Alfred P. Sloan Foundation 1934

Deep Carbon Observatory

Carnegie Institution for Science

NSF

NASA

GENESIS:
The Scientific Quest for Life's Origin

Scientific American—Bright Horizons 17

Robert M. Hazen—8 July 2013

Geophysical Laboratory & George Mason University

Four Possibilities

Life' s origin could have been:

1. A miracle – an act of divine intervention

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Four Possibilities

Life' s origin could have been:

1. A miracle – an act of divine intervention
2. An event consistent with chemistry and physics, but extremely unlikely
3. **An inevitable consequence of natural laws, given an appropriate environment and sufficient time**

Chemical Evolution

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

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

Four Possibilities

Life's origin could have been:

1. A miracle – an act of divine intervention
2. An event consistent with chemistry and physics, but extremely unlikely
3. An inevitable consequence of natural laws, given an appropriate environment and sufficient time
4. **The result of intelligent design**

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

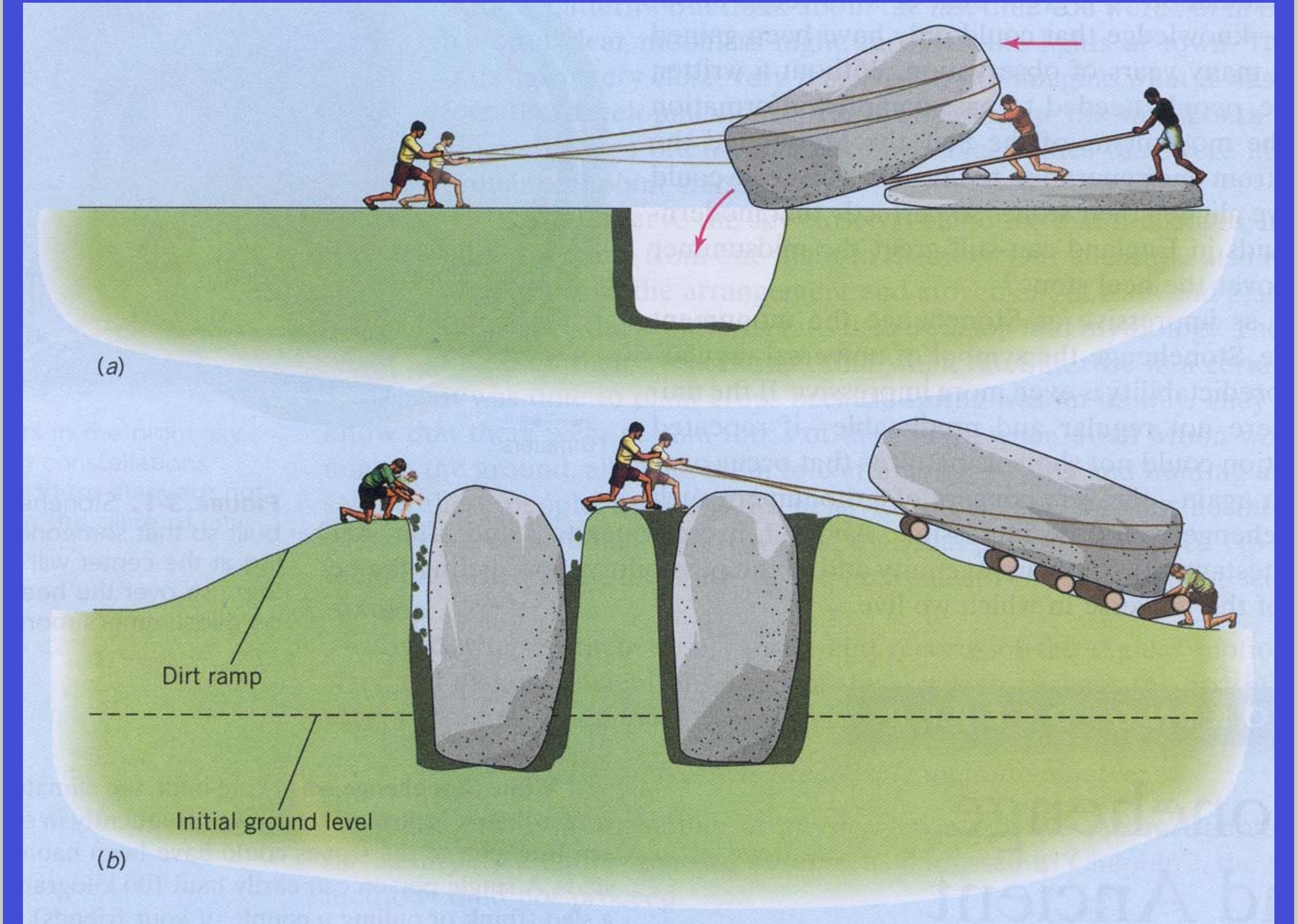
“Intelligent design should not be taught in high school biology classes as an alternative to evolution.”
American Chemical Society

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)

OUTLINE

1. What is emergent complexity?
2. Emergence of biomolecules
3. Emergence of organized molecular systems
4. Emergence of self-replicating molecular systems
5. Emergence of natural selection

What is Emergent Complexity?

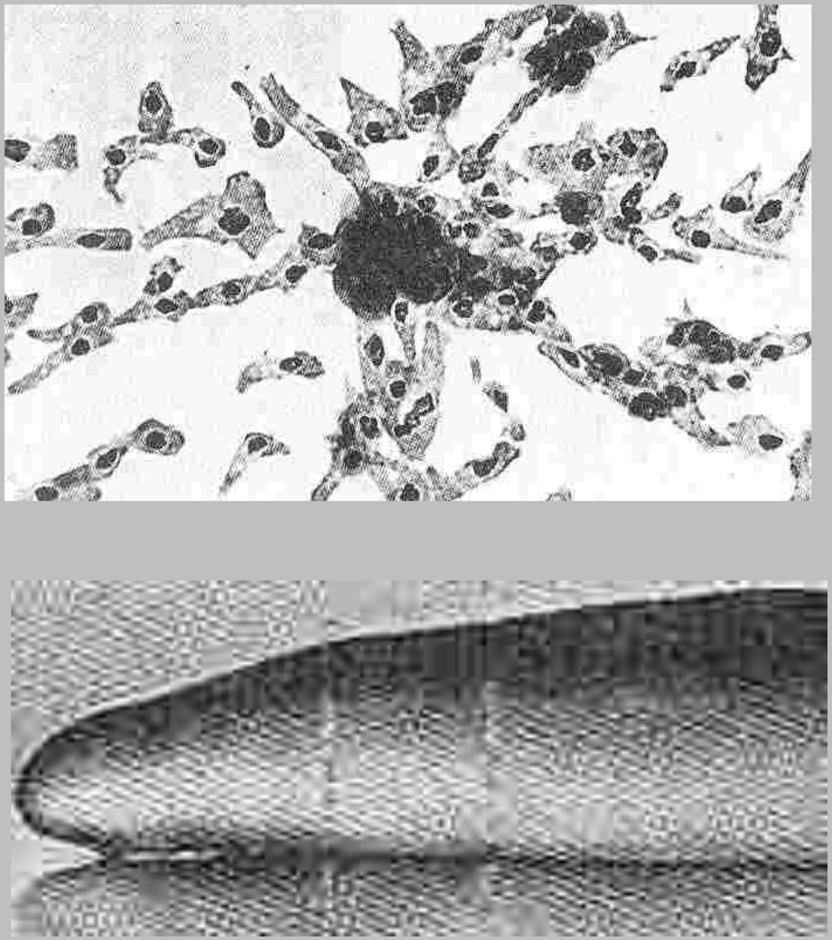
Emergent phenomena arise from interactions among numerous individual particles, or "agents."

