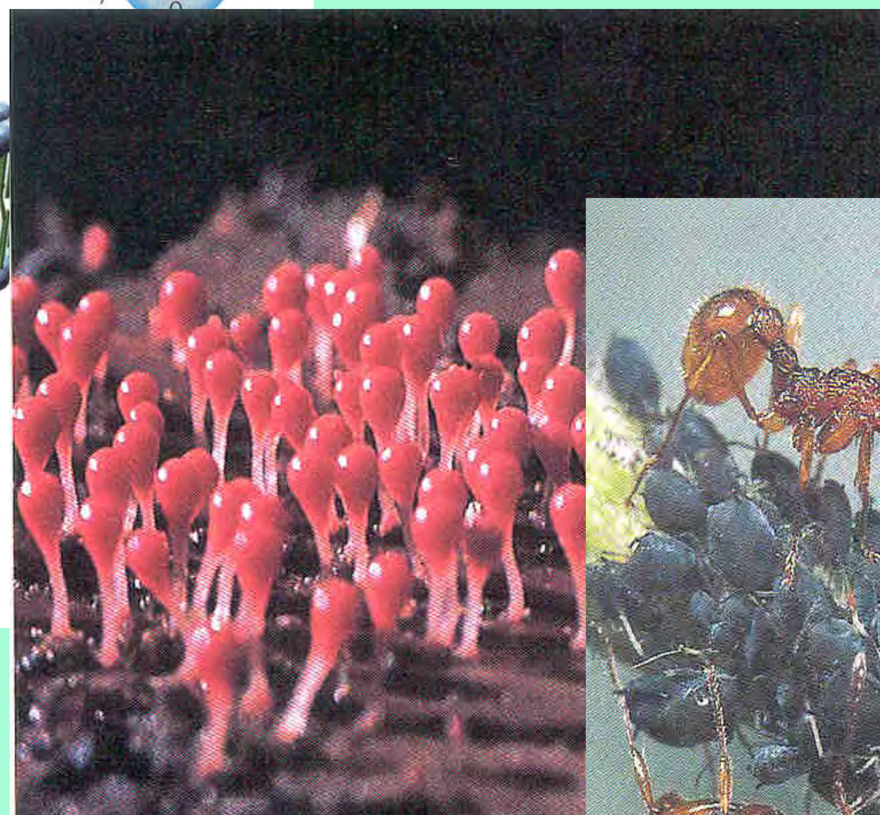






Emergent Phenomena – Life





Emergent Phenomena – Society

Central Assumptions of Origin-of-Life Research

The first life forms were carbon-based.

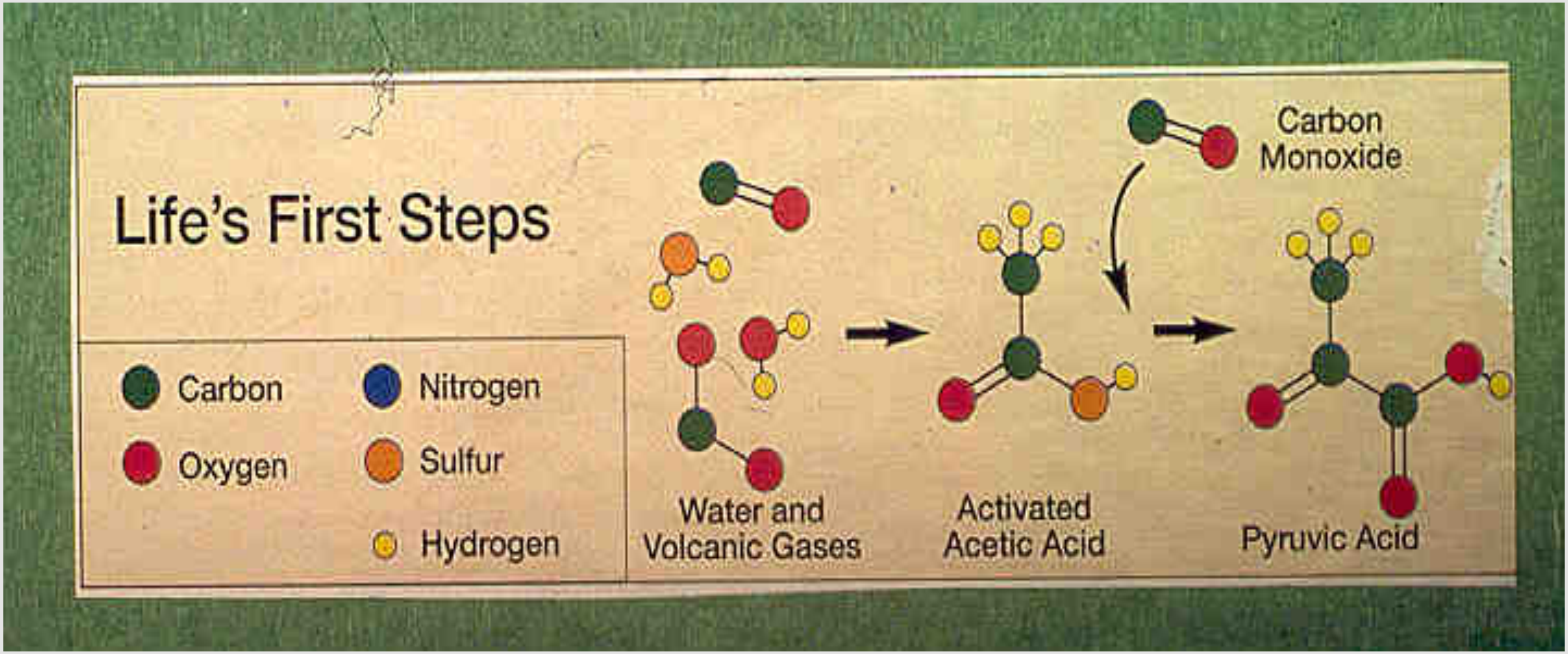
Life's origin was a chemical process that relied on water, air, and rock.

The origin of life required a sequence of emergent steps of increasing complexity.

Life's Origins: Four Emergent Steps

1. Emergence of biomolecules
2. Emergence of organized molecular systems
3. Emergence of self-replicating molecular systems
4. Emergence of natural selection

STEP 1:
Emergence of Biomolecules



The strategy is to use simple molecules to build larger molecules.

The Miller-Urey Experiment

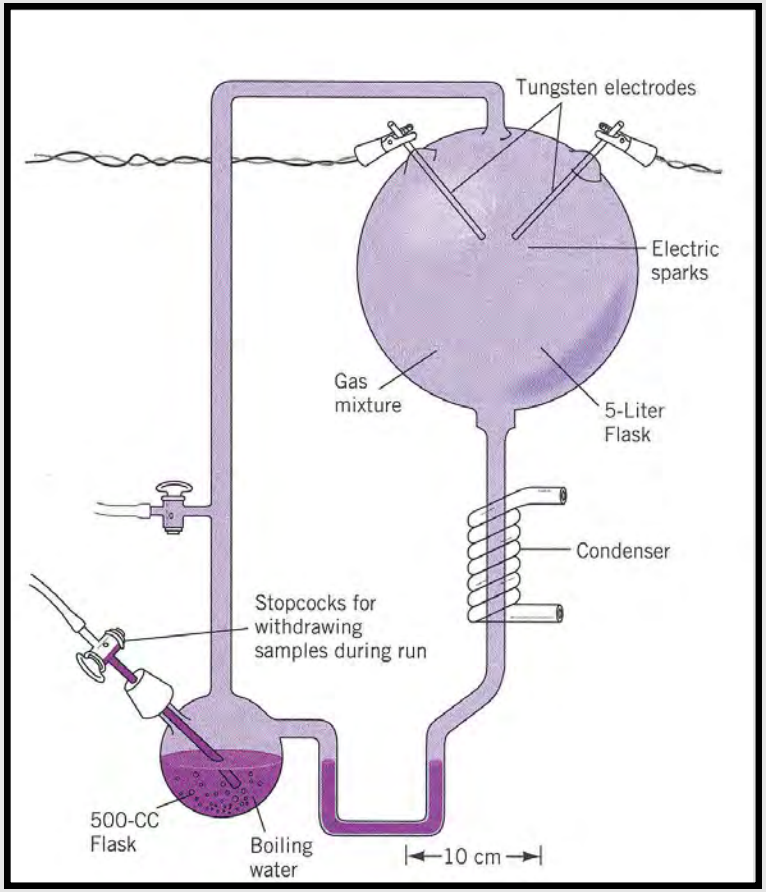
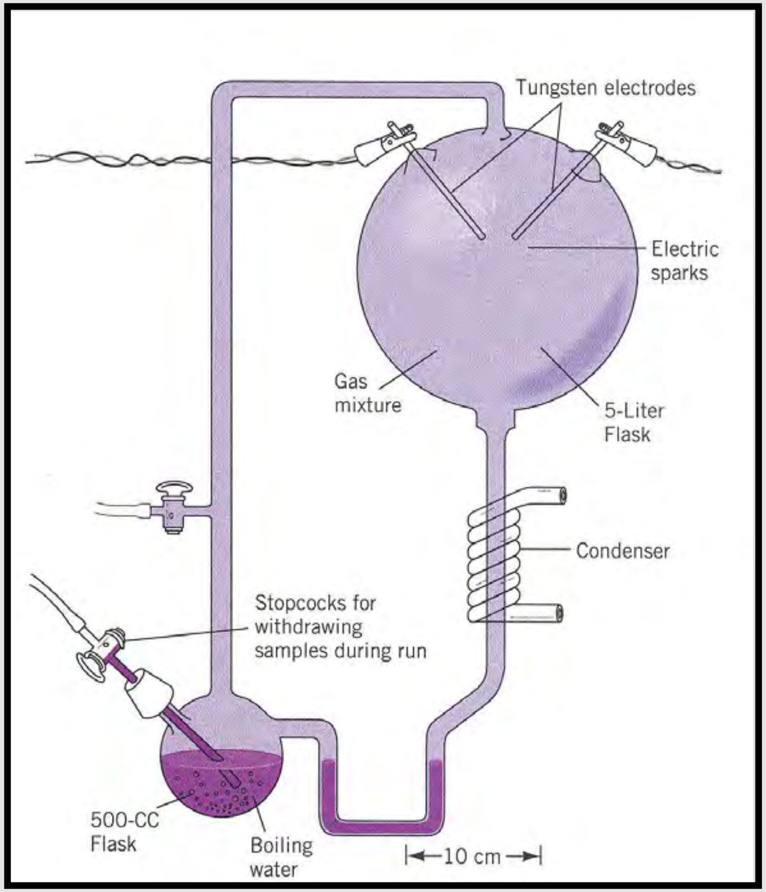


Table 3–8 Some of the products shown to form under prebiotic conditions

Amino acids	*Carboxylic acids*
Glycine	Formic acid
Alanine	Acetic acid
α-Aminobutyric acid	Propionic acid
Valine	Straight and branched fatty acids (C_4–C_{10})
Leucine	Glycolic acid
Isoleucine	Lactic acid
Proline	Succinic acid
Aspartic acid	
Glutamic acid	*Nucleic acid bases*
Serine	Adenine
Threonine	Guanine
Sugars	Xanthine
Straight and branched pentoses and hexoses	Hypoxanthine
	Cytosine
	Uracil

Organic synthesis near the ocean-atmosphere interface.

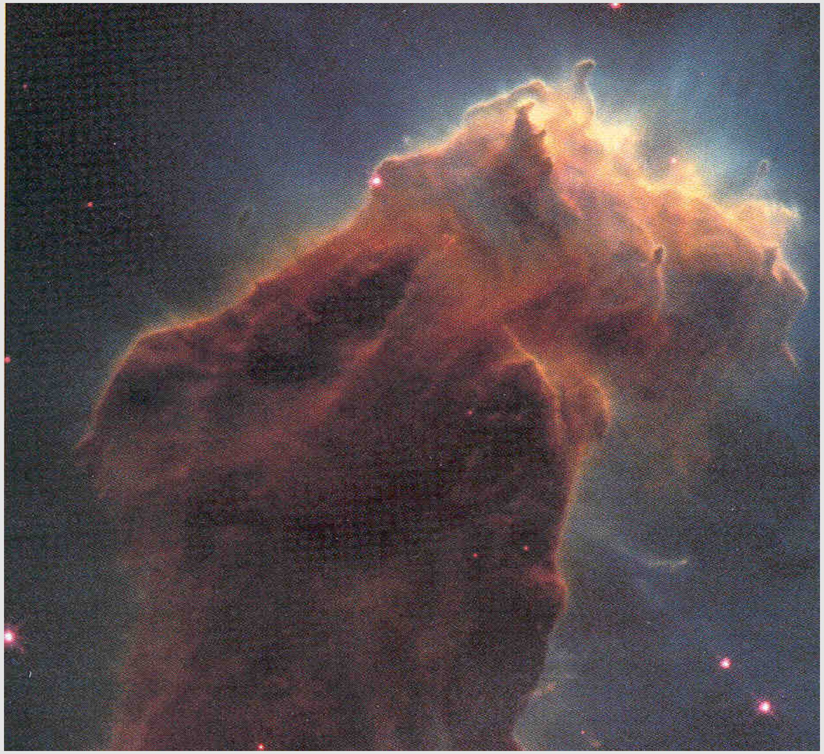
The Miller-Urey Experiment

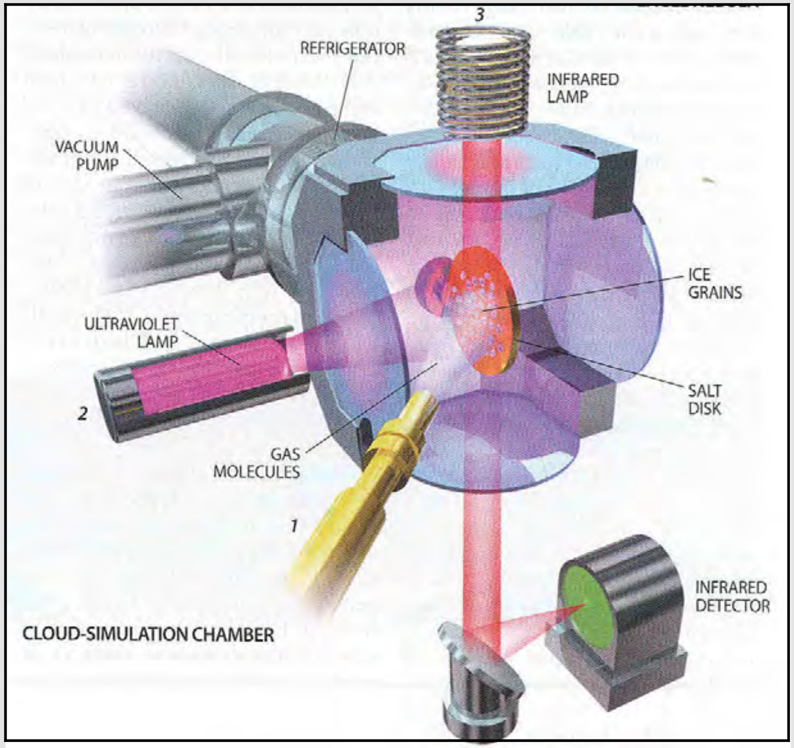


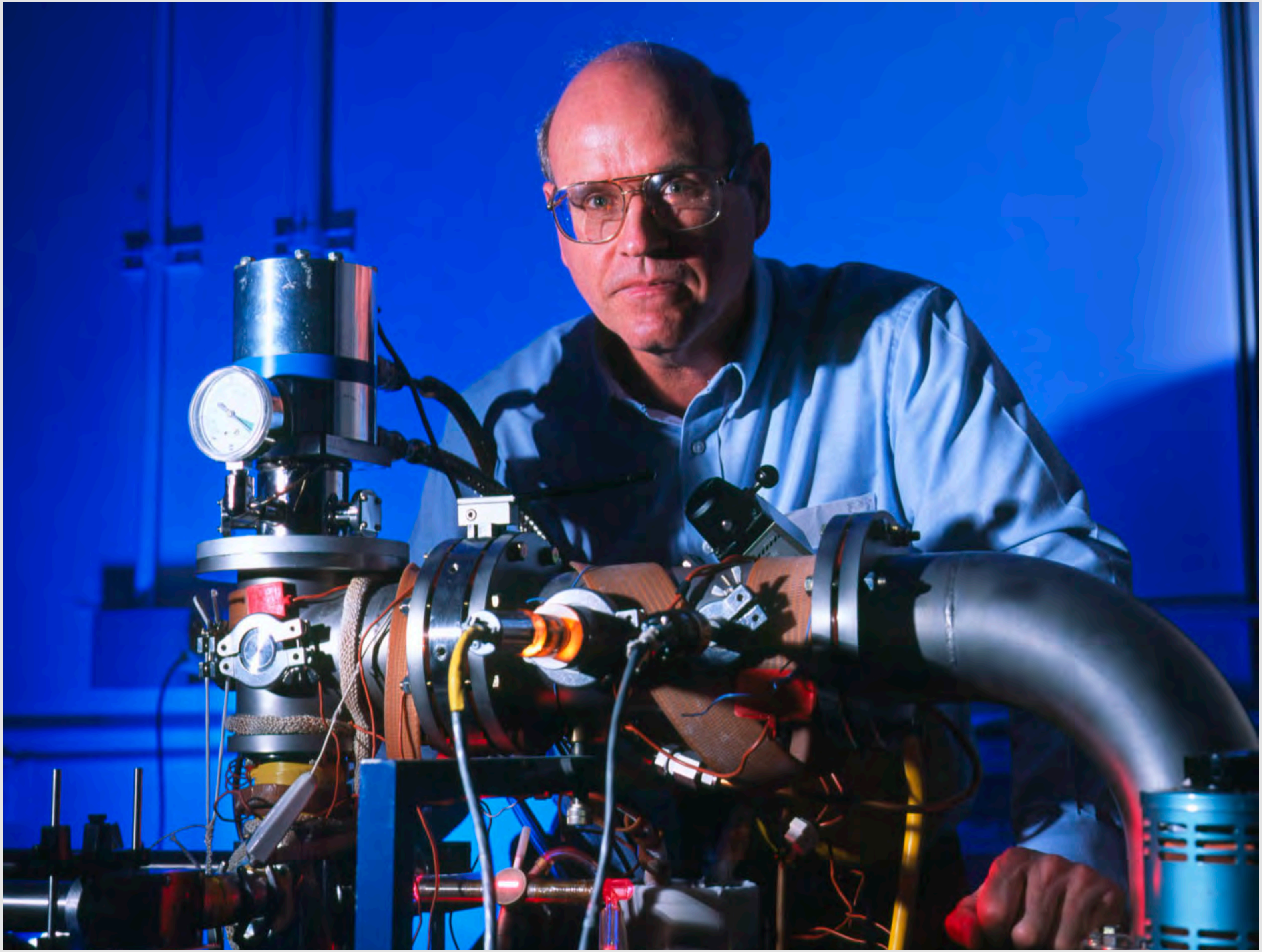
Organic synthesis near the ocean-atmosphere interface.

Organic Synthesis in Interstellar "Dense" Molecular Clouds

Experiments at NASA Ames simulate this environment.

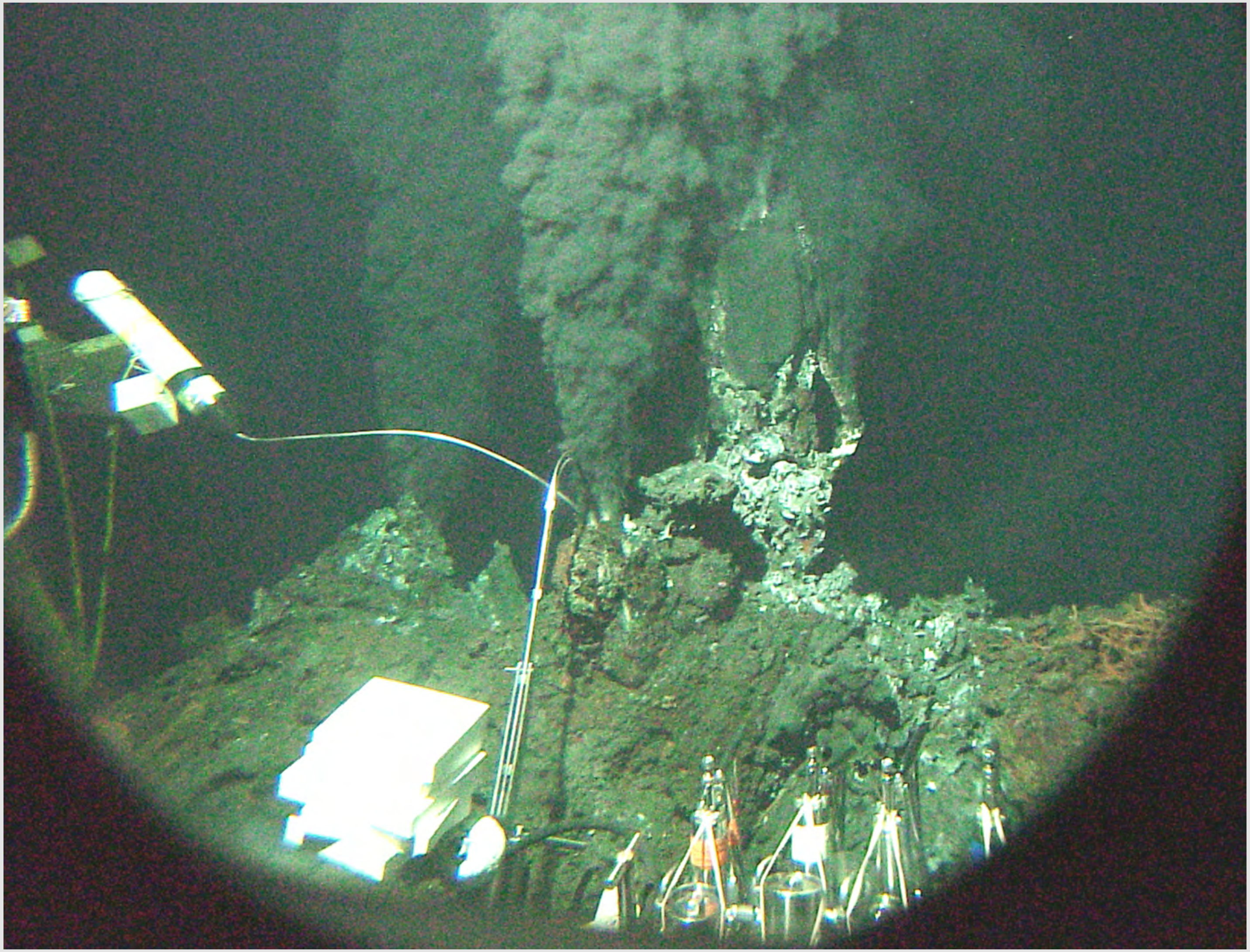






Louis J. Allamandola, NASA-ARC

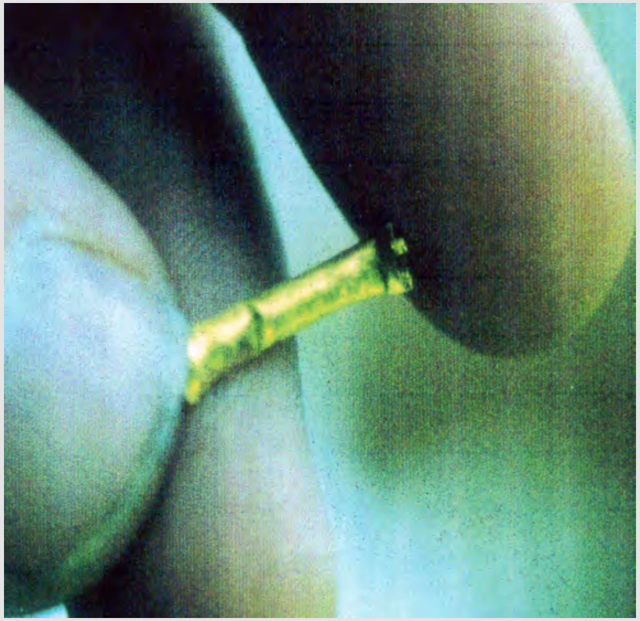
The Hydrothermal Hypothesis



A "BLACK SMOKER"

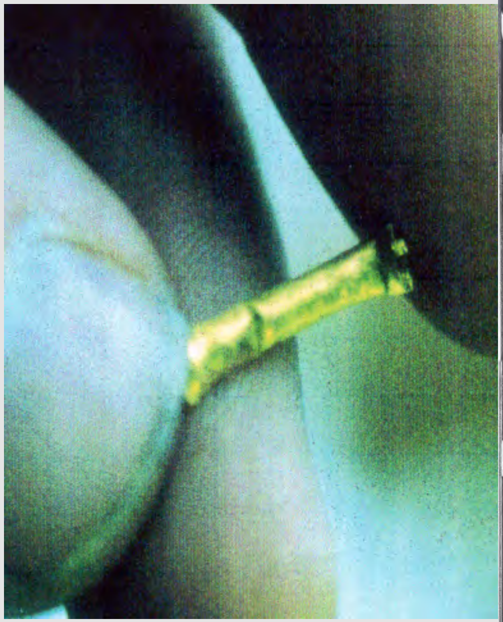
Hydrothermal Organic Synthesis

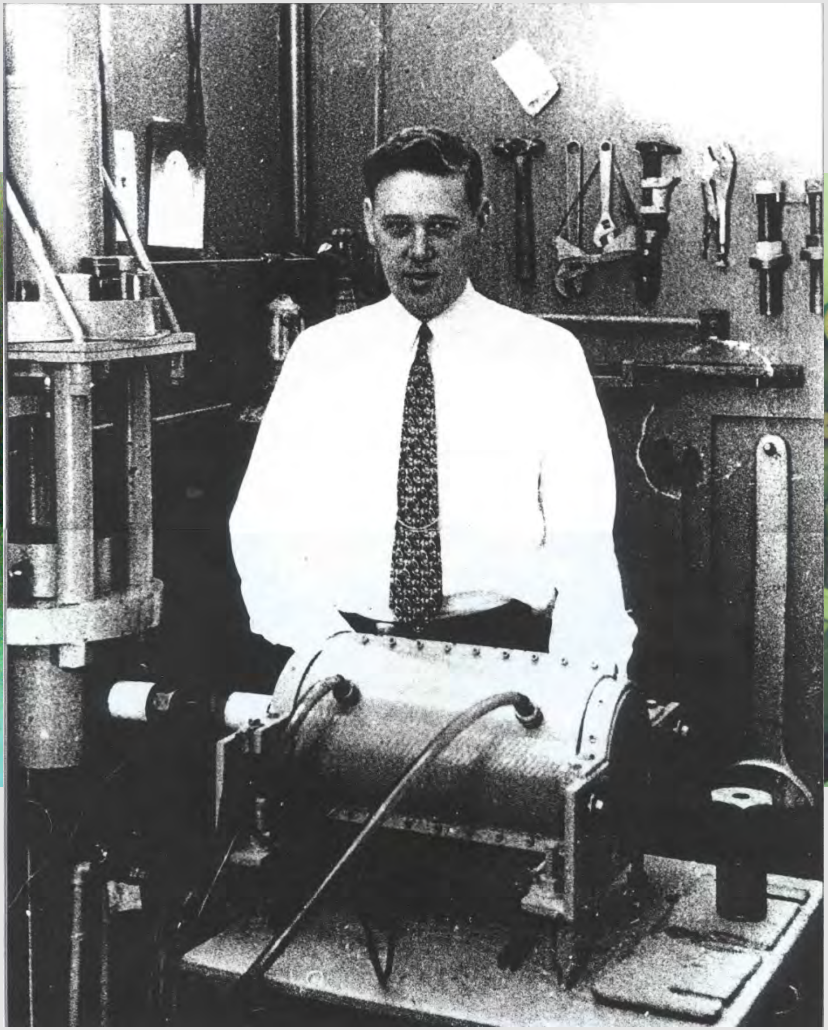
Gold tube reactors



Capsules are run in a gas-media pressure apparatus.

Hydrothermal Organic Synthesis

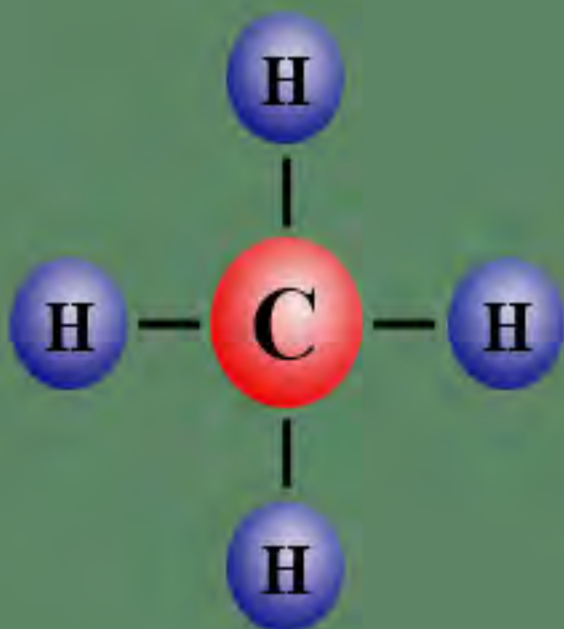




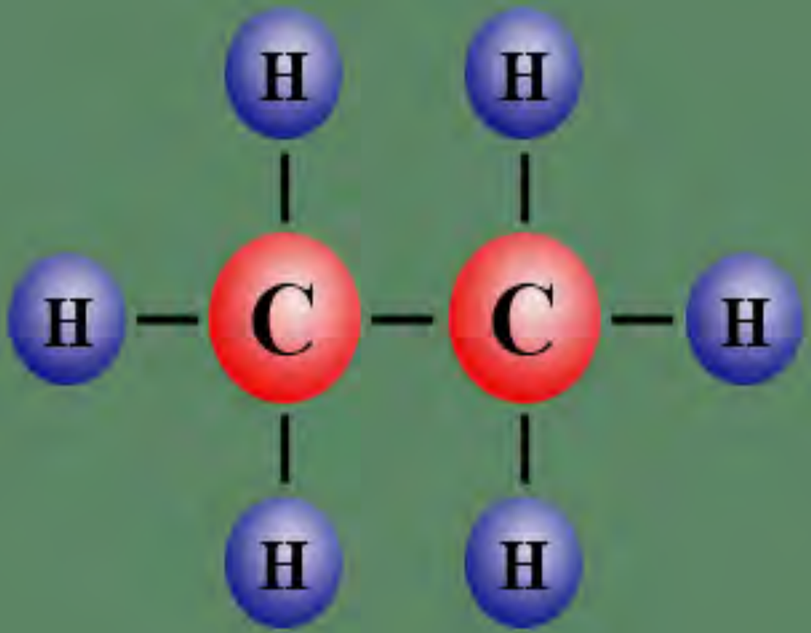
Hatten S. Yoder, Jr.