The Emergence of Slime Mold

Dictyostelium

→

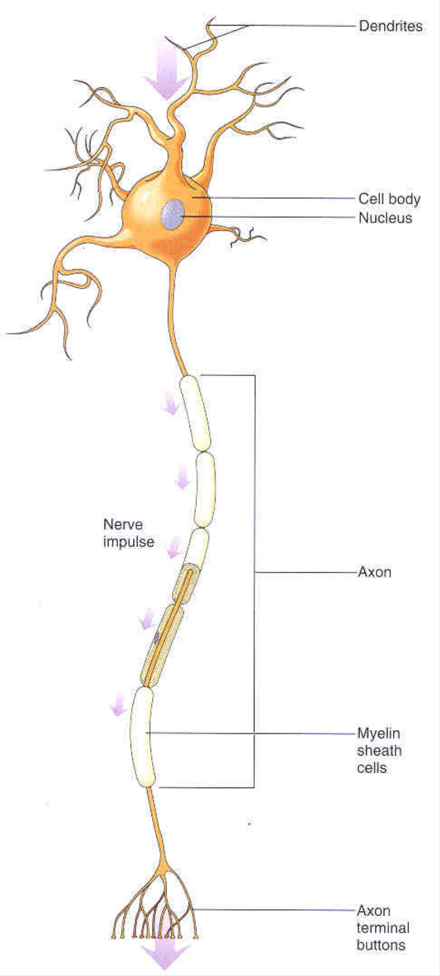
Chemical Potential Gradients



The Emergence of Slime Mold

Dictyostelium

The Emergence of Consciousness



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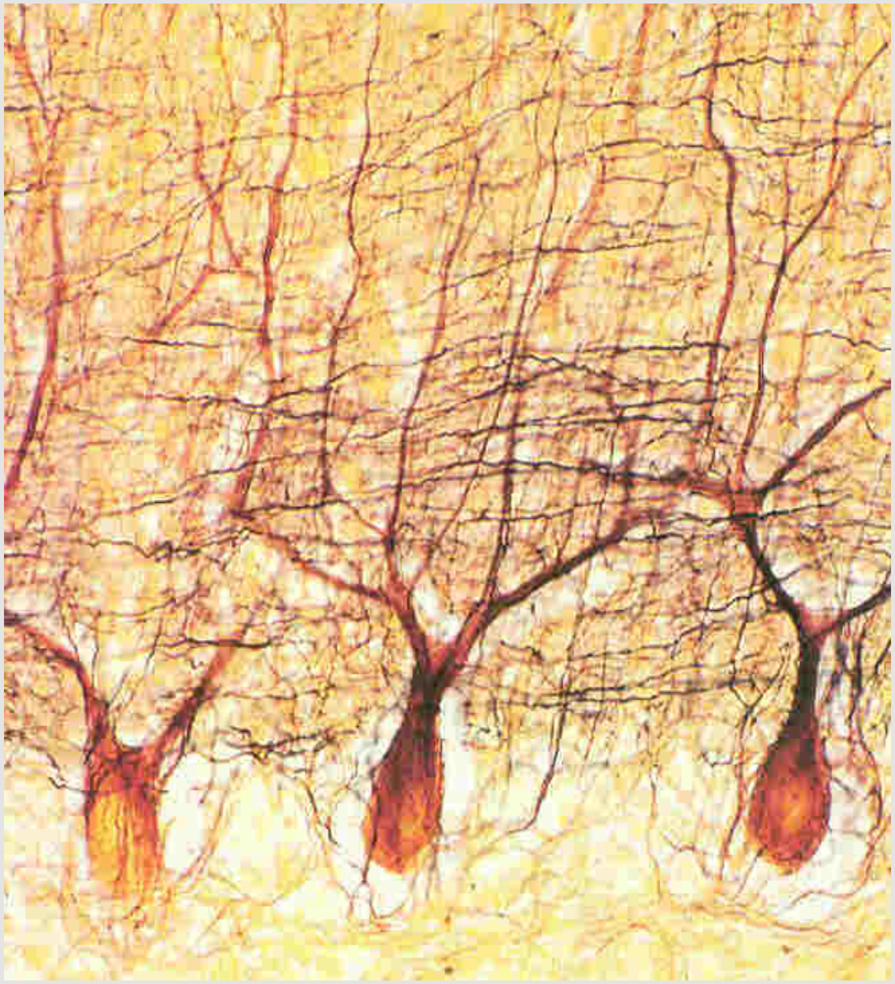
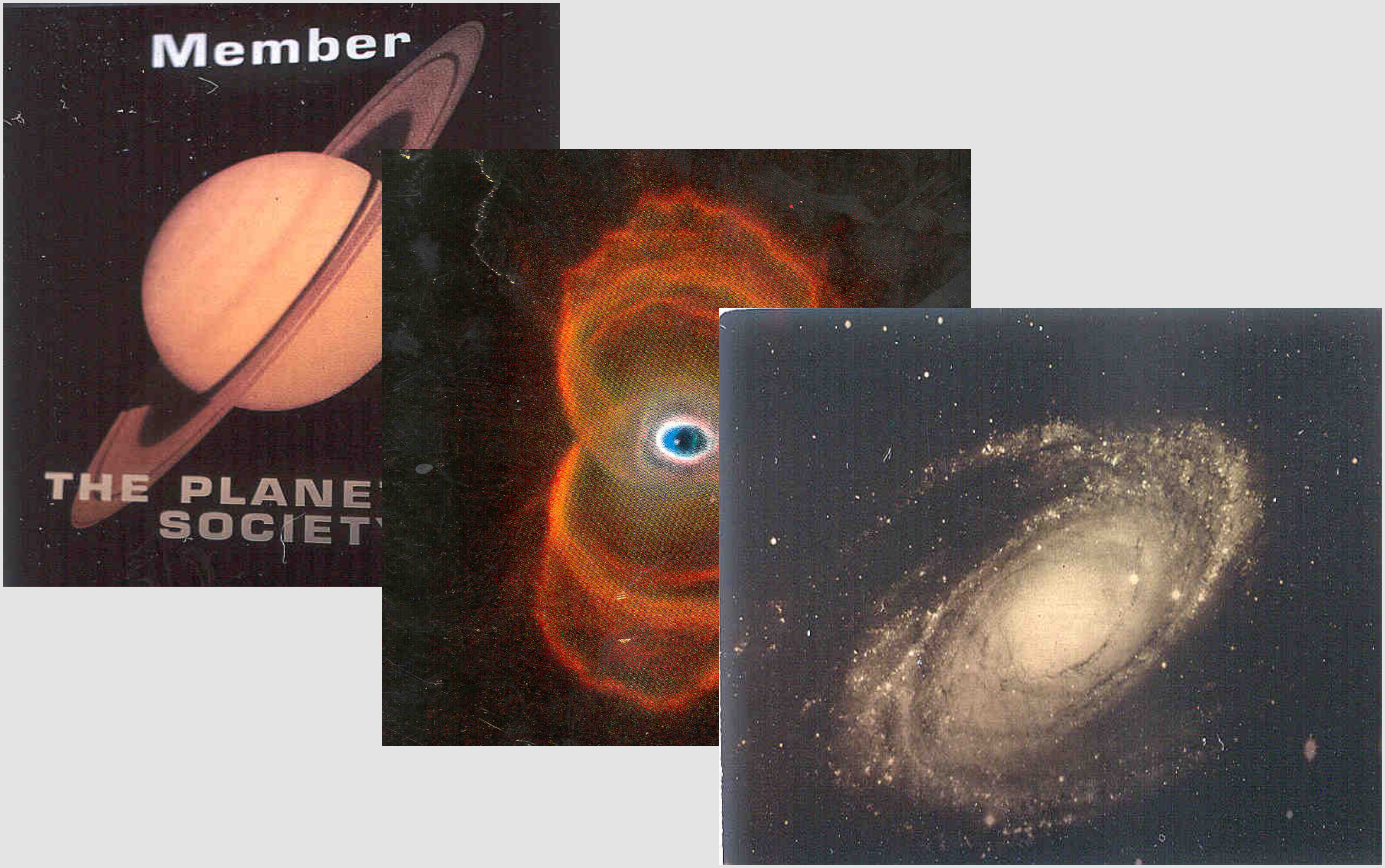
Neural connections and electrical impulses



The Emergence of Consciousness

Emergent Phenomena – Space



Emergent Phenomena – Life

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.

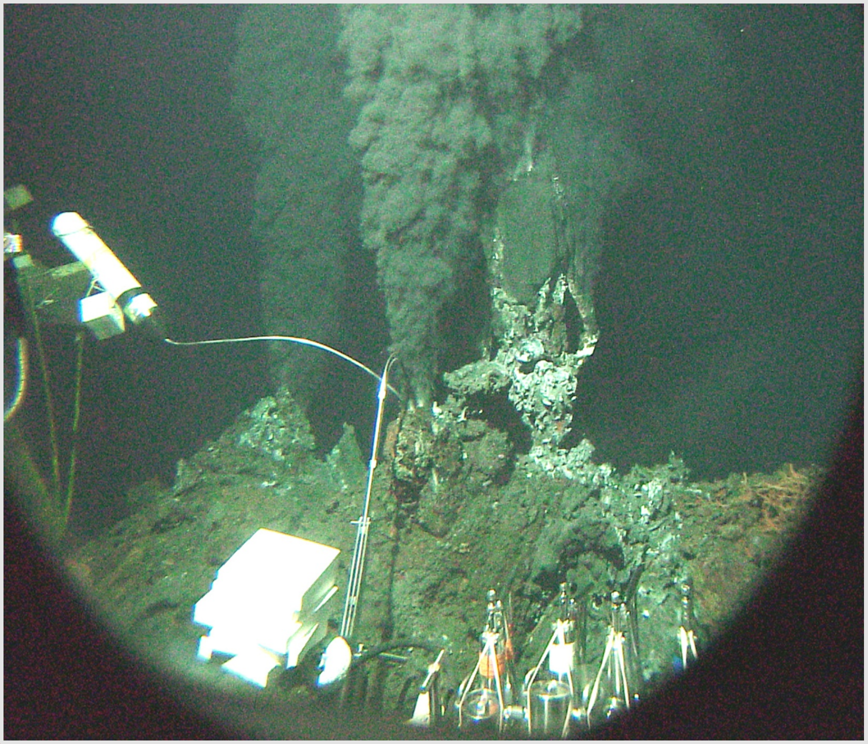
The origin of life required a sequence of emergent steps of increasing complexity.

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

Key Conclusion: Life cannot evolve in a static environment

Geochemical complexities are key to understanding life's origins:



Gradients

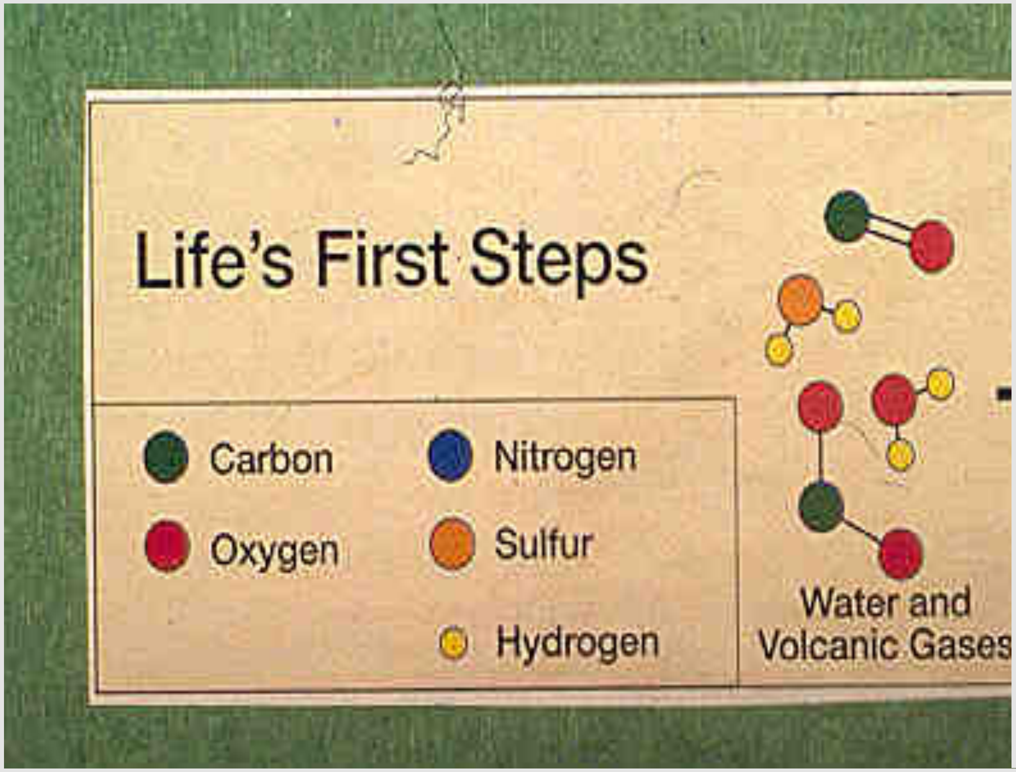
Cycles

Fluxes

Interfaces

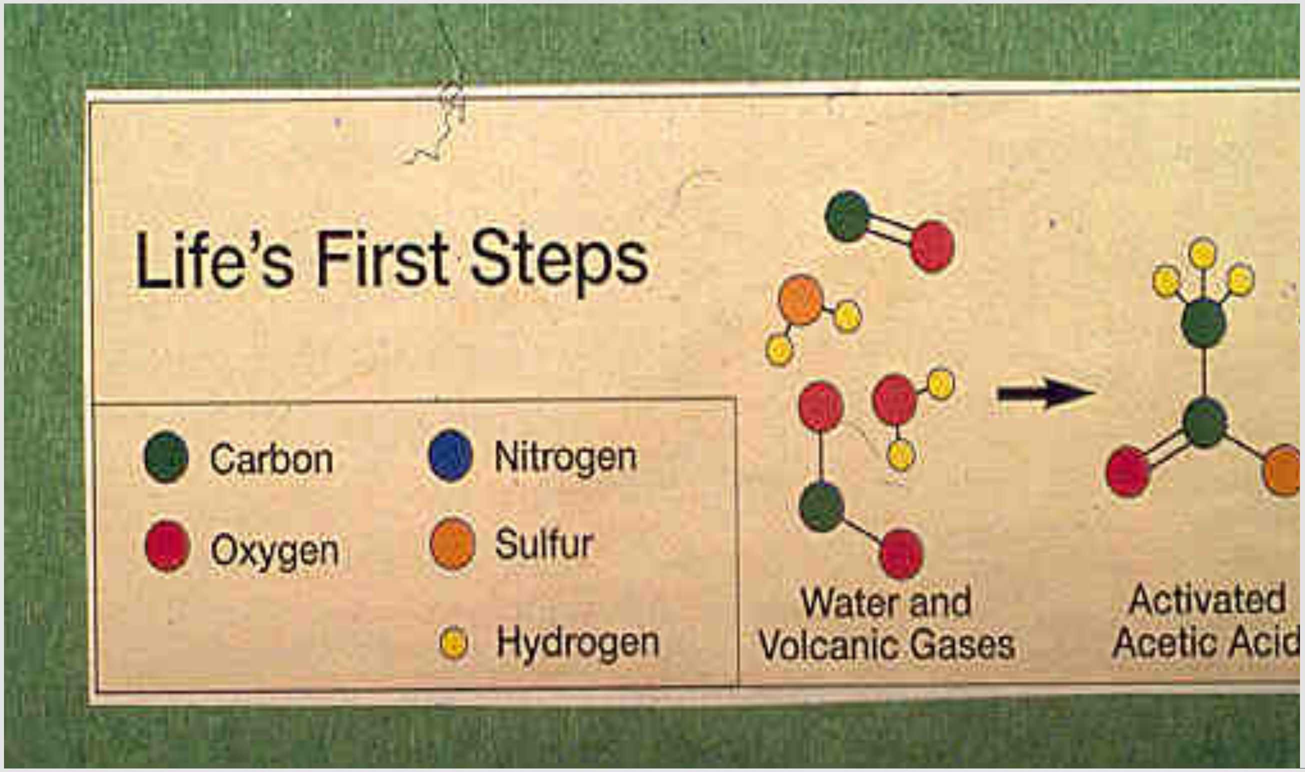
Chemical complexity

STEP 1:
Emergence of Biomolecules



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

STEP 1:
Emergence of Biomolecules



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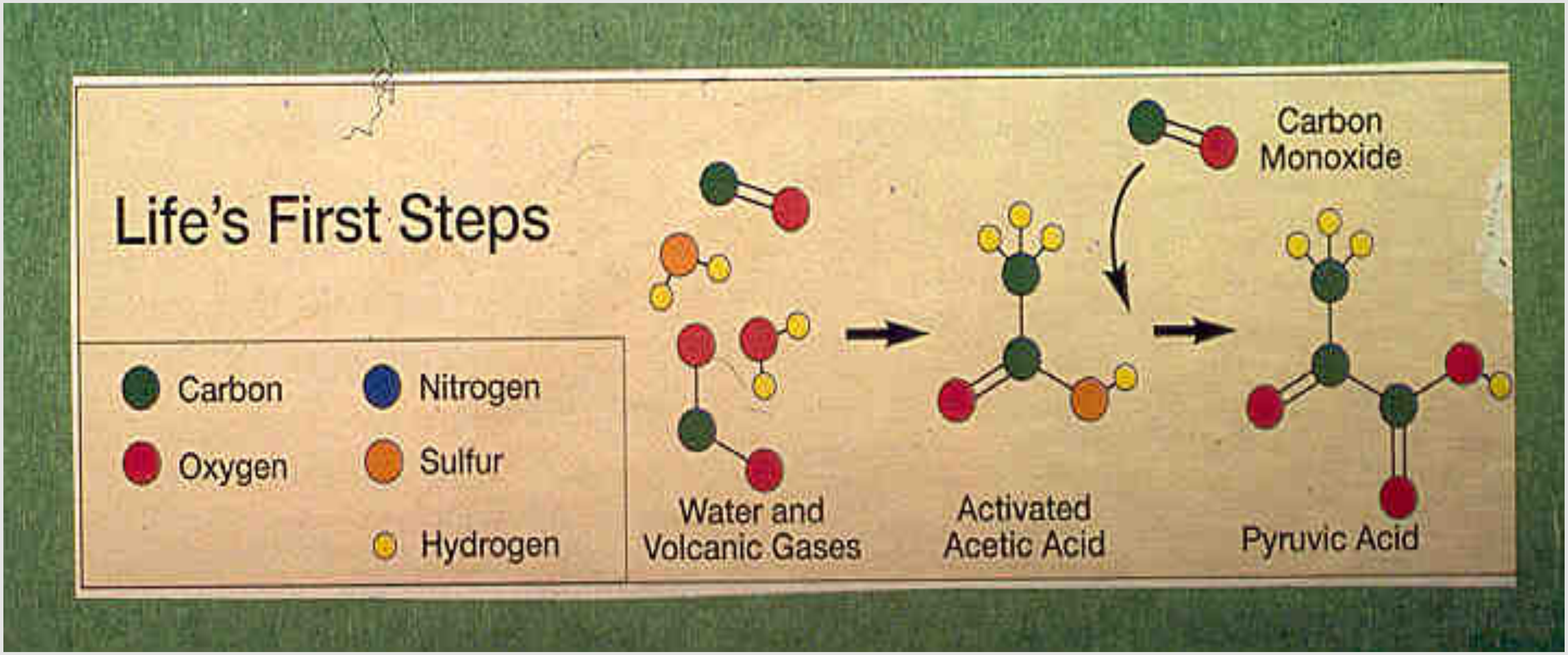
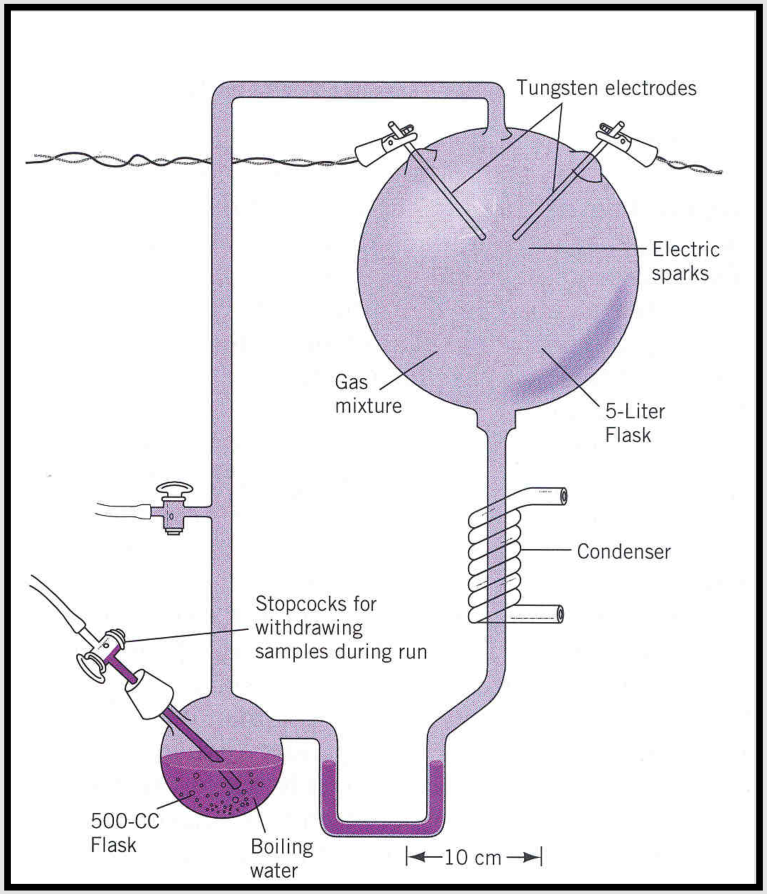
STEP 1:
Emergence of Biomolecules



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

The Miller-Urey Experiment



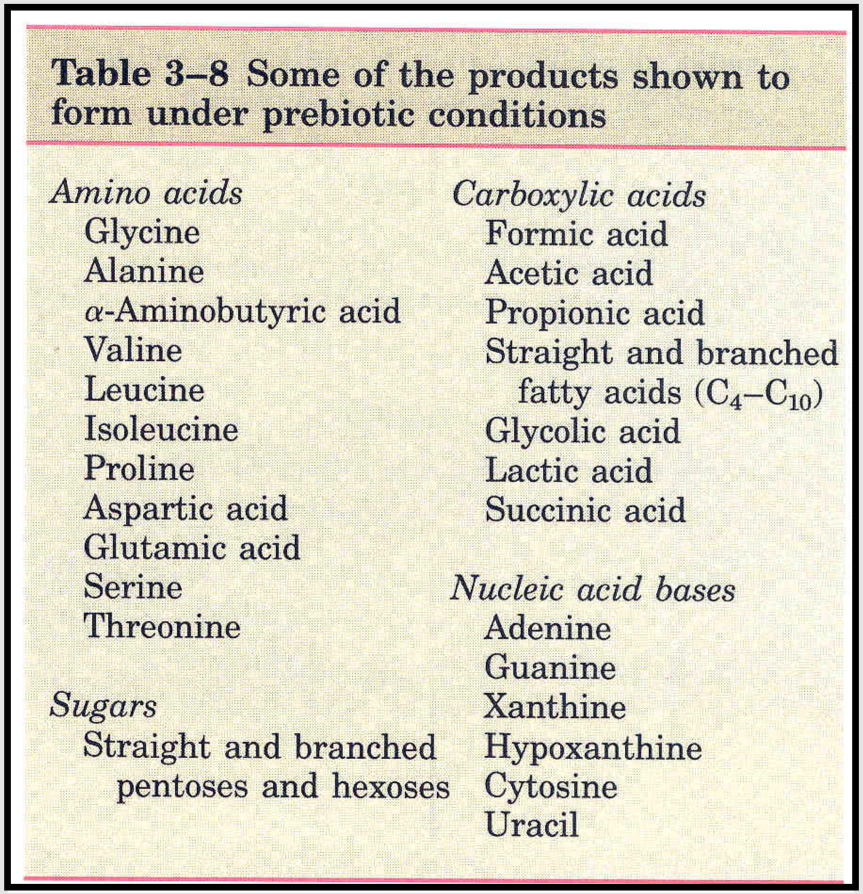


Table 3–8 **Some of the products shown to form under prebiotic conditions**

Amino acids
- Glycine
- Alanine
- α-Aminobutyric acid
- Valine
- Leucine
- Isoleucine
- Proline
- Aspartic acid
- Glutamic acid
- Serine
- Threonine

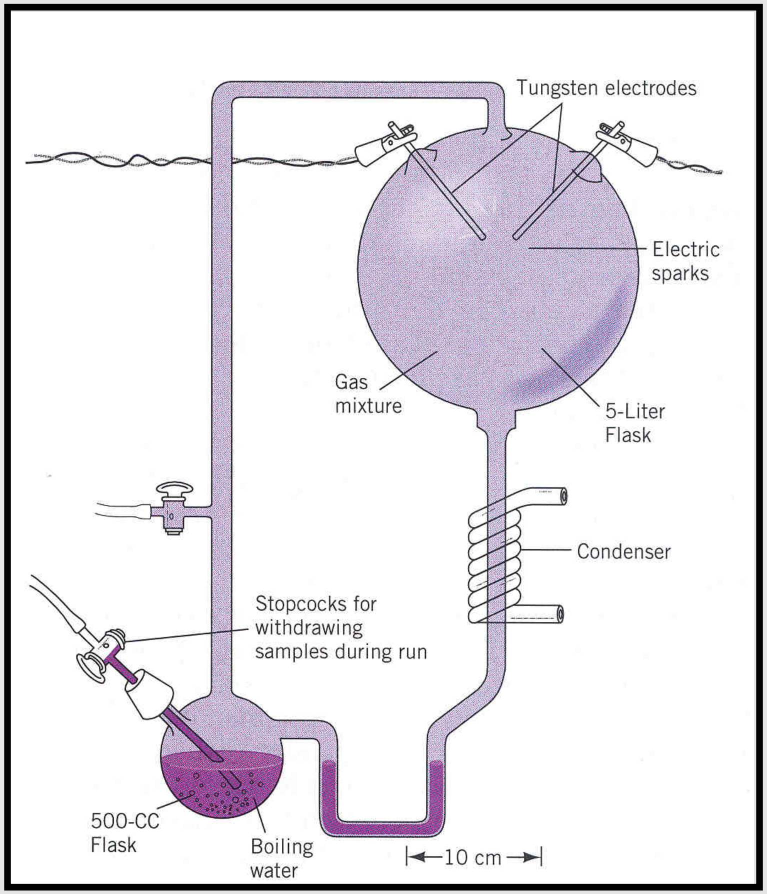
Sugars
- Straight and branched pentoses and hexoses

Carboxylic acids
- Formic acid
- Acetic acid
- Propionic acid
- Straight and branched fatty acids (C_4–C_{10})
- Glycolic acid
- Lactic acid
- Succinic acid

Nucleic acid bases
- Adenine
- Guanine
- Xanthine
- Hypoxanthine
- Cytosine
- Uracil

Organic synthesis near the ocean-atmosphere interface.