George D. Cody

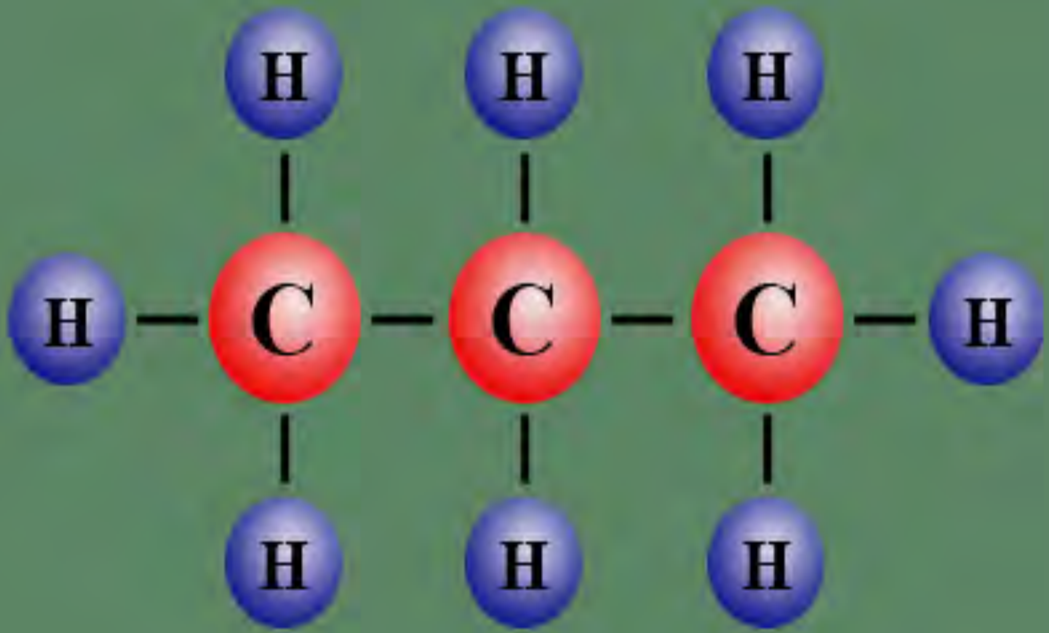
METHANE



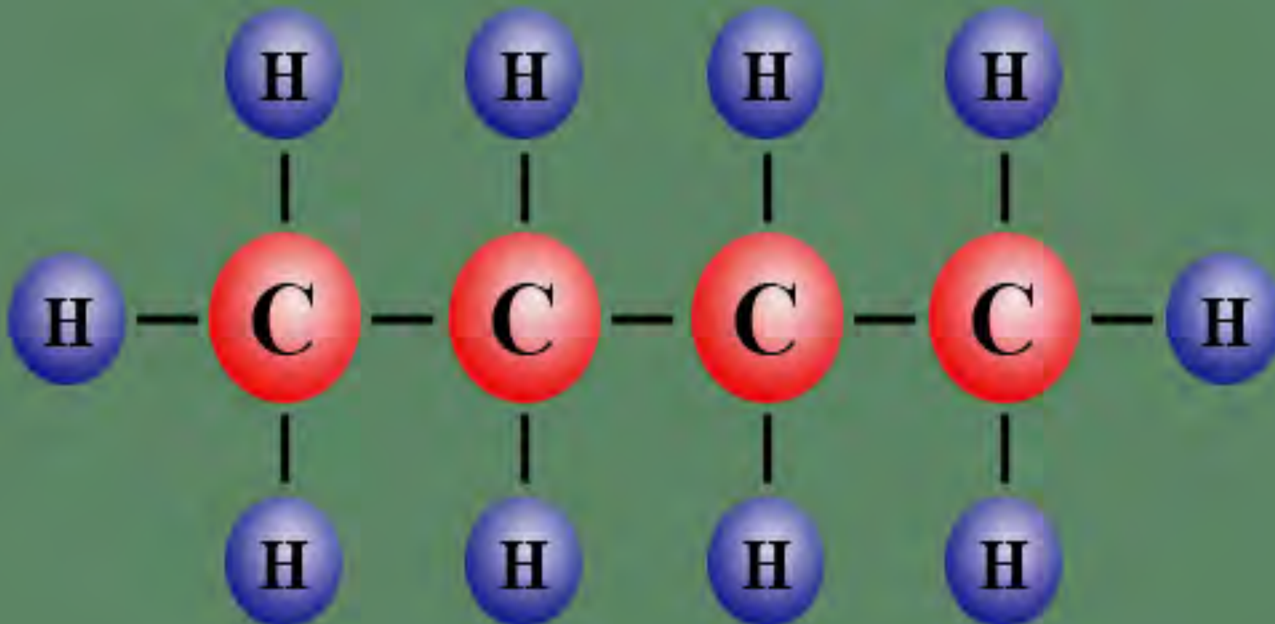
ETHANE



PROPANE

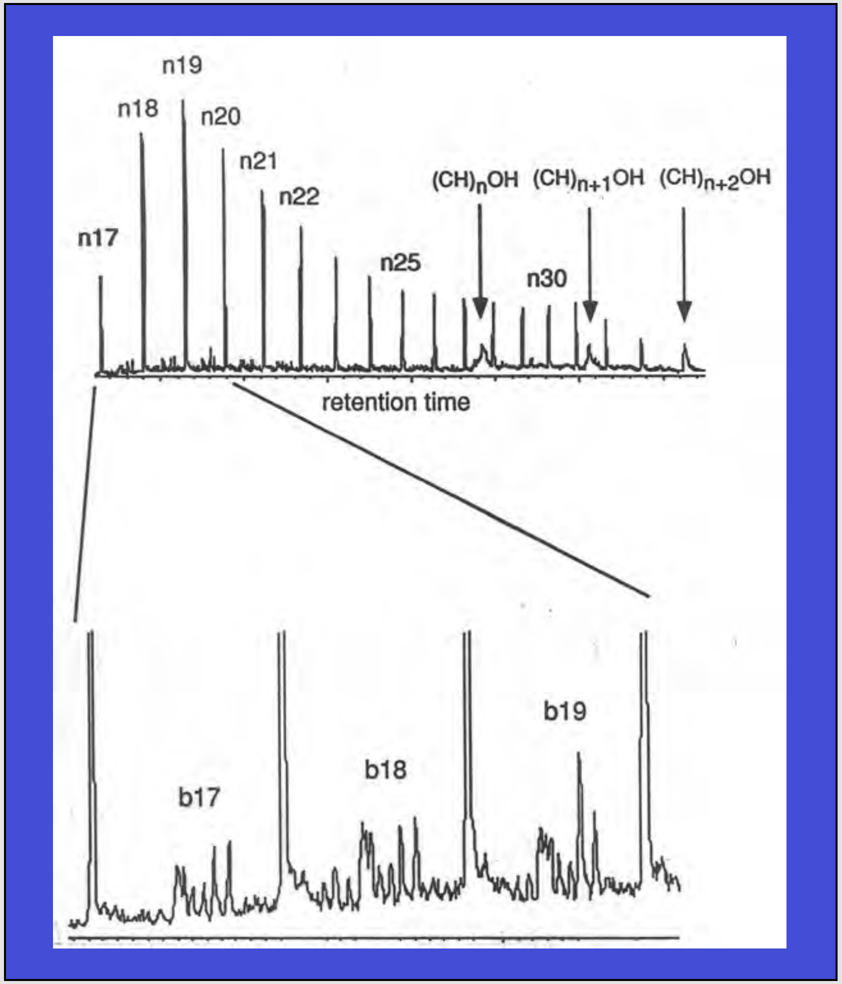


BUTANE

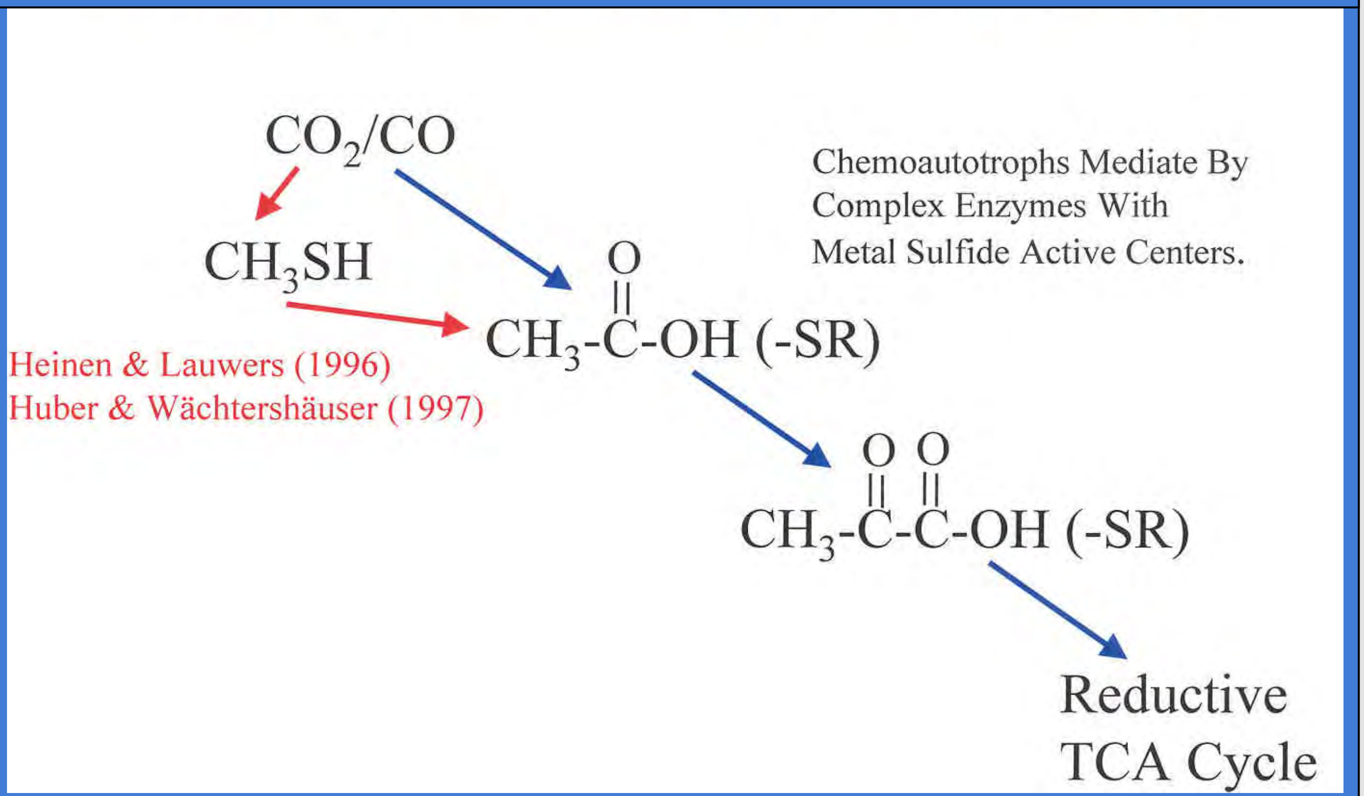


Carbon-Addition Reactions: Hydrothermal F-T Synthesis (+CH_2)

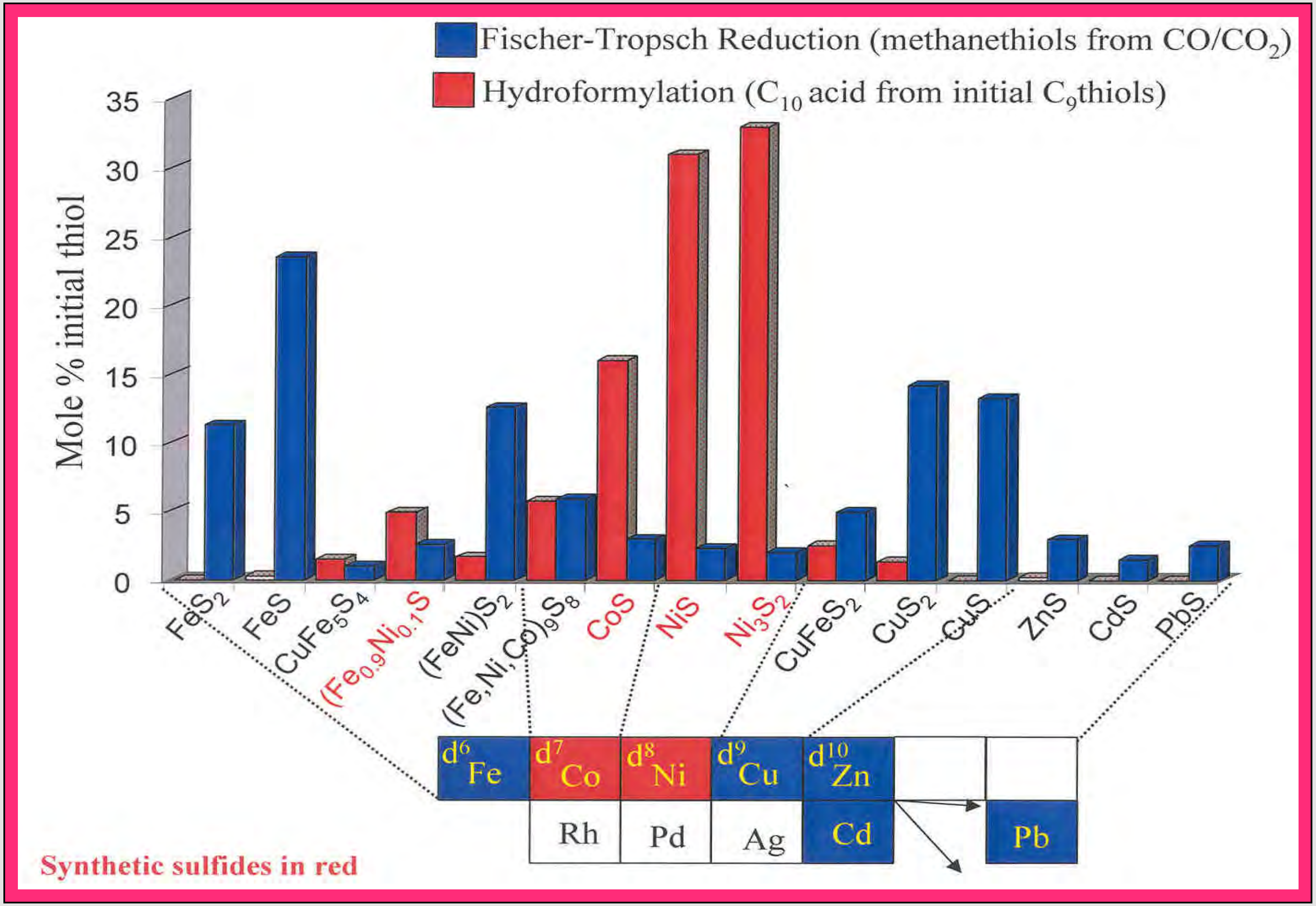
- **Reactants:**
  $CO_2 + H_2 + H_2O$
- **Catalyst:**
  Iron metal
- **Conditions:**
  300°C
  500 atm
  24 hours



Carbon-Addition Reactions: Hydroformylation (+CO)



Mineral Catalyzed Carbon-Addition Reactions



STEP 1: CONCLUSIONS

The prebiotic synthesis of biomolecules occurred with relative ease.

Minerals played key roles.

STEP 2:
The Emergence of Organized Molecular Systems

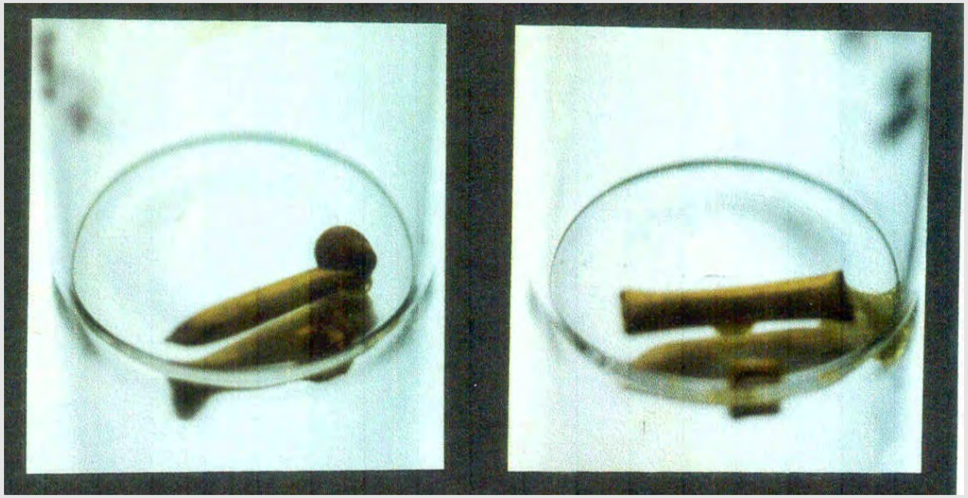
Prebiotic synthesis processes are facile but indiscriminate.

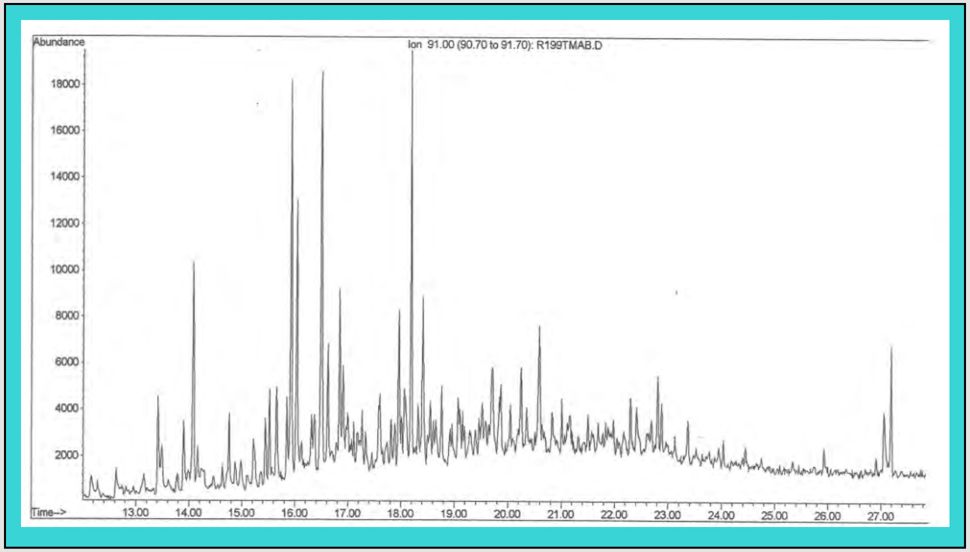
Yet a fundamental attribute of life is a high degree of molecular selectivity and organization.

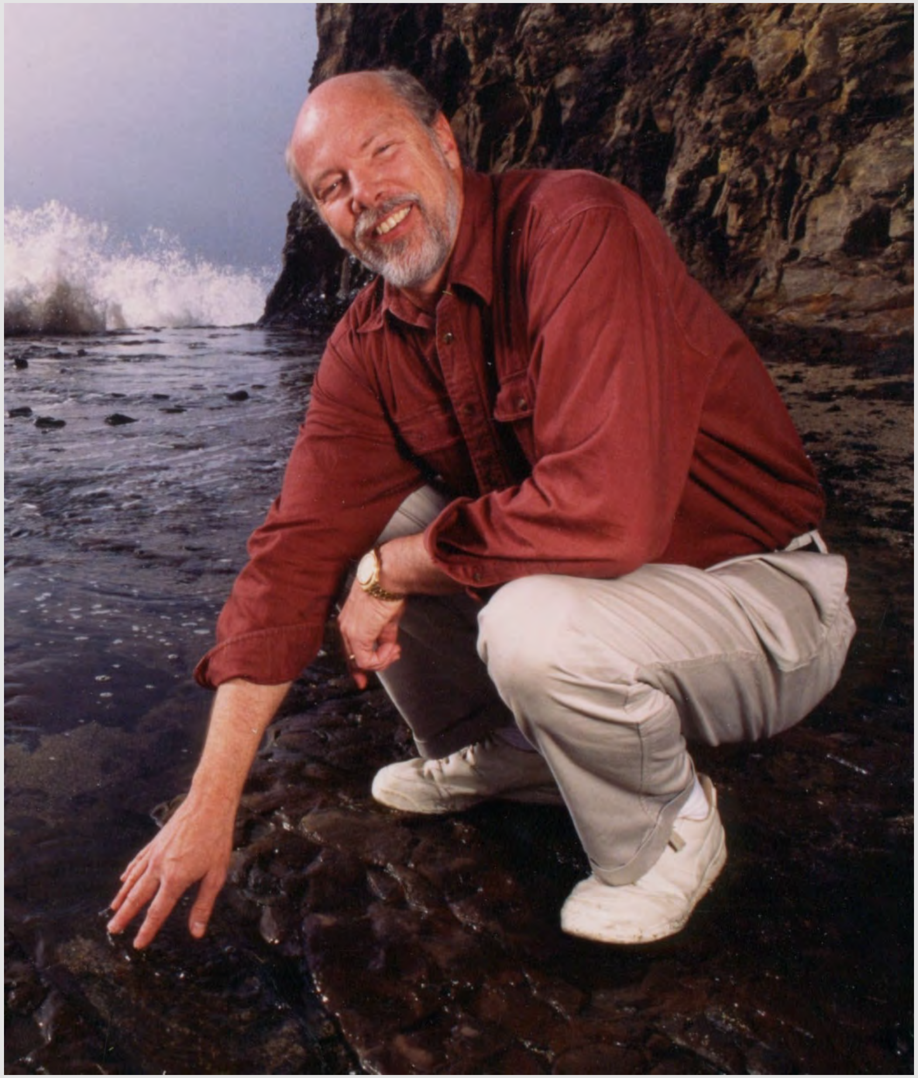
What prebiotic processes might have contributed to such selection and organization?

Self-Organization

- **Reactants:**
  Pyruvic acid + CO_2 + H_2O
- **Conditions:**
  $200^{o}C$
  2,000 atm
  2 hours
- **Products: A diverse suite of organic molecules**