The Miller-Urey Experiment

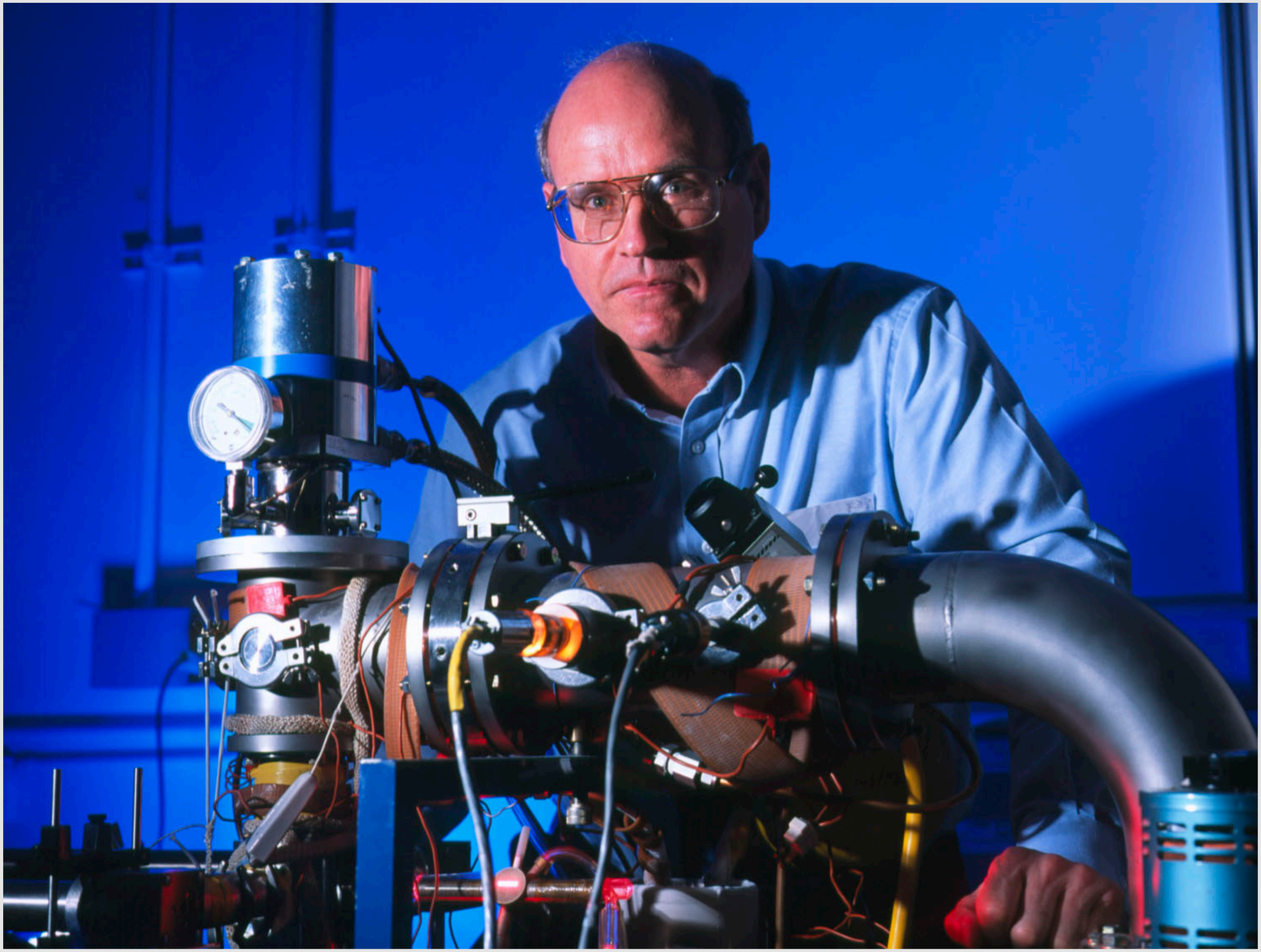


Nutrition Facts

Serving Size 1 cup (30g)
Servings Per Container 17

Amount Per Serving	Wheaties	with 1/2 cup skim milk
Calories	110	150
Calories from Fat	10	10
	% Daily Value**	
Total Fat 1g*	**1%**	**2%**
Saturated Fat 0g	**0%**	**0%**
Trans Fat 0g		
Polyunsaturated Fat 0g		
Monounsaturated Fat 0g		
Total Carbohydrate 24g	**8%**	**10%**
Dietary Fiber 3g	**12%**	**12%**
Sugars 4g		
Other Carbohydrate 17g		
Protein 3g		

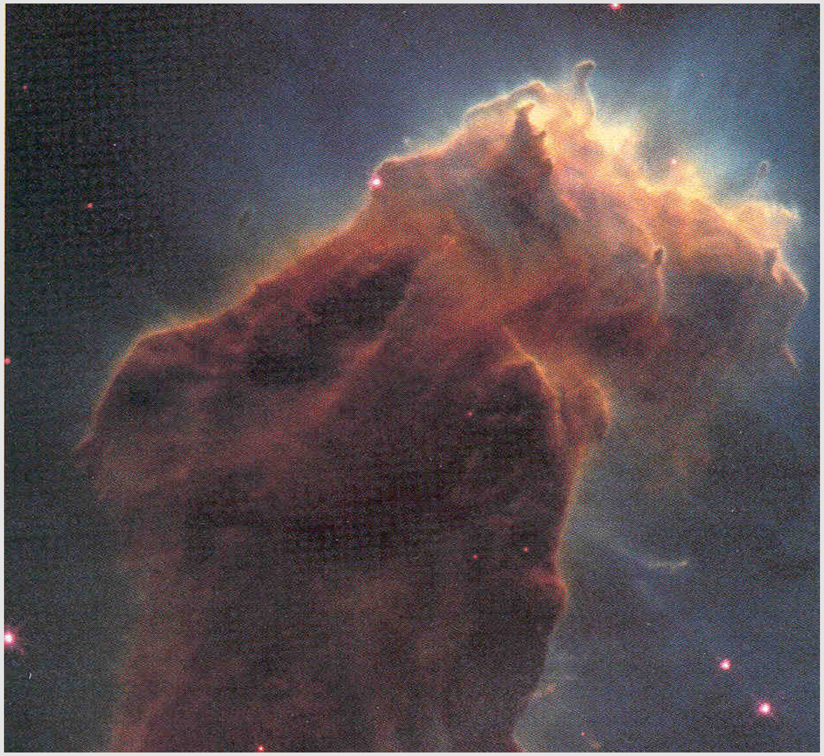
Organic synthesis near the ocean-atmosphere interface.

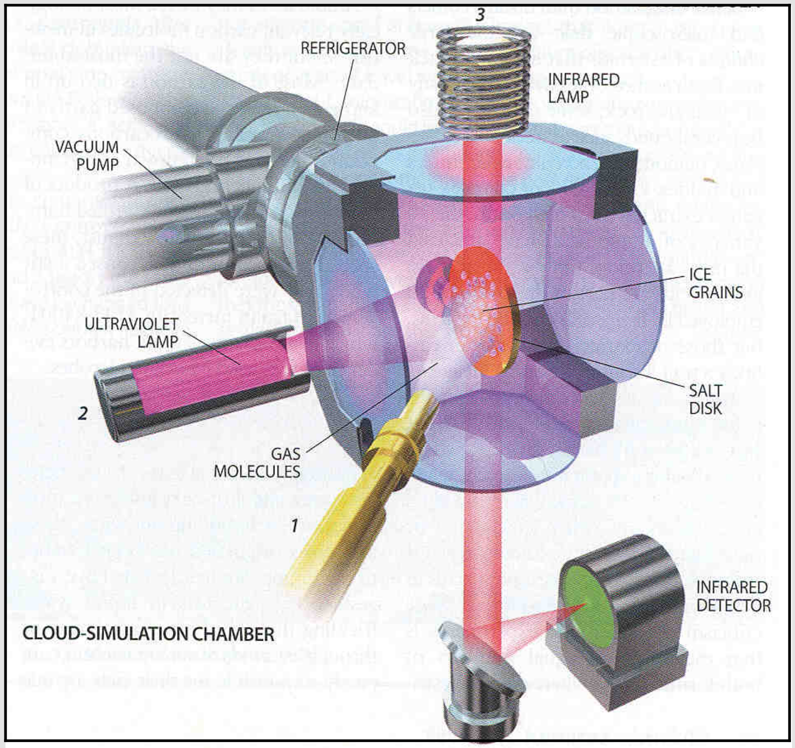


Louis J. Allamandola, NASA-ARC

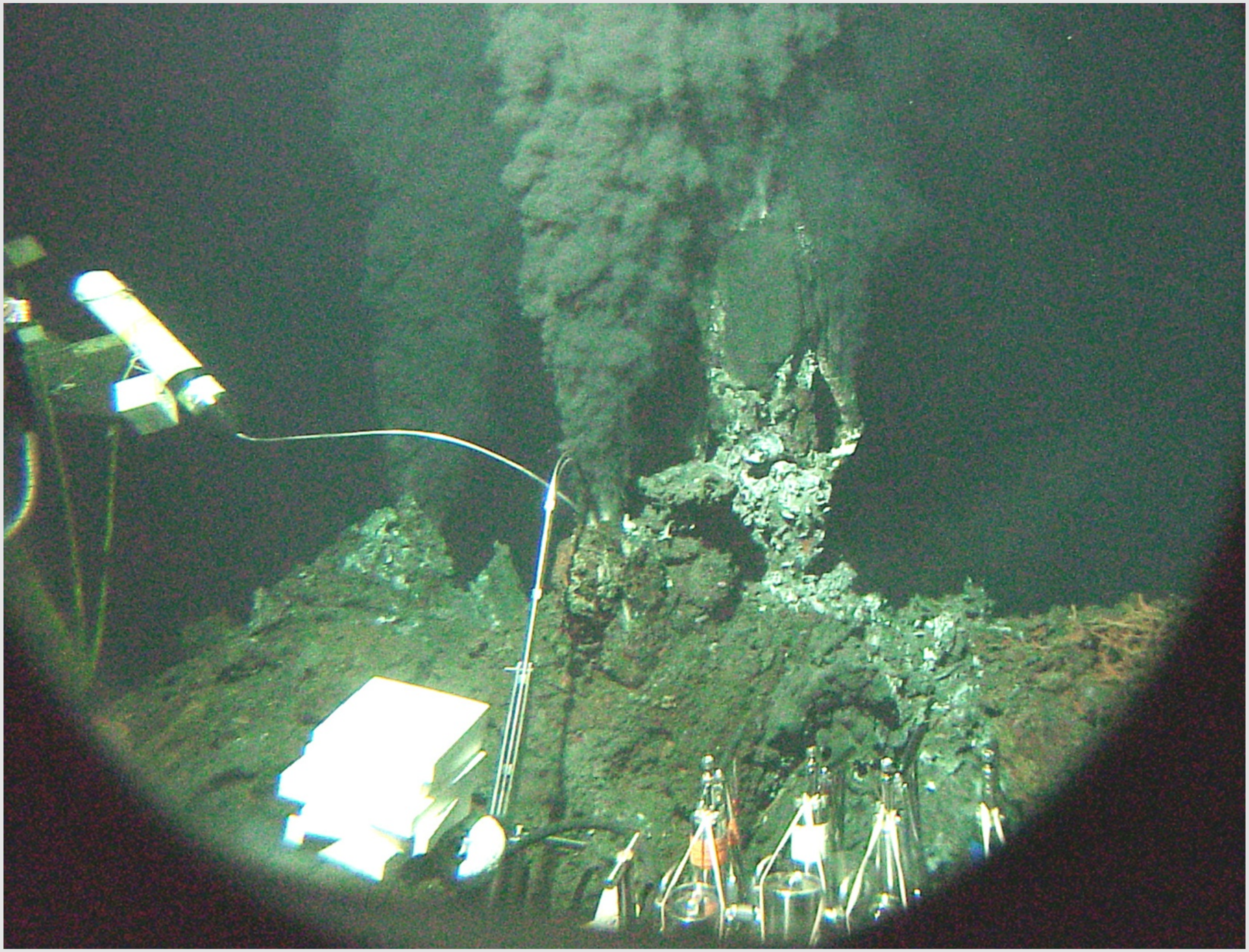
Organic Synthesis in Interstellar "Dense" Molecular Clouds

Experiments at NASA Ames simulate this environment.