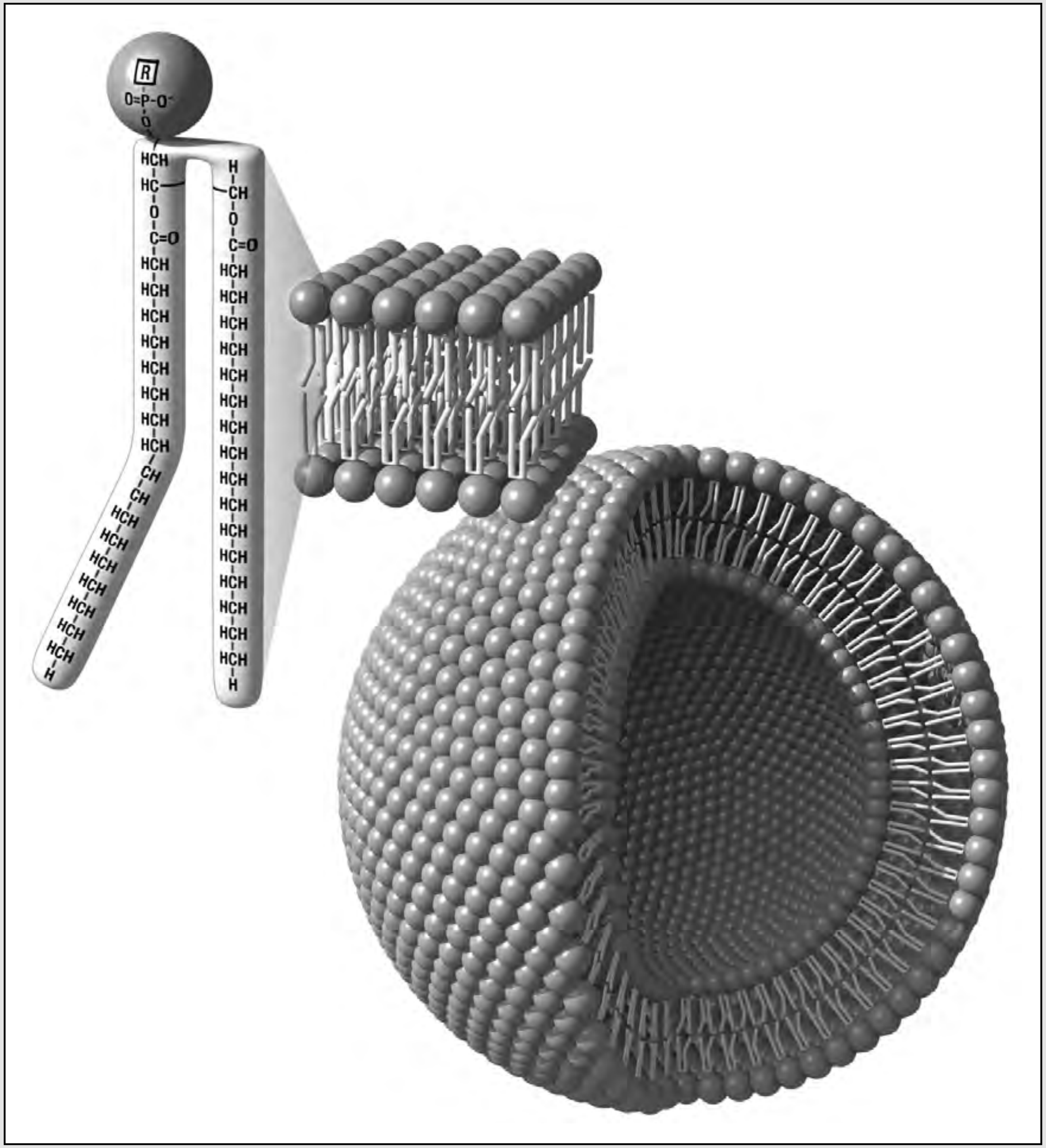


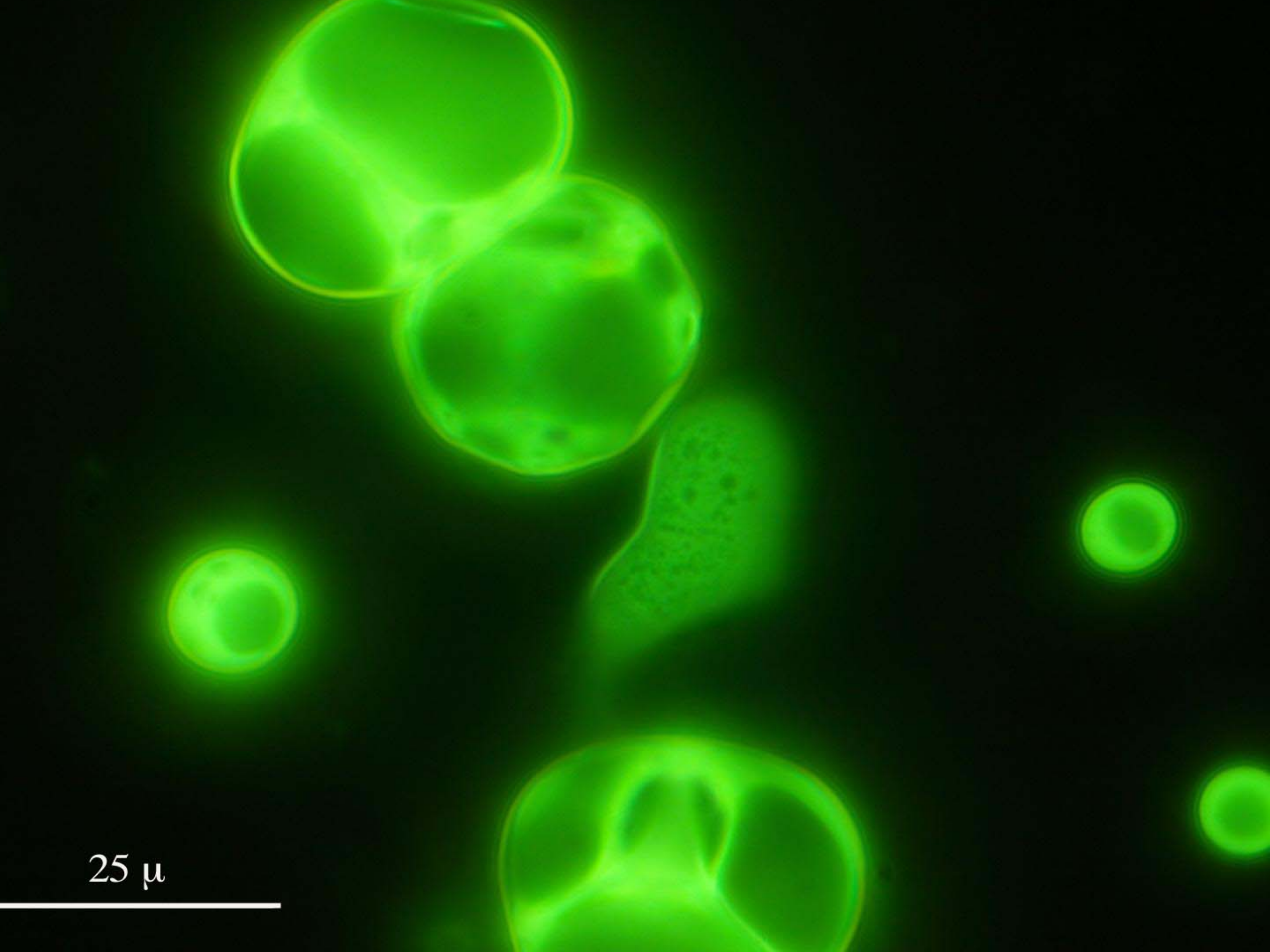


David Deamer

Marilyn Fogel

Self-Assembling Amphiphile Molecules




25 µ

Biological Homochirality

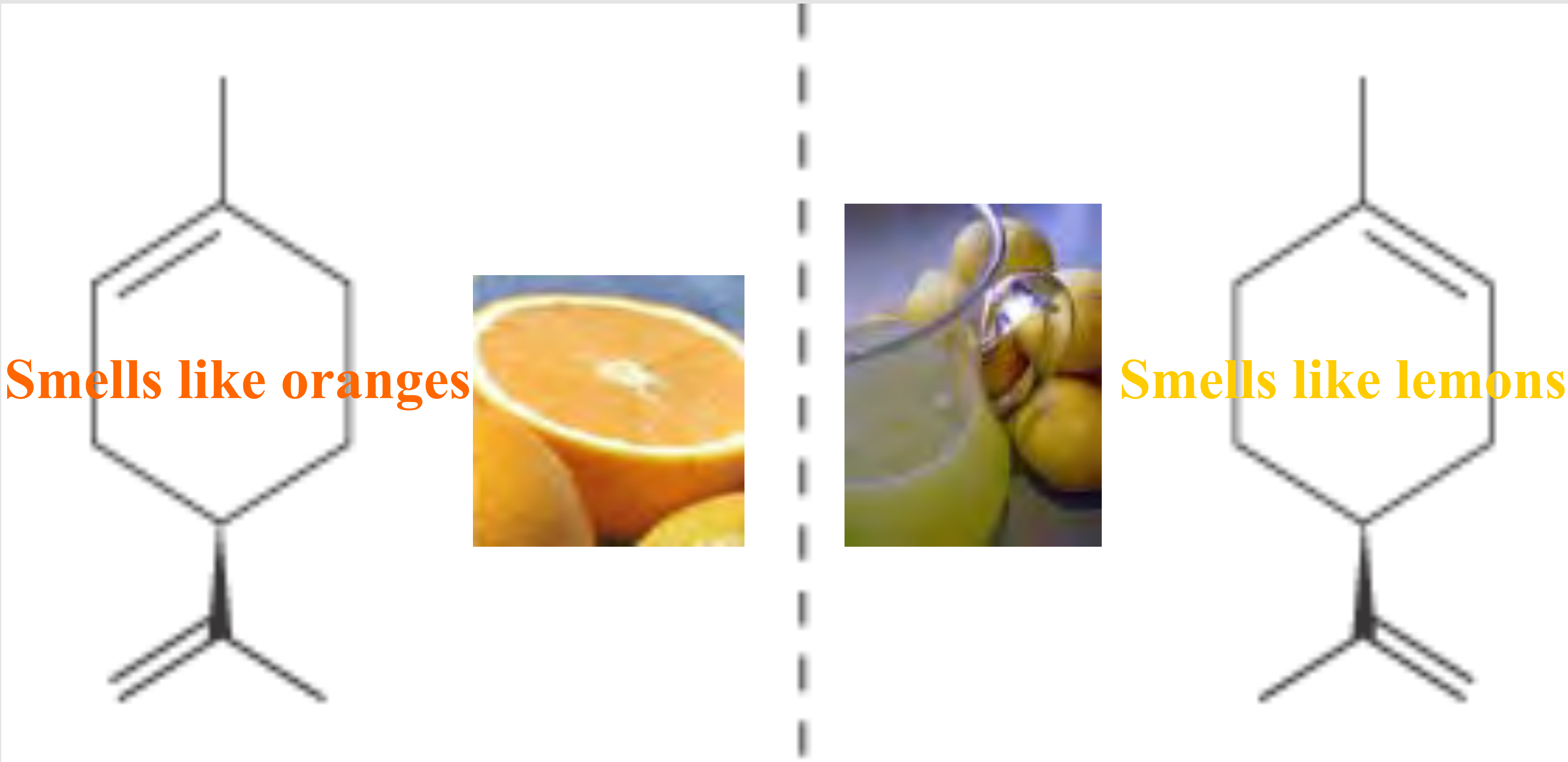
The motivation for this research lies in the fact that many of life's essential molecules are chiral.

(L)-enantiomer (R)-enantiomer

How did life on Earth become homochiral?

Annual sales of chiral pharmaceuticals approaches $200 billion.

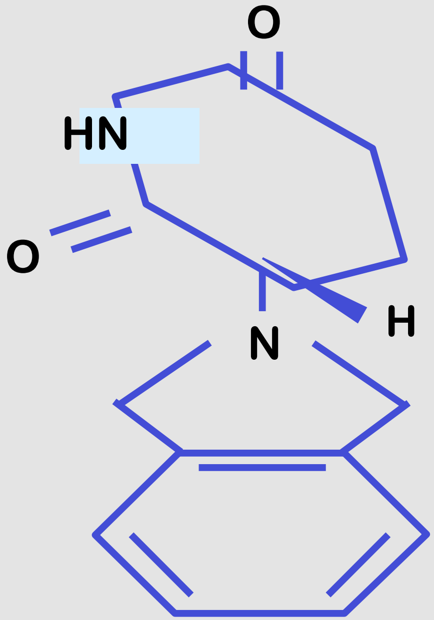
Chiral Purity is Important



R-Limonene	Mirror	L-Limonene

Chiral Purity is Important

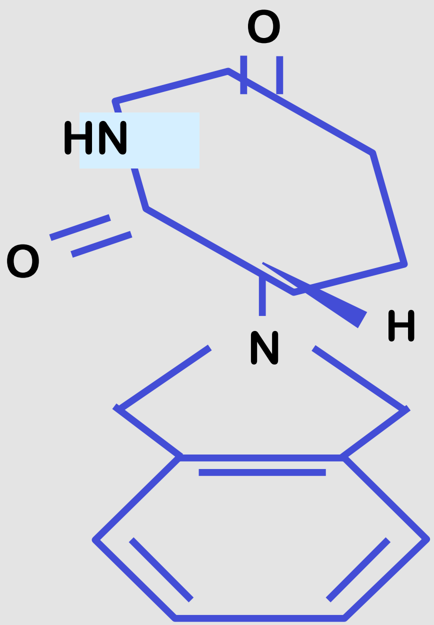
Thalidomide



R-enantiomer
Analgesic (Good)

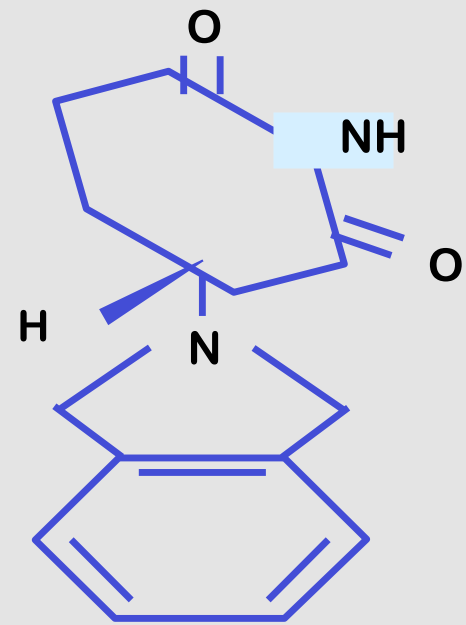
Chiral Purity is Important

Thalidomide



R-enantiomer

Analgesic (Good)



S-enantiomer

Teratogen (Bad)

Prebiotic Chiral Selection

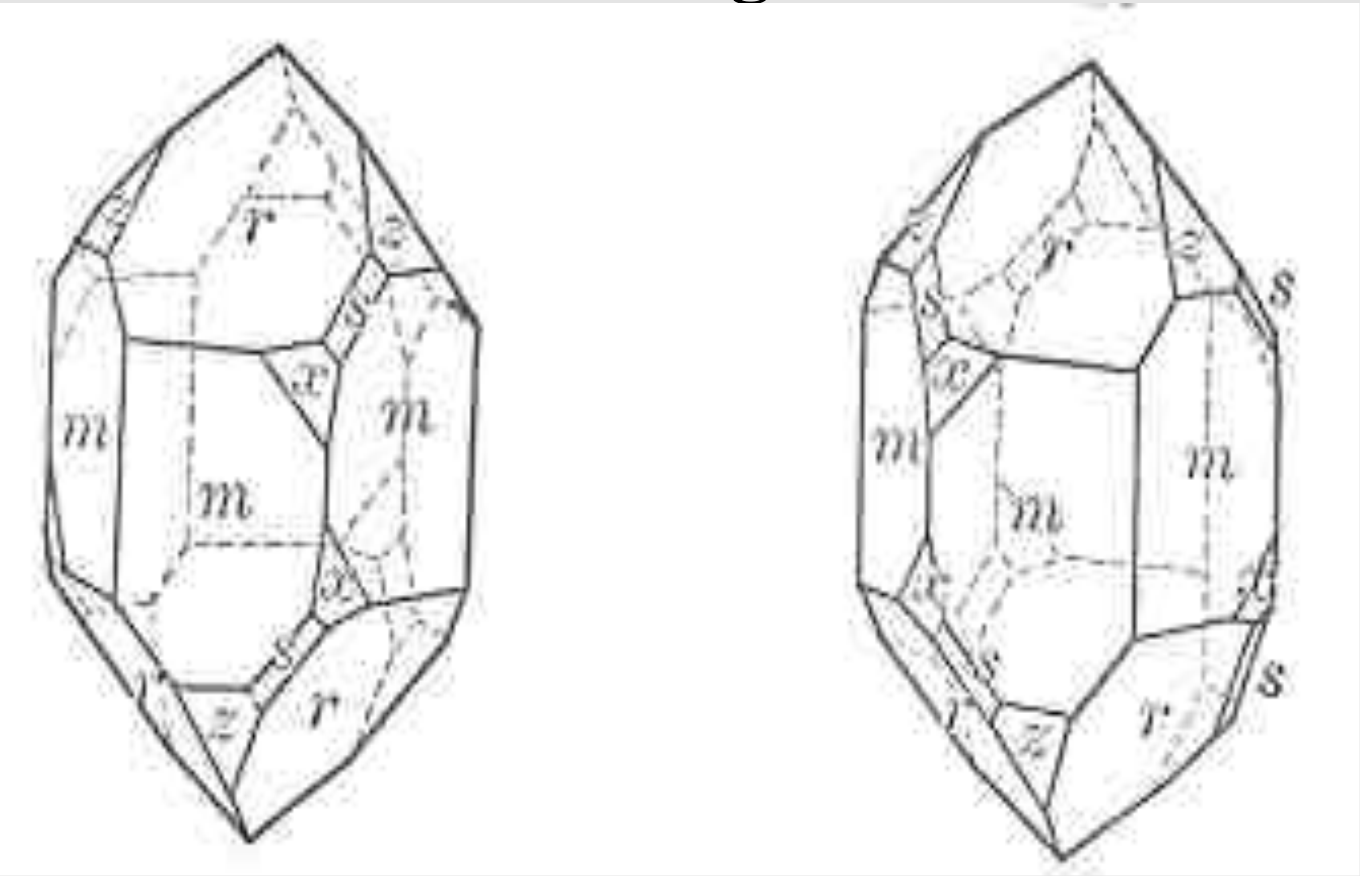
- Prebiotic synthesis processes produce mixtures of left and right molecules.

- But life demonstrates a remarkable degree of chiral selectivity.

What is the mechanism of symmetry breaking?

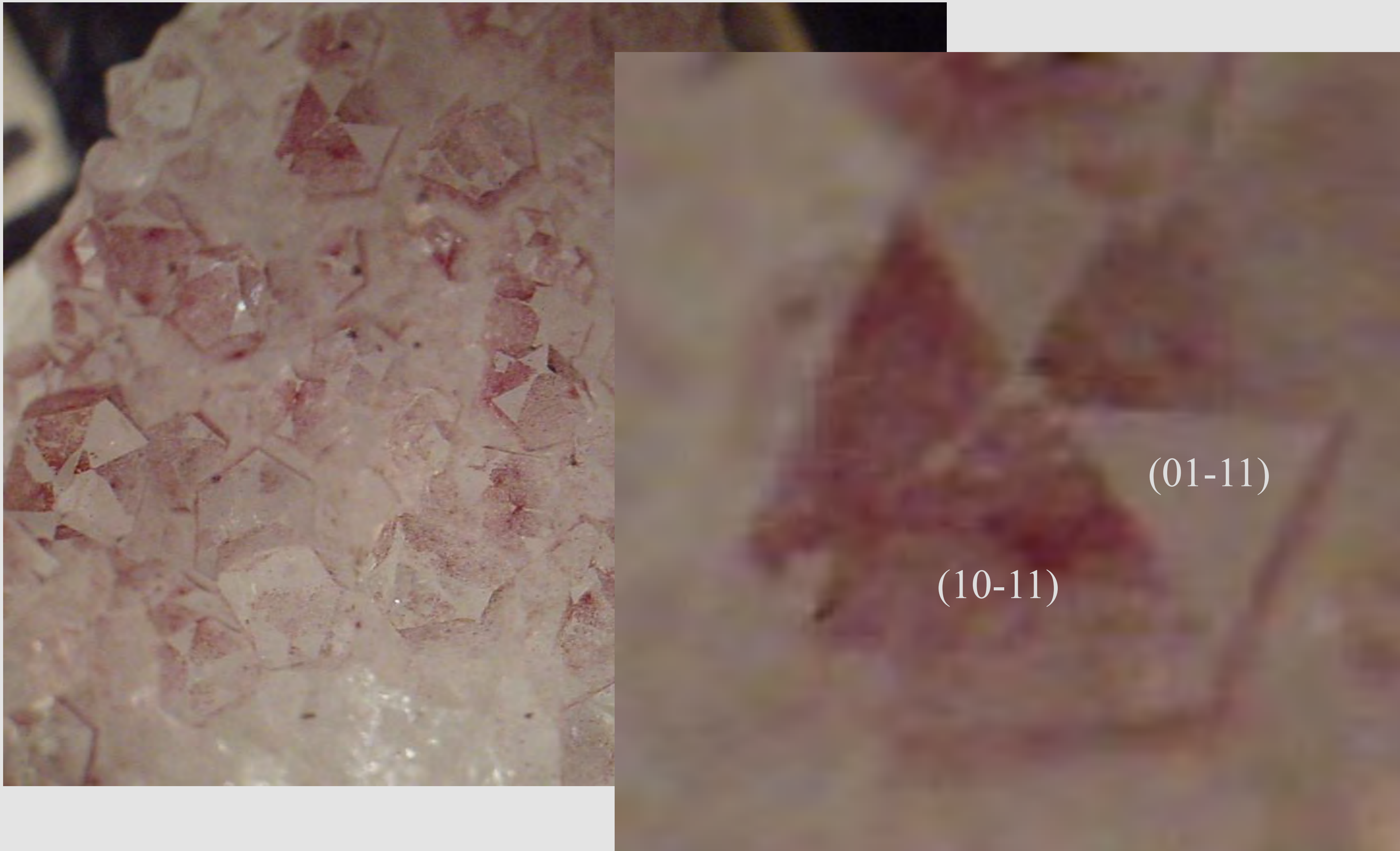
Quartz – SiO_2

Quartz is the only common chiral rock-forming mineral

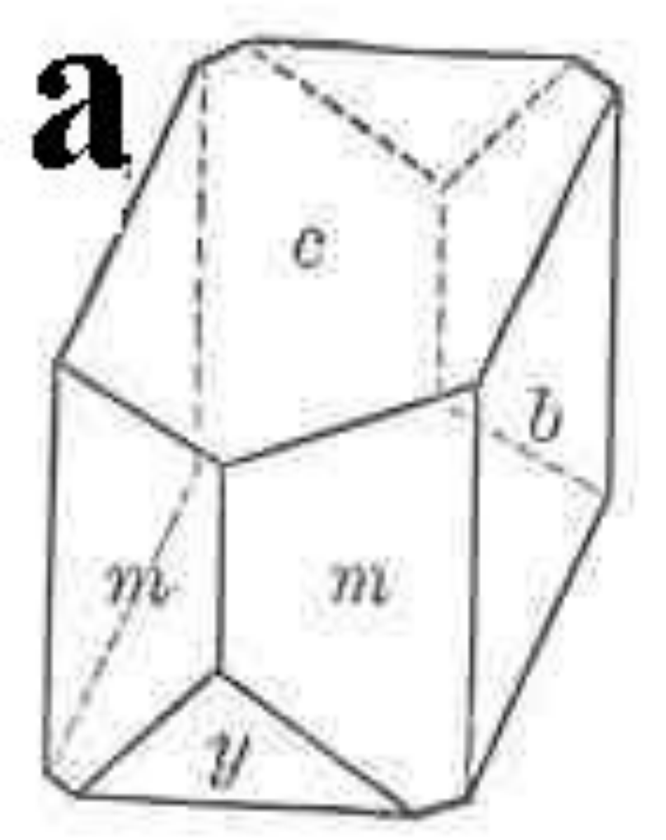


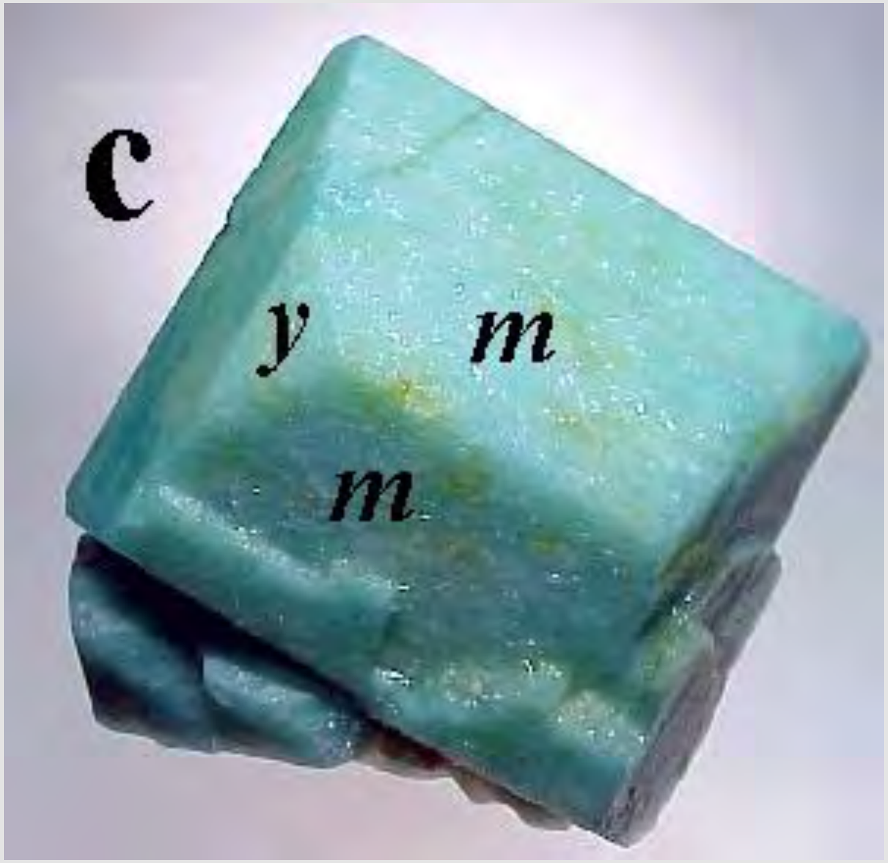
Right Left

Quartz: Face-Specific Adsorption

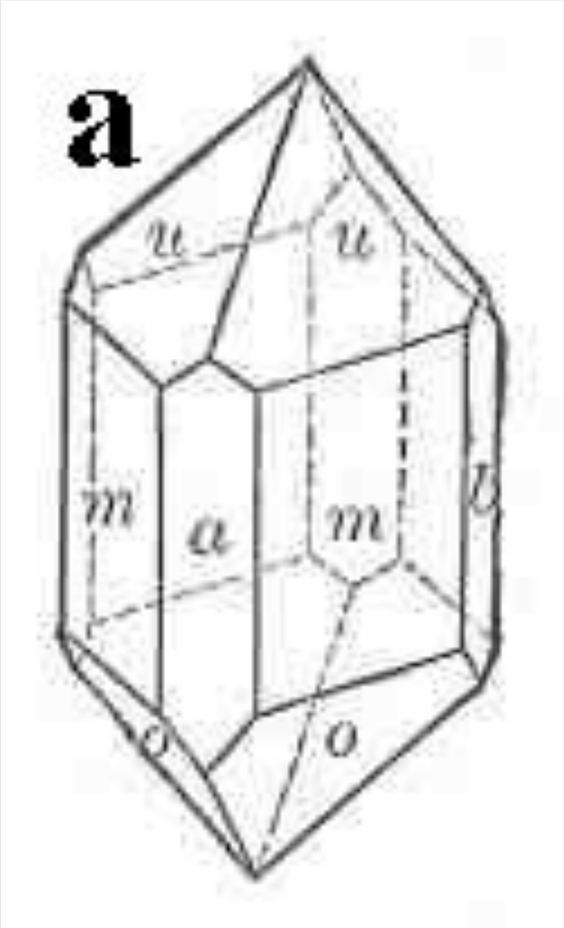


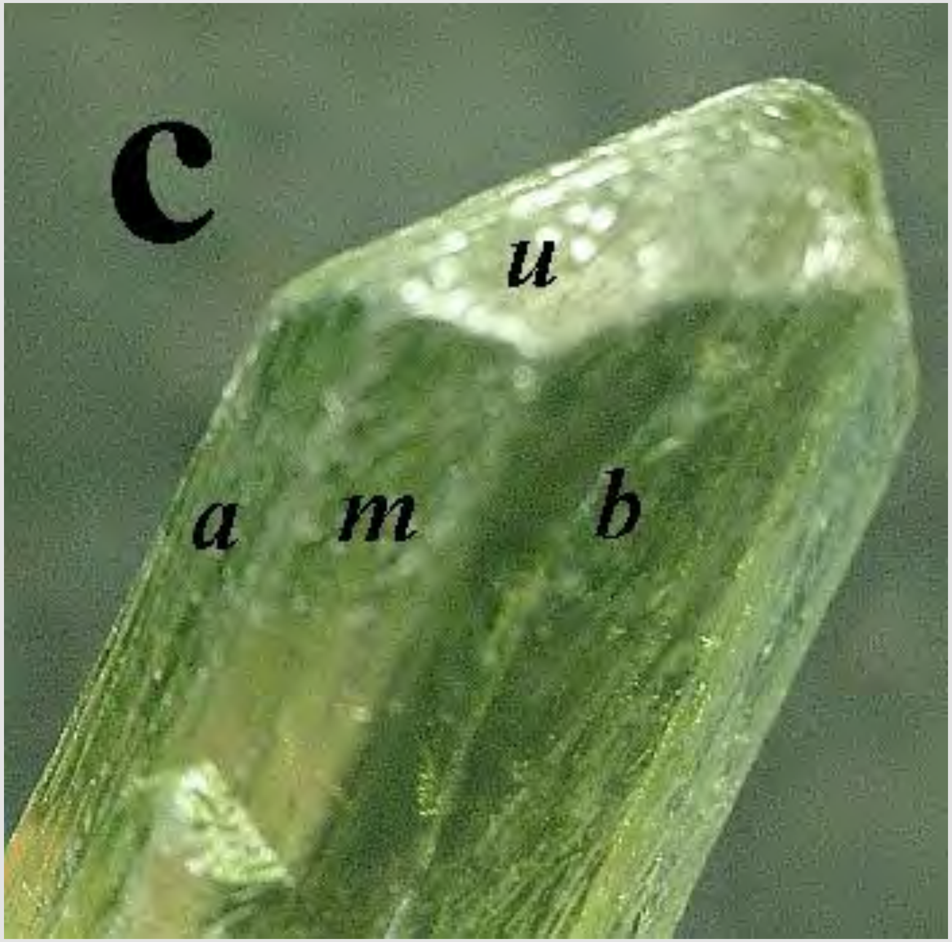
Feldspar (110)



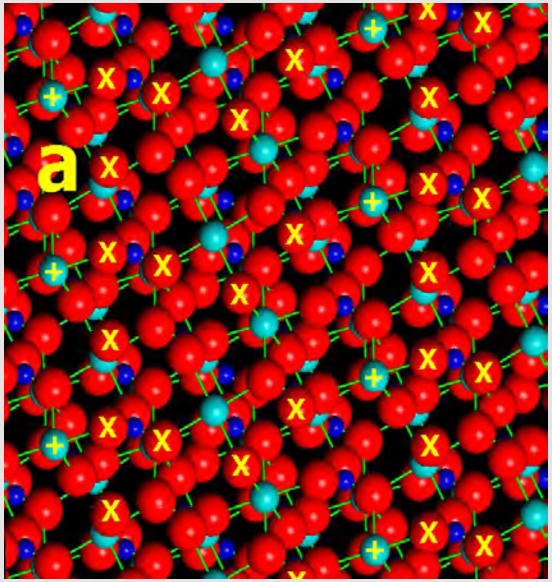


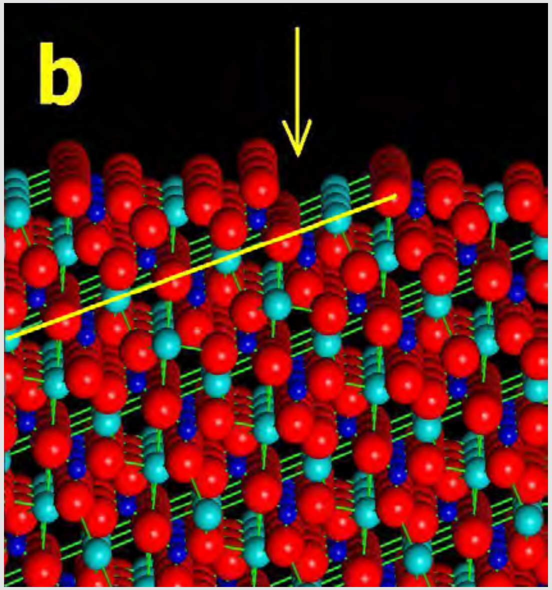
Diopside – (110) Face

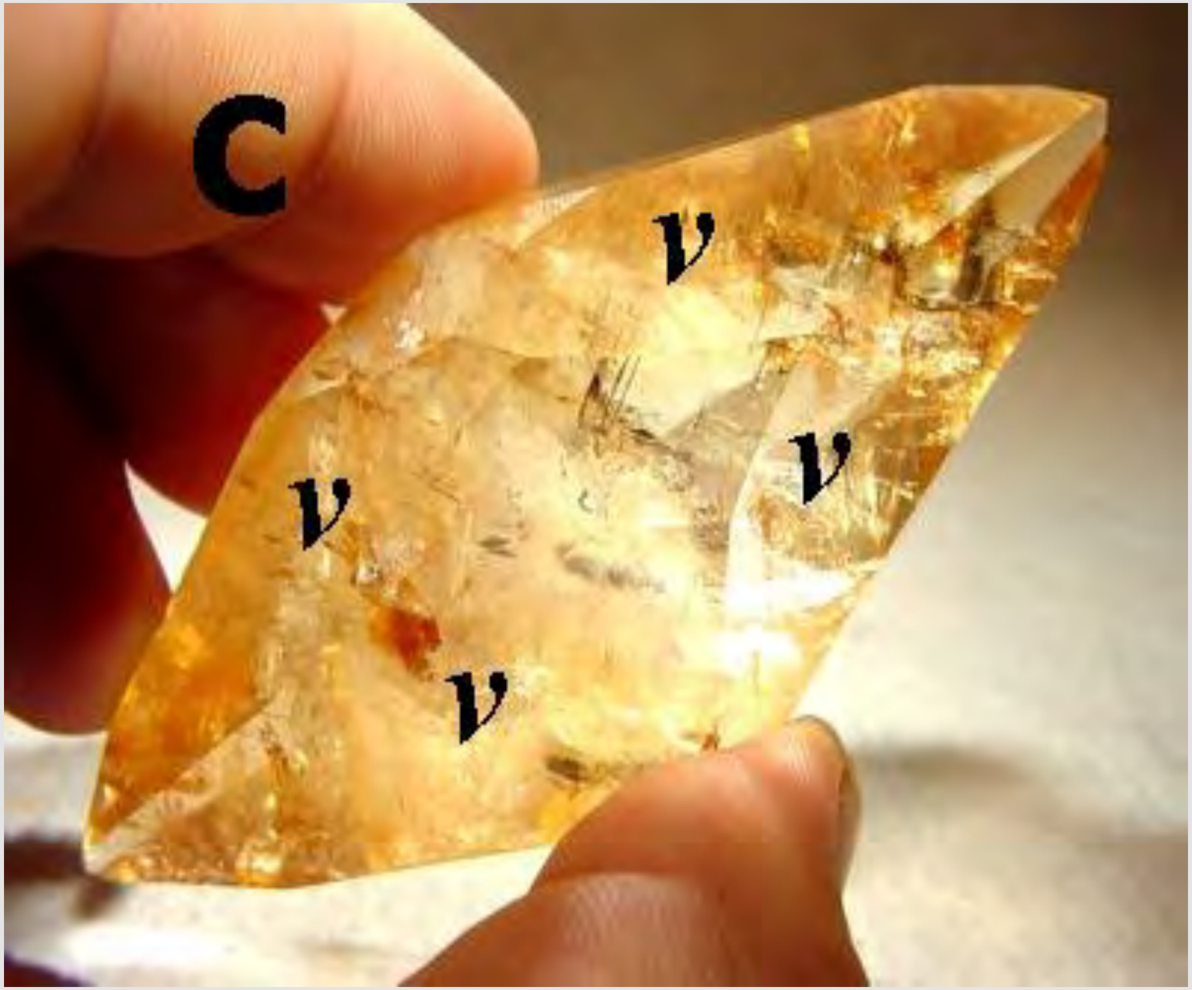




Calcite (214) Faces







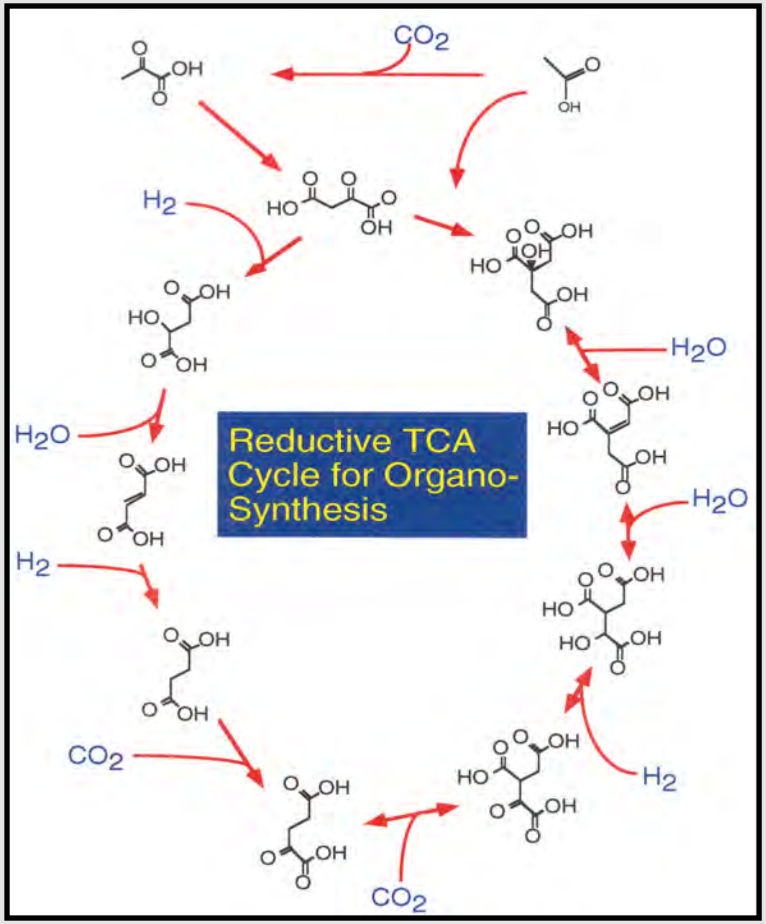
Minerals and Chiral Selection

Mineral surfaces select chiral amino acids

STEP 2: CONCLUSIONS

Prebiotic molecules can be selected and concentrated, both by self-organization and by adsorption on mineral surfaces.