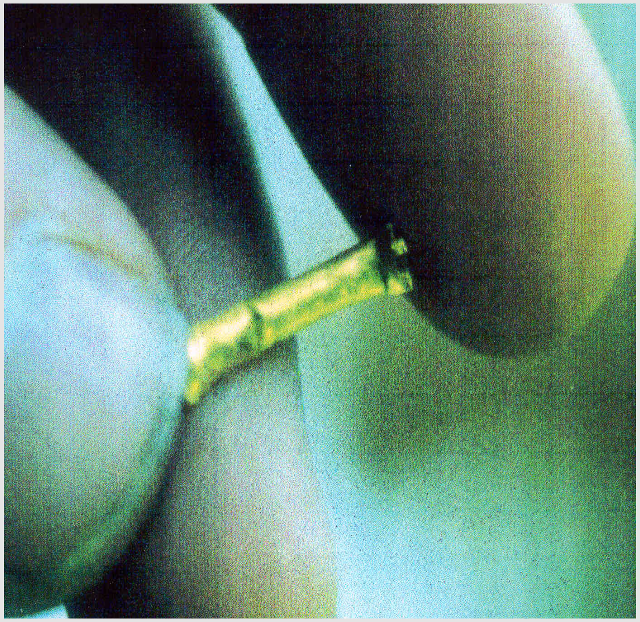
The Hydrothermal Hypothesis

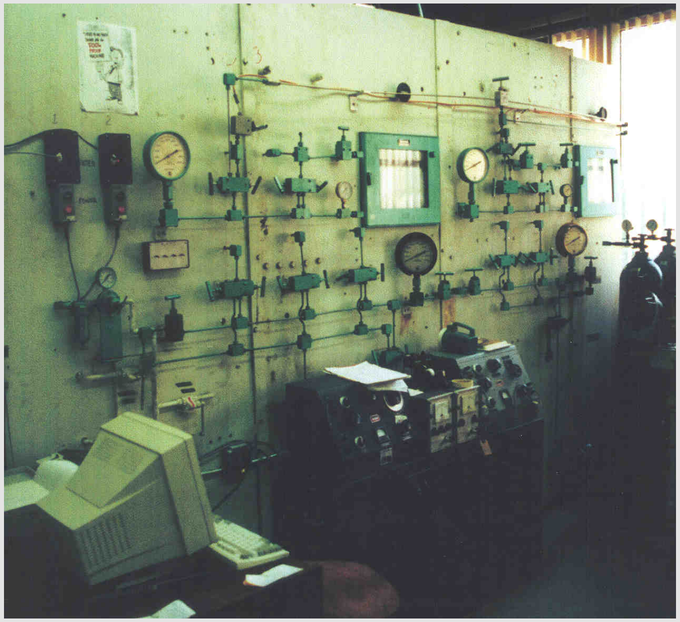


A “BLACK SMOKER”

Hydrothermal Organic Synthesis

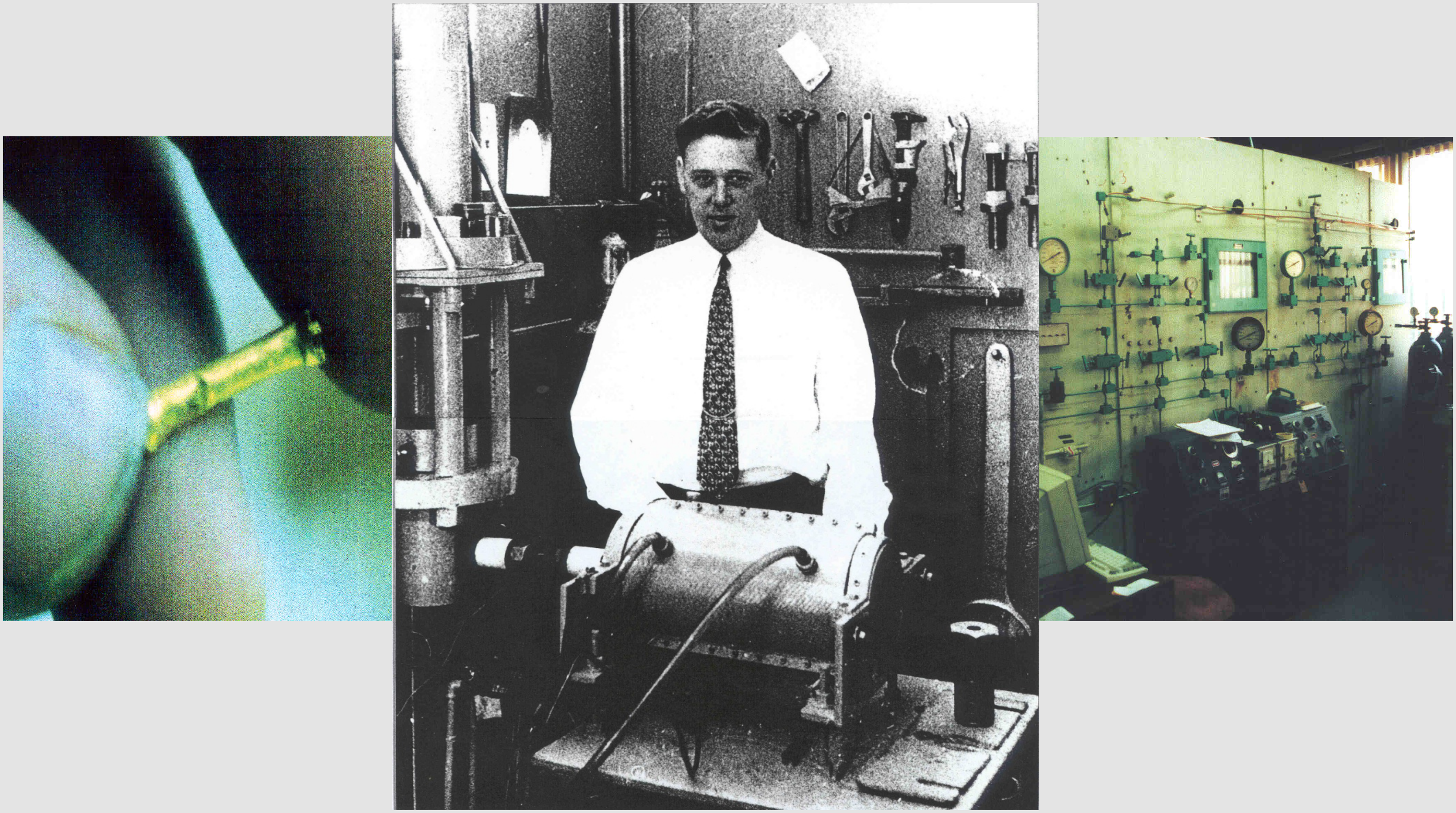
Gold tube reactors





Capsules are run in a gas-media pressure apparatus.

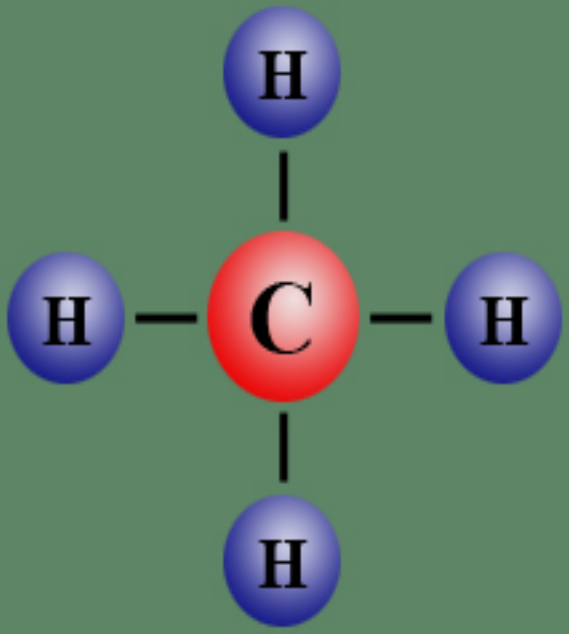
Hydrothermal Organic Synthesis



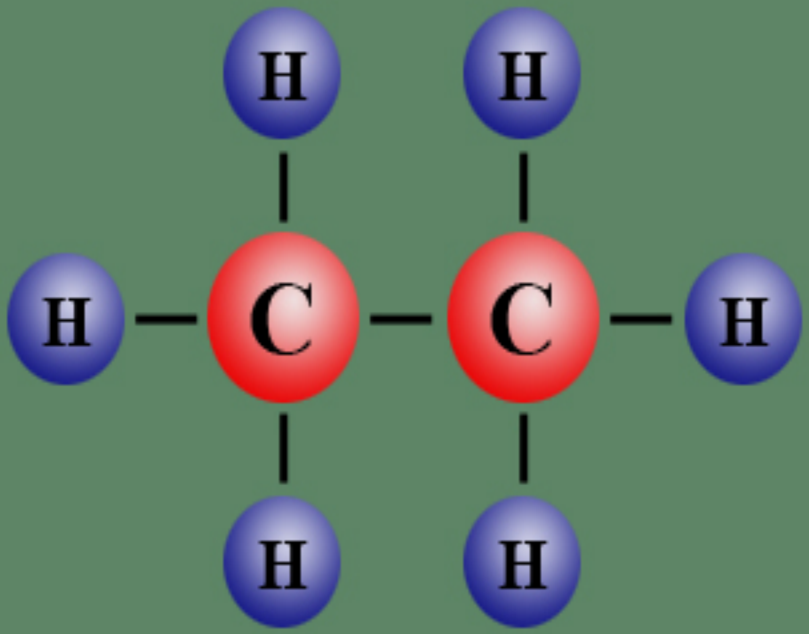
Hatten S. Yoder, Jr.