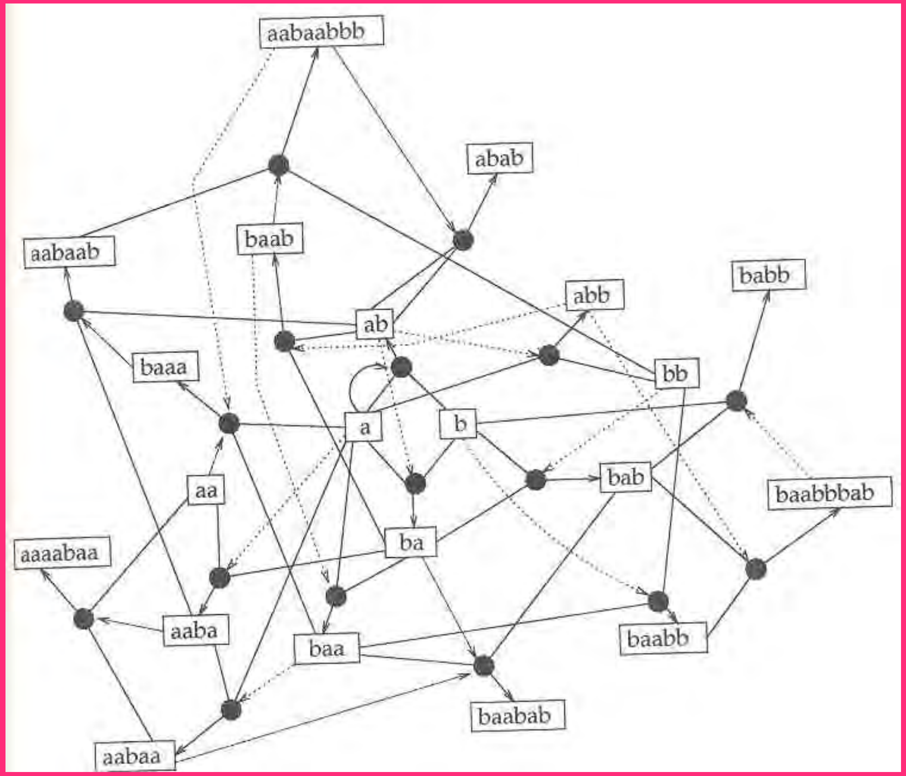
STEP 3:
The Emergence of Self-Replicating Molecular Cycles



The abiotic synthesis of such a “metabolic” cycle represents a “Holy Grail” for our experimental program.

Harold J. Morowitz

The Emergence of Self-Replicating Molecular Cycles



Farmer, Kauffman & Packard (1986)
Autocatalytic cycles

Which came first?
METABOLISM vs. GENETICS

Those who favor genetics first note that RNA can act as both an information-carrying molecule and an enzyme.

All cells use RNA;
hence the RNA World scenario.

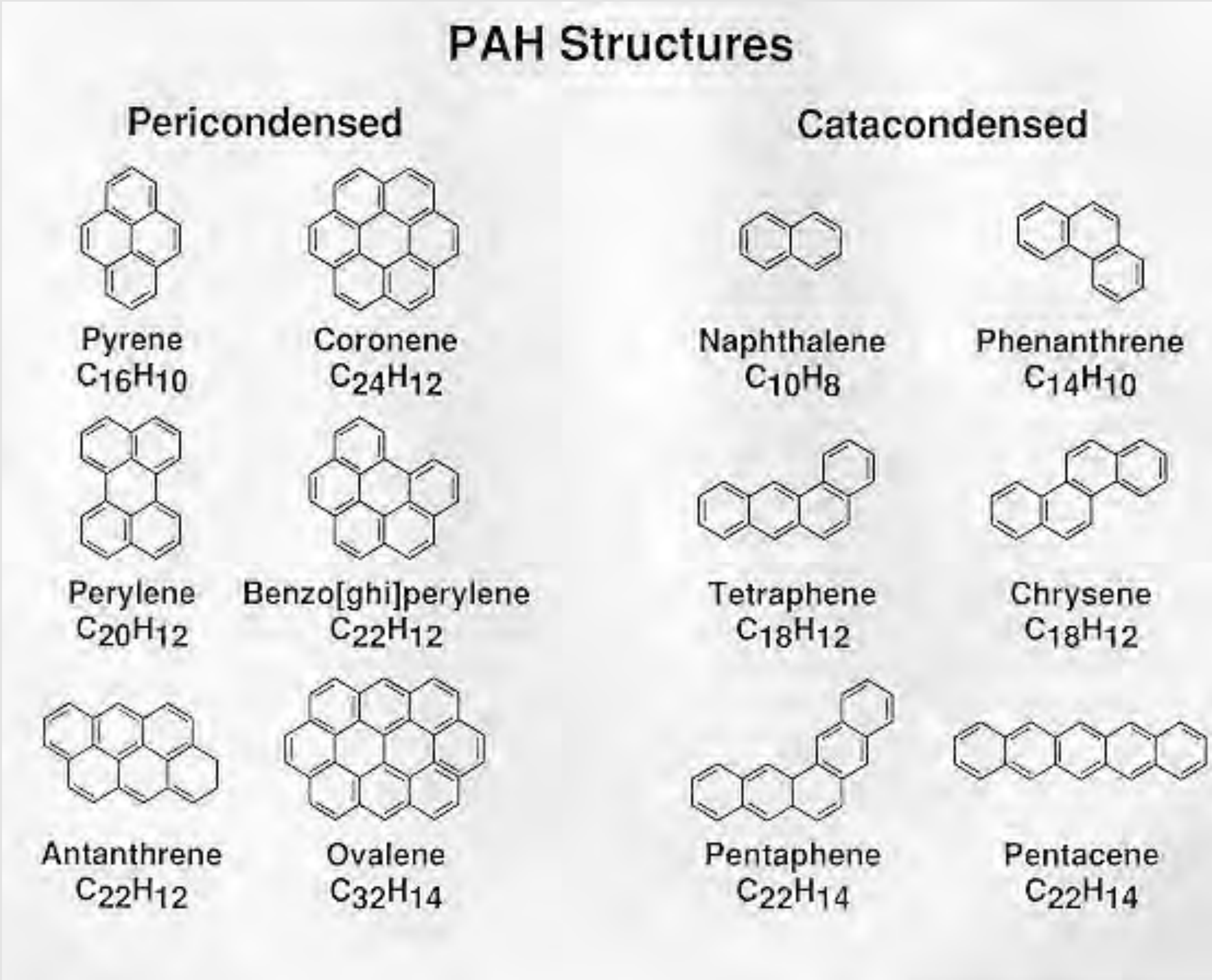
The RNA World Dilemma

RNA is an implausible prebiotic molecule, because there's no known way to synthesize it in a prebiotic environment.

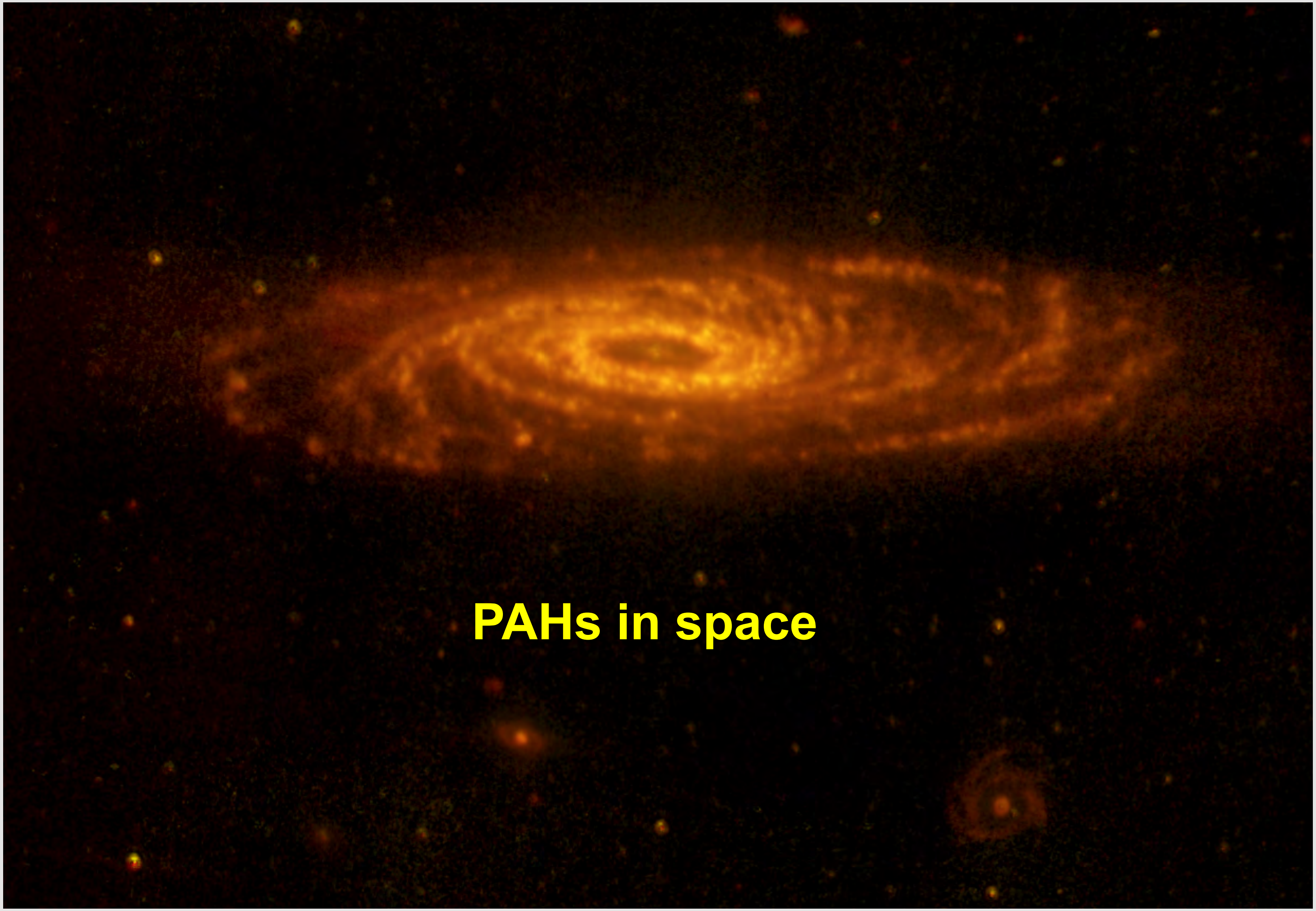
What happened between the soup and the RNA world?

The "PAH World"