George D. Cody

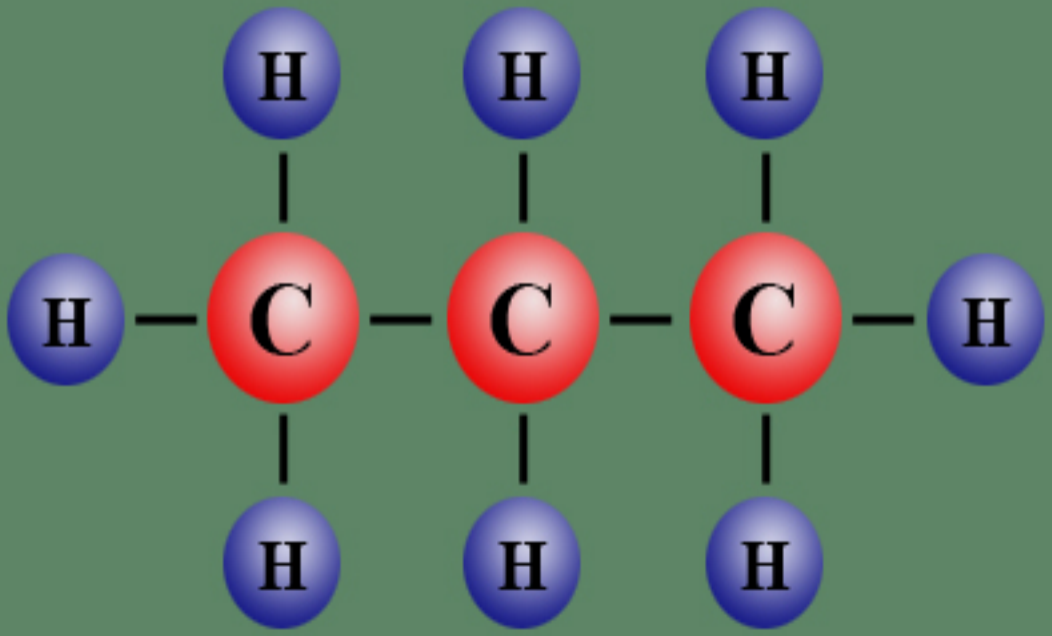
METHANE



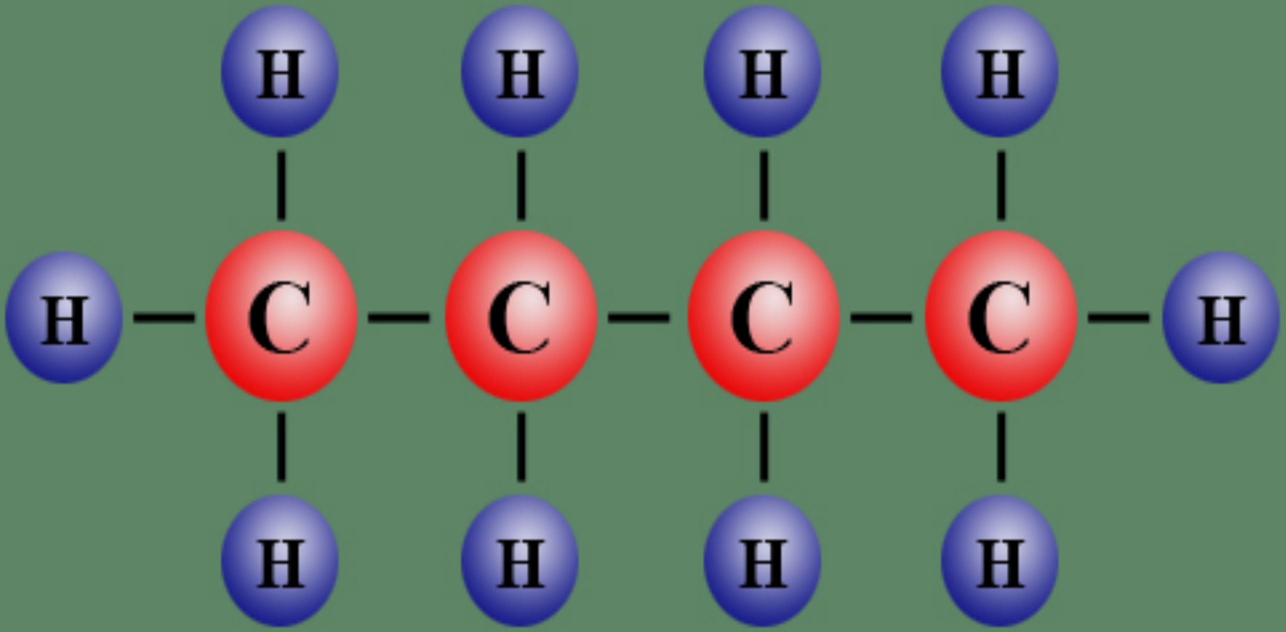
ETHANE



PROPANE

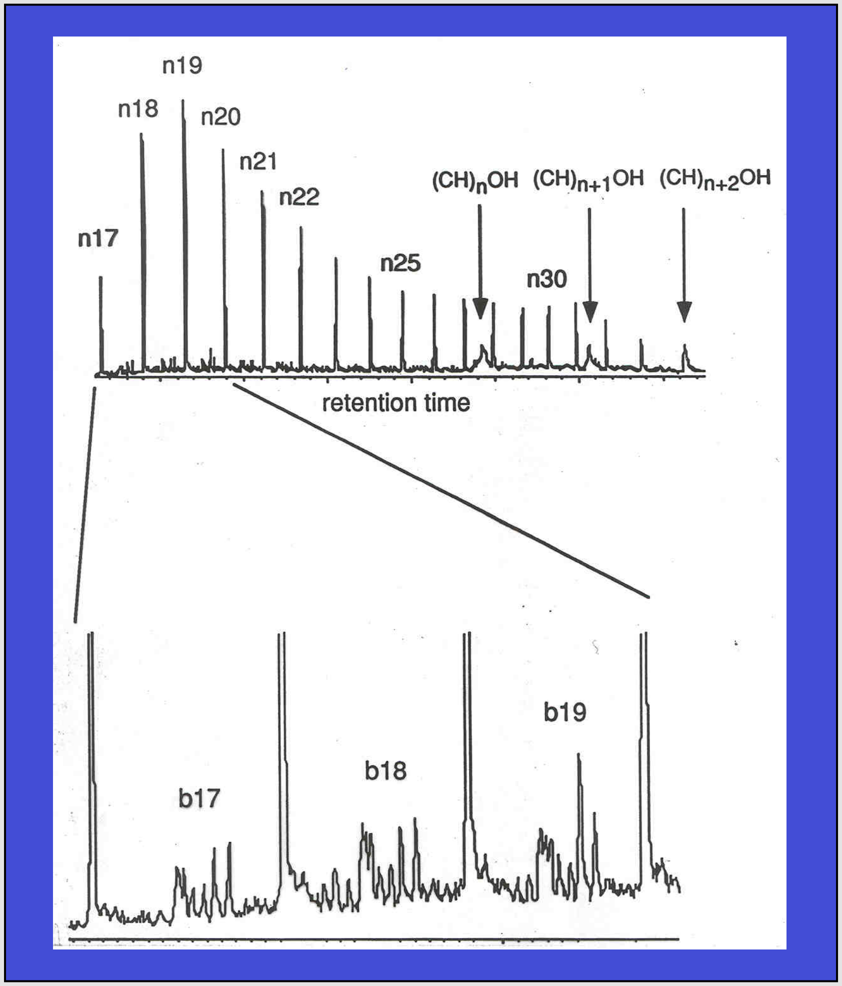


BUTANE

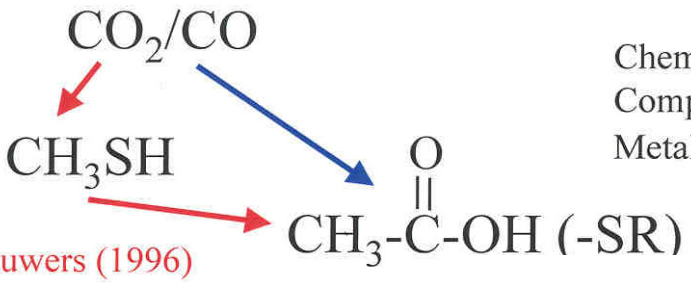


Carbon-Addition Reactions: Hydrothermal F-T Synthesis (+CH_2)

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



Carbon-Addition Reactions: Hydroformylation (+CO)



CO_2/CO

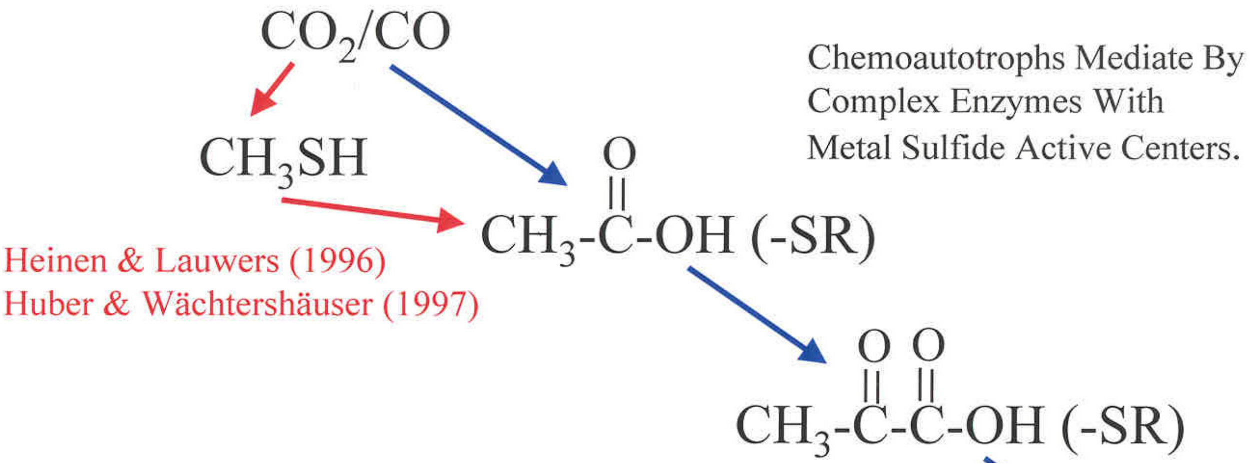
CH_3SH

$$CH_3\text{-}\overset{\overset{O}{||}}{C}\text{-}OH\ (\text{-}SR)$$

Heinen & Lauwers (1996)
Huber & Wächtershäuser (1997)

Chemoautotrophs Mediate By
Complex Enzymes With
Metal Sulfide Active Centers.

Carbon-Addition Reactions: Hydroformylation (+CO)



CO_2/CO

CH_3SH

$CH_3\text{-}\overset{\overset{O}{||}}{C}\text{-}OH$ (-SR)

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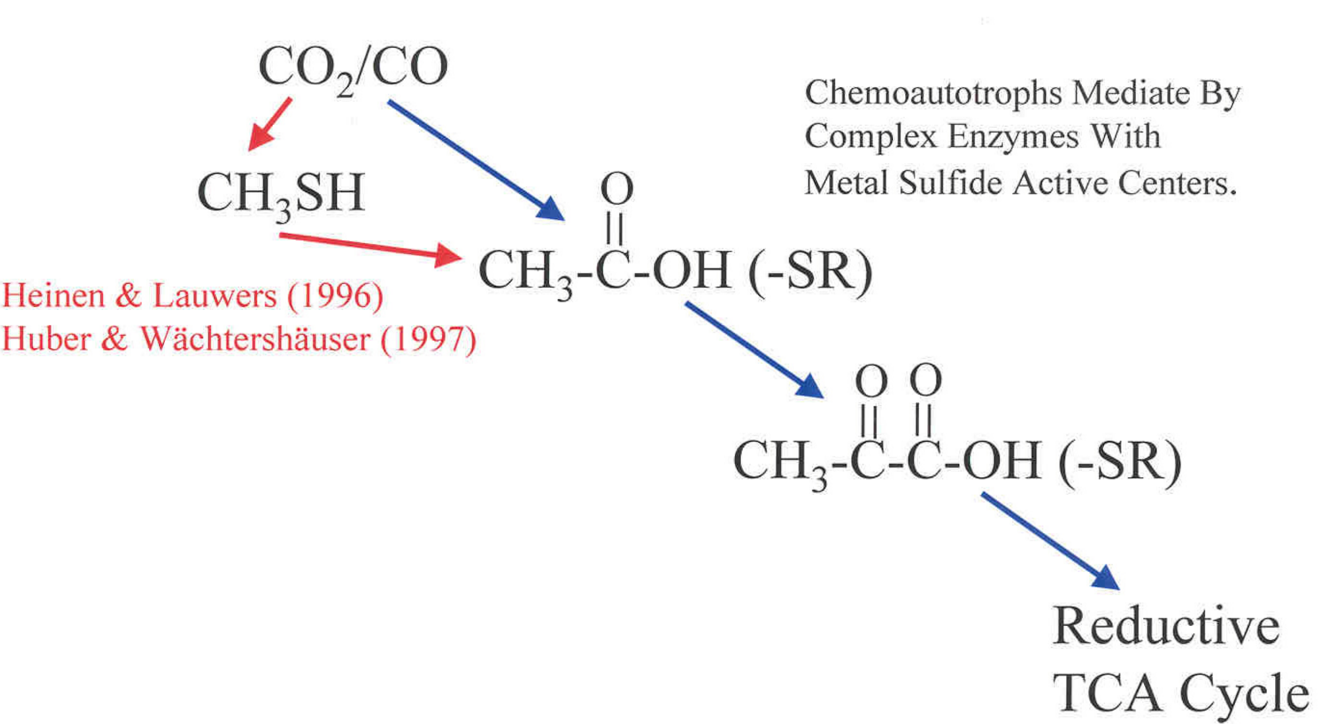