Dave Deamer and Nick Platts at UCSC

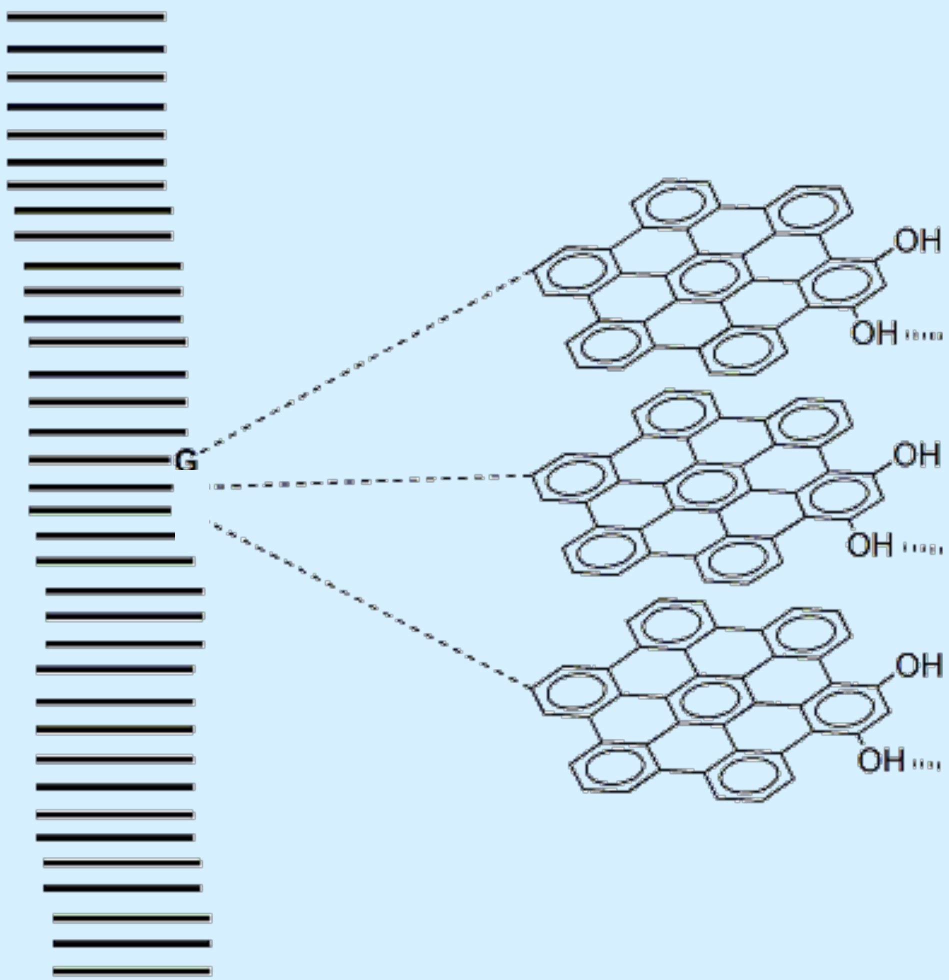


NASA Astrochemistry Group, ARC/NAI

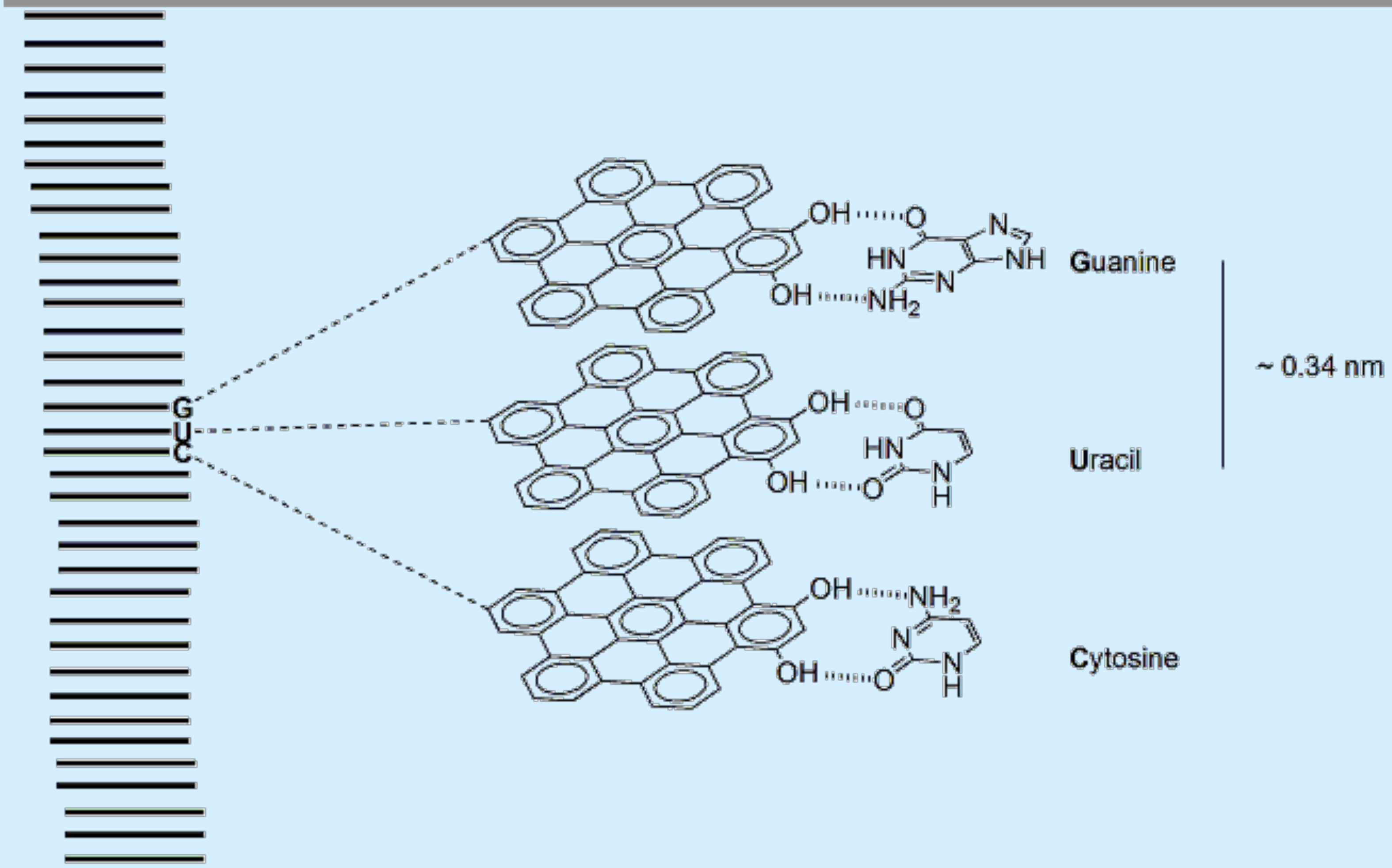


Spitzer Space Telescope image of NGC 7331
at 5.8 - 8.0 μm (infrared)

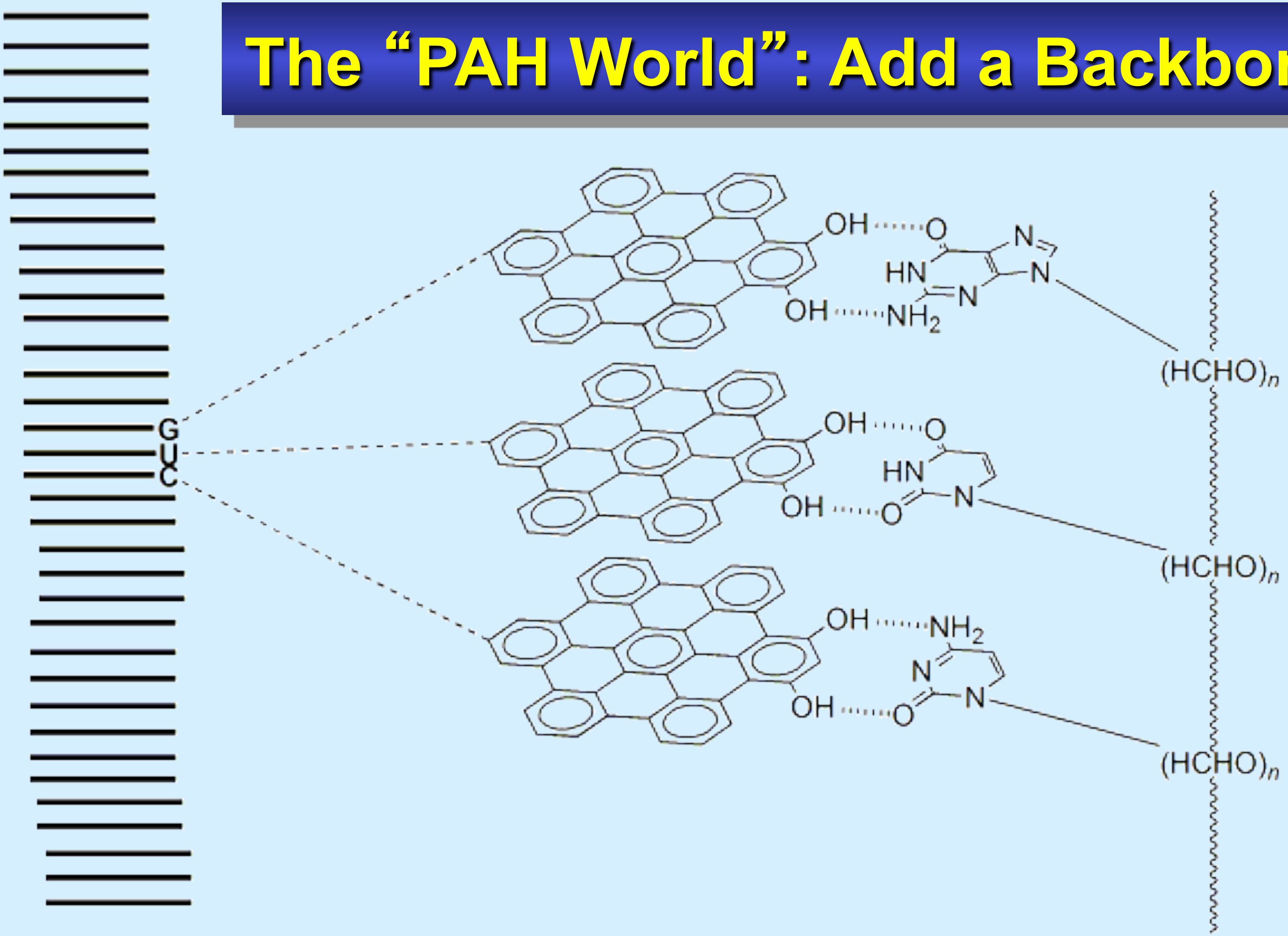
The "PAH World": Stack the PAHs



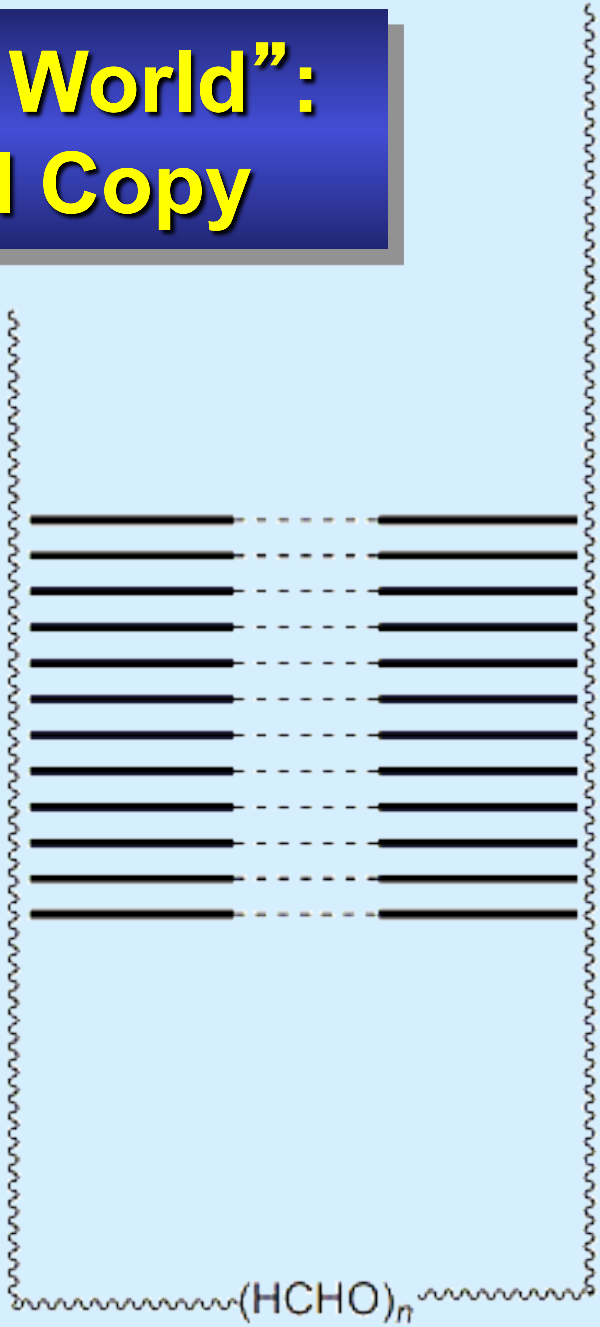
The "PAH World": Attach bases



The "PAH World": Add a Backbone



The "PAH World": Fold and Copy



STEP 3: CONCLUSIONS

We haven’t yet synthesized a plausible prebiotic molecule or cycle of molecules that can replicate itself, but we may be getting close.

STEP 4:
The Emergence of Natural Selection

At some point a self-replicating system of molecules was established.

Mutations must have occurred from time to time.

In such a system, competition and natural selection appear to be inevitable.

Molecular evolution has been demonstrated in the laboratory!

Jack Szostak, Harvard University
Experiments in Molecular Evolution

CONCLUSIONS

The origin of life on Earth is best understood in terms of a sequence of emergent chemical events, each of which added a degree of structure and complexity to the prebiotic world.

While we don't yet know all the details, there is no compelling evidence to suggest that life's origin was other than a natural process.

With thanks to:

NASA Astrobiology Institute
National Science Foundation
Carnegie Institution of Washington

Feedback: Eye Evolution

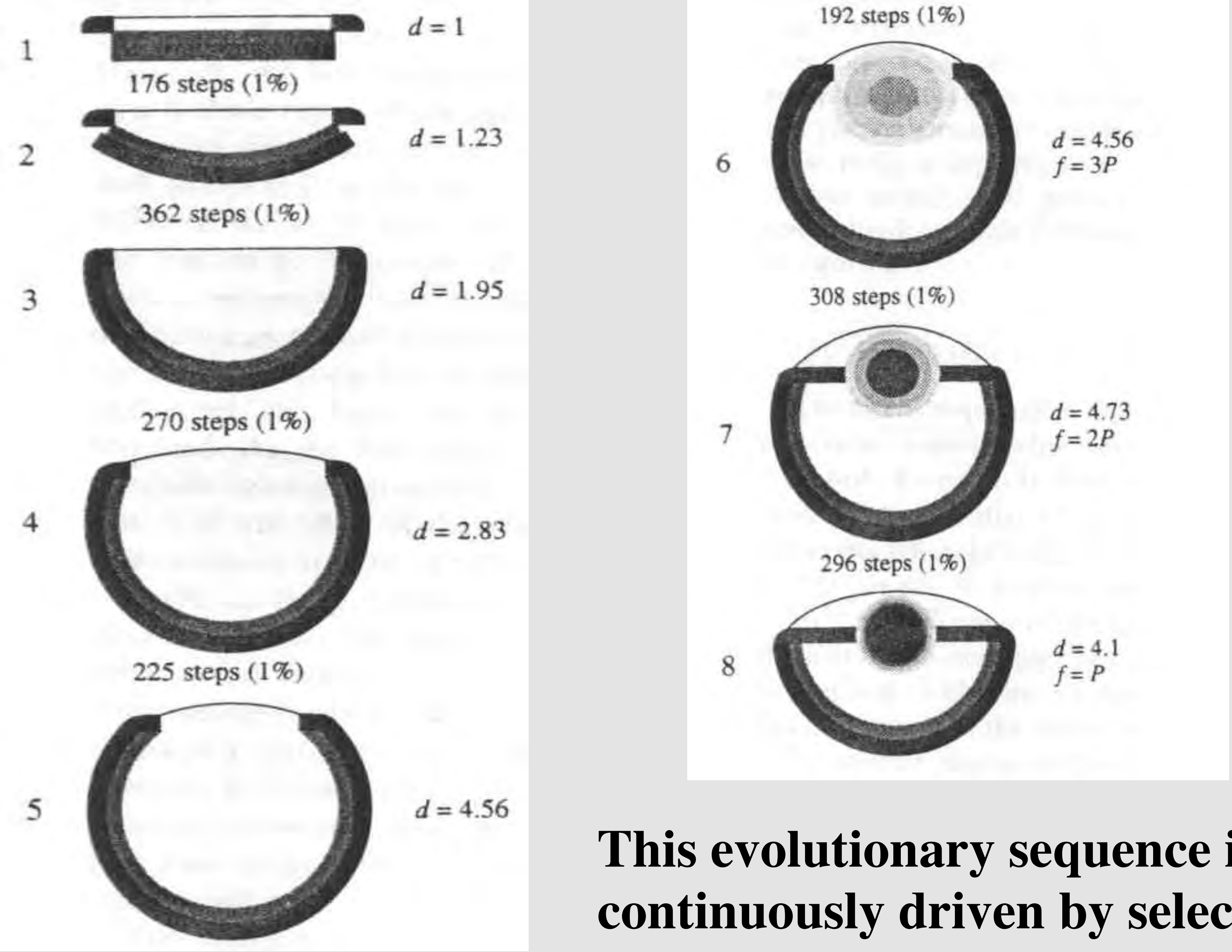
D. Nilsson & S. Pelger, "A pessimistic estimate for the time required for an eye to evolve." ***Proc. R. Soc. Lond. B*** **256, 53-58 (1994).**

Selection rules for model eye evolution:

1. Vary curvature, aperture, and central refractive index randomly by ±1%.

2. If visual acuity (spatial resolution) increases, then retain that variation.

Feedback: Eye Evolution



This evolutionary sequence is continuously driven by selection.