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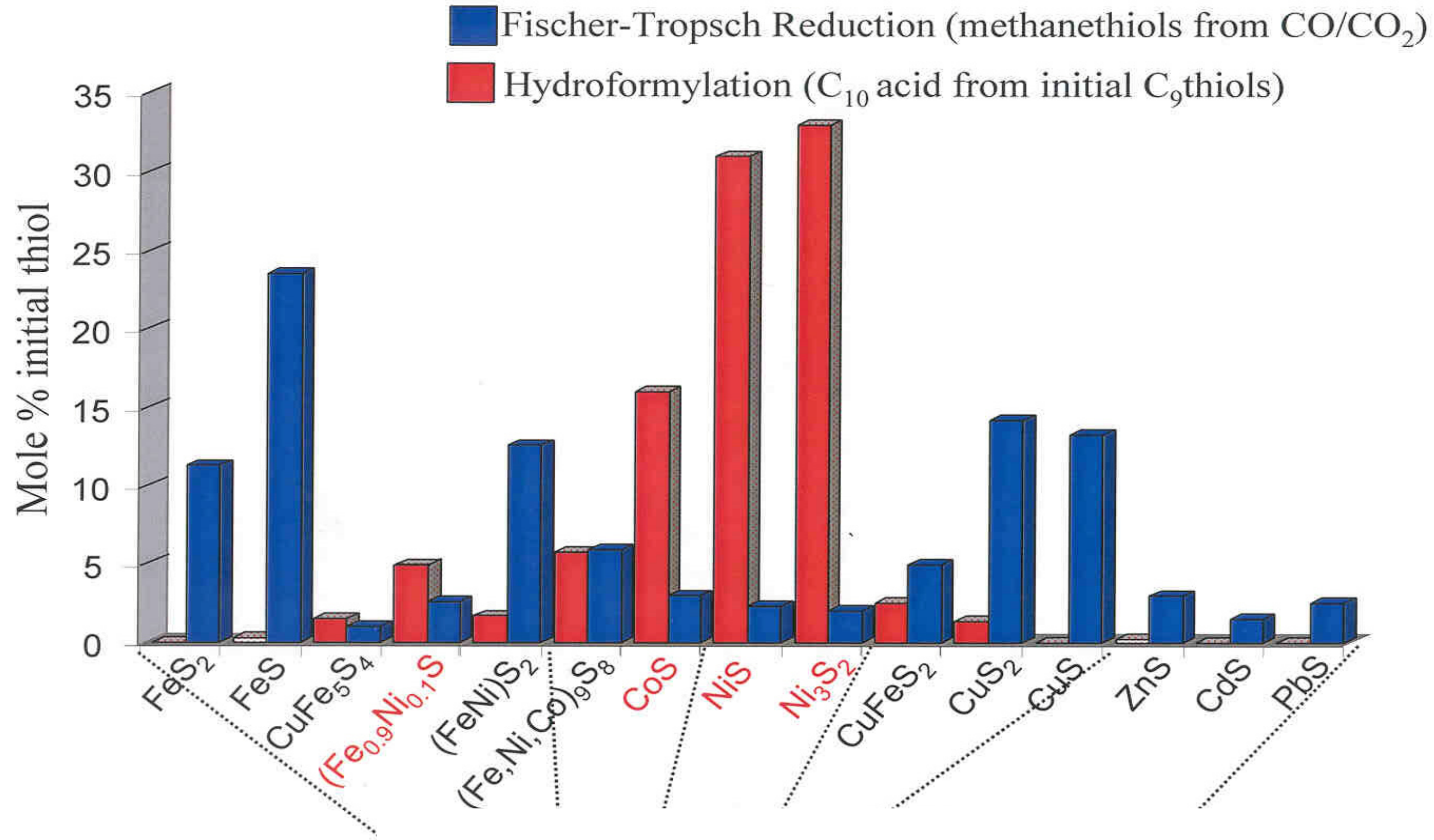
$CH_3\text{-}\overset{\displaystyle O}{\overset{||}{C}}\text{-}\overset{\displaystyle O}{\overset{||}{C}}\text{-}OH\ (\text{-}SR)$

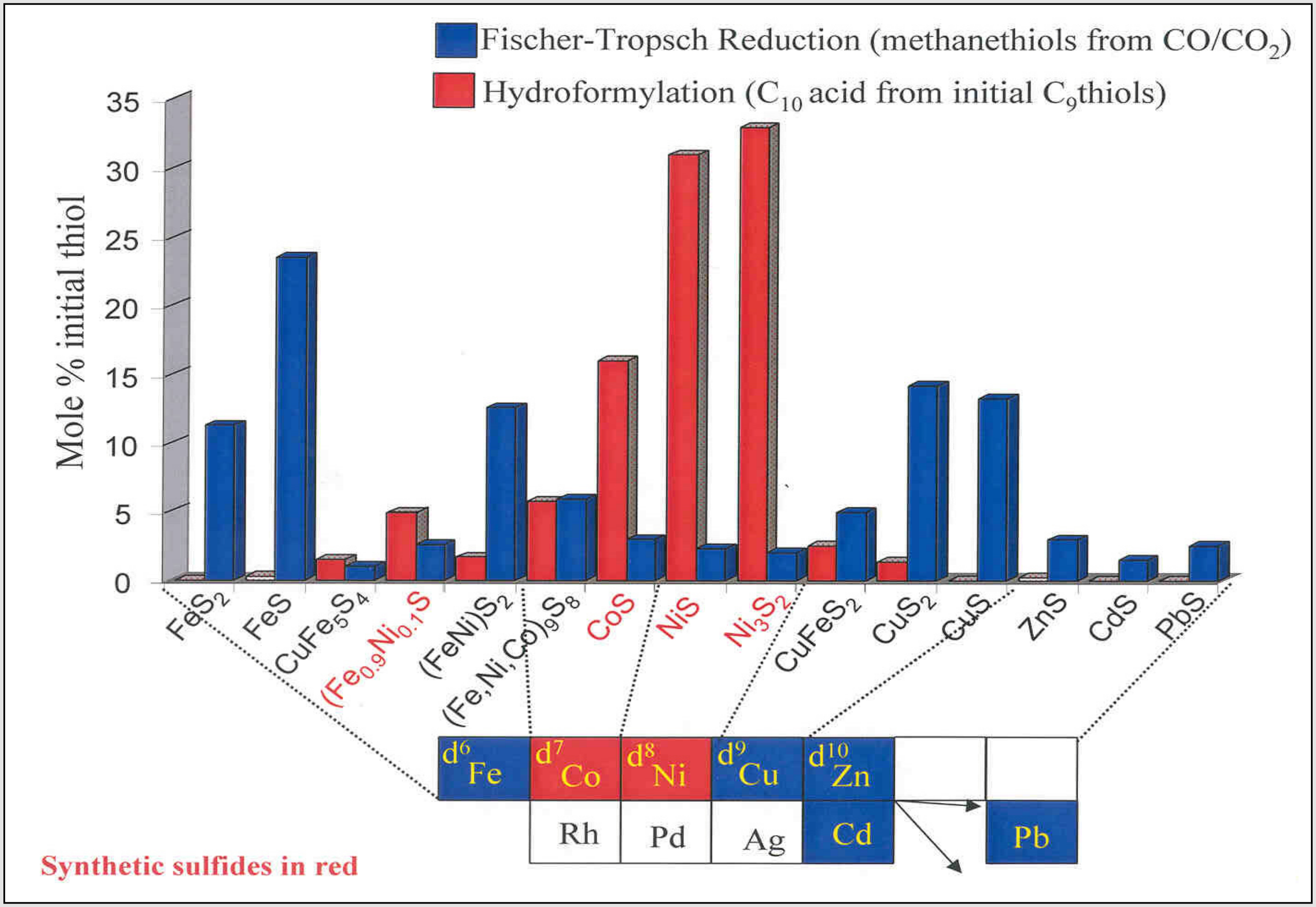
Reductive
TCA Cycle

Mineral Catalyzed Carbon-Addition Reactions



Synthetic sulfides in red

Mineral Catalyzed Carbon-Addition Reactions



Synthetic sulfides in red

STEP 1: CONCLUSIONS

The prebiotic synthesis of biomolecules occurred with relative ease.

Minerals played key roles.

STEP 2:

The Emergence of Organized Molecular Systems

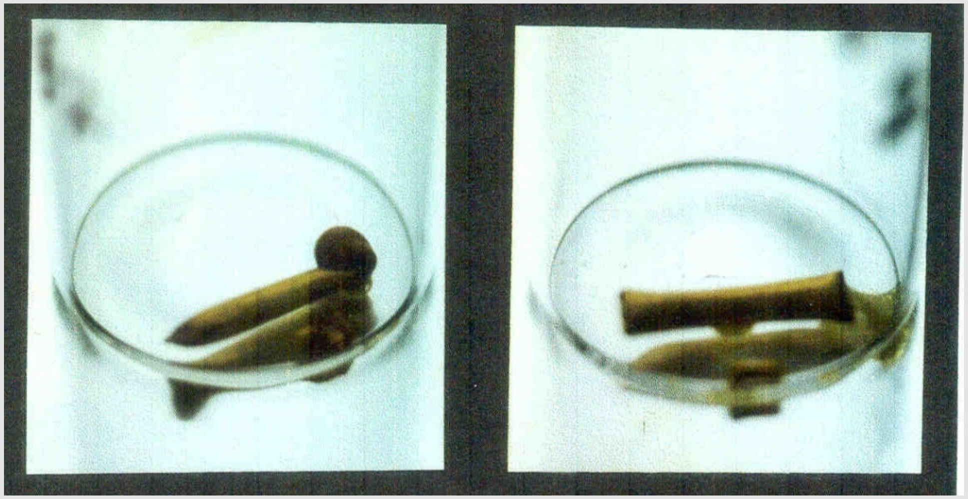
Prebiotic synthesis processes are facile but indiscriminate.

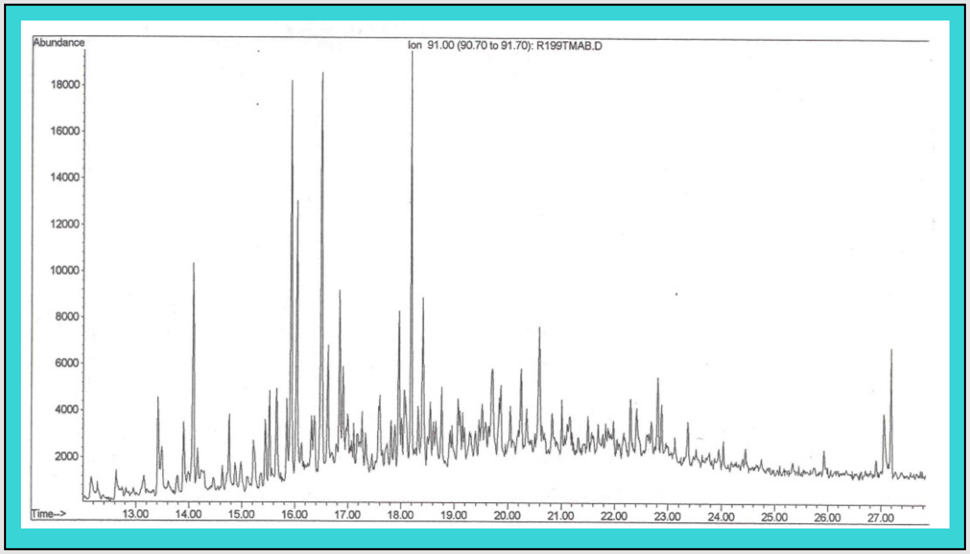
Yet a fundamental attribute of life is a high degree of molecular selectivity and organization.

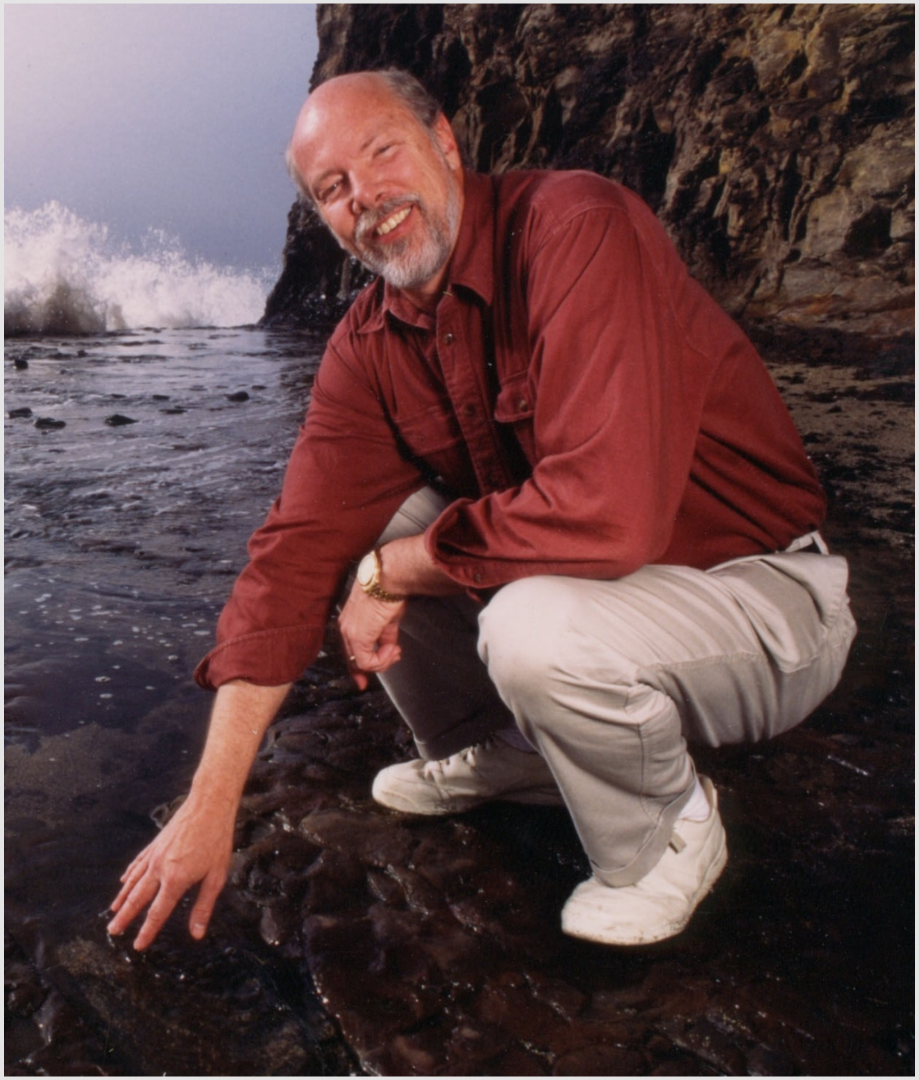
What prebiotic processes might have contributed to such selection and organization?

Self-Organization

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



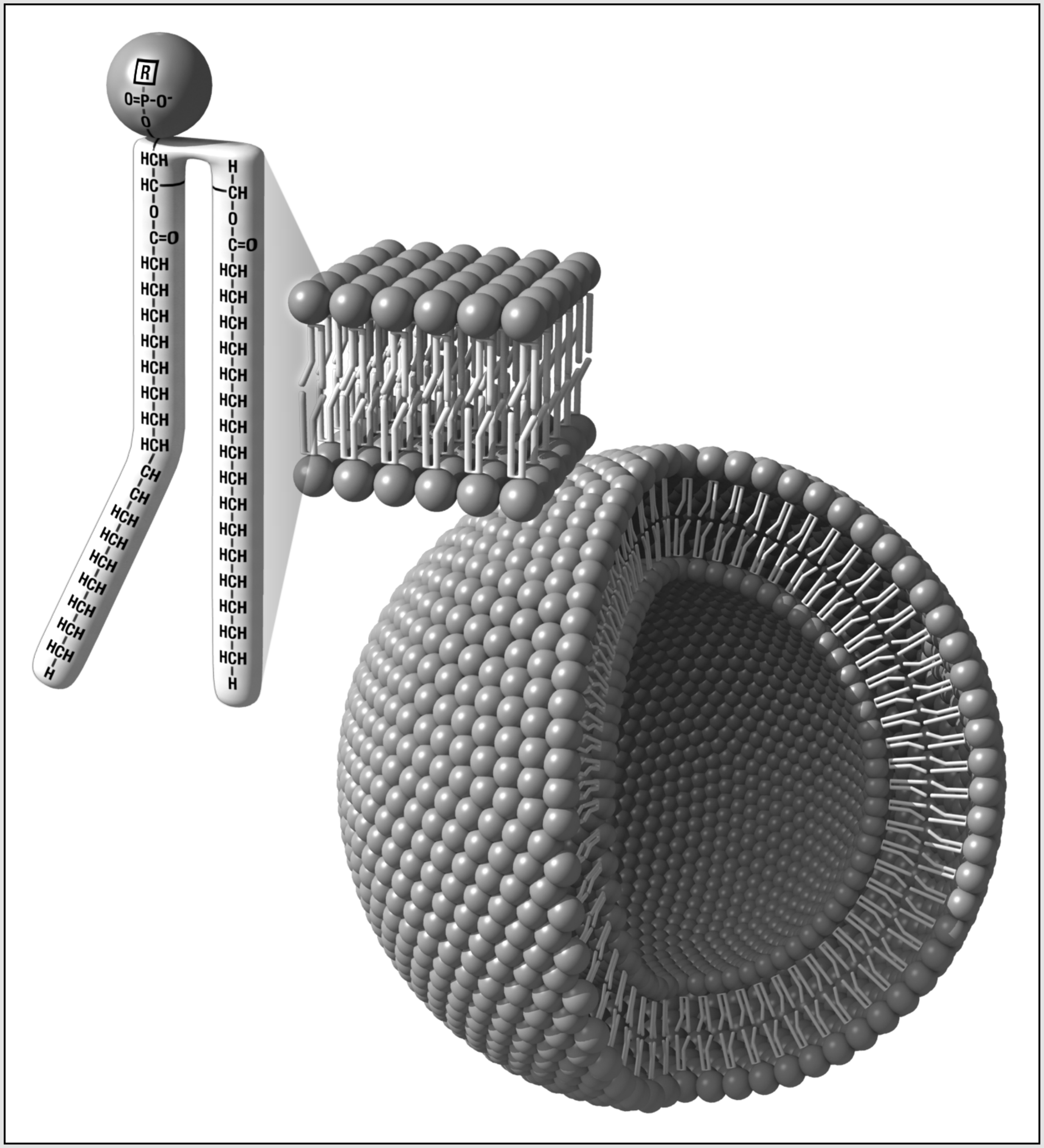


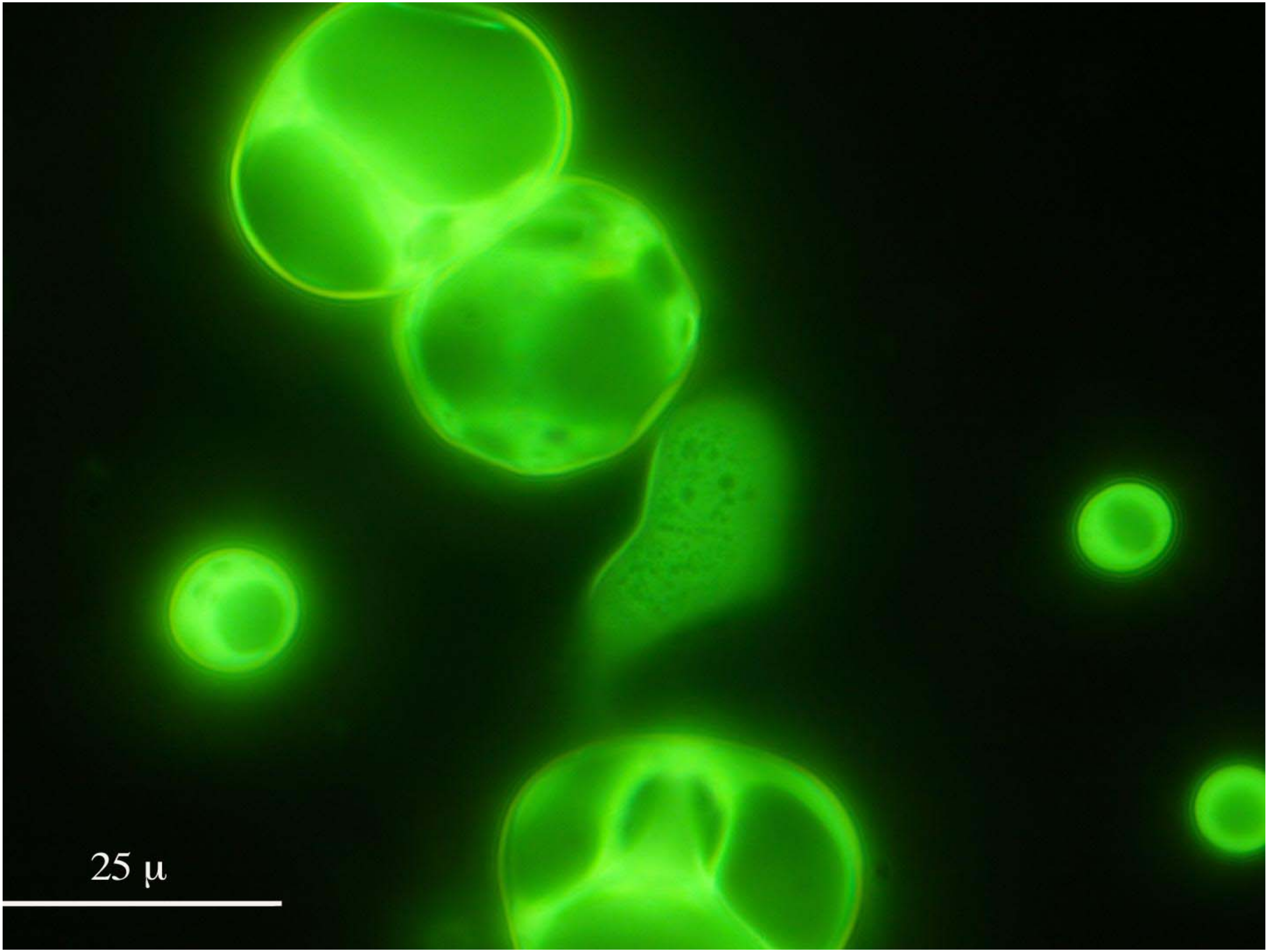


David Deamer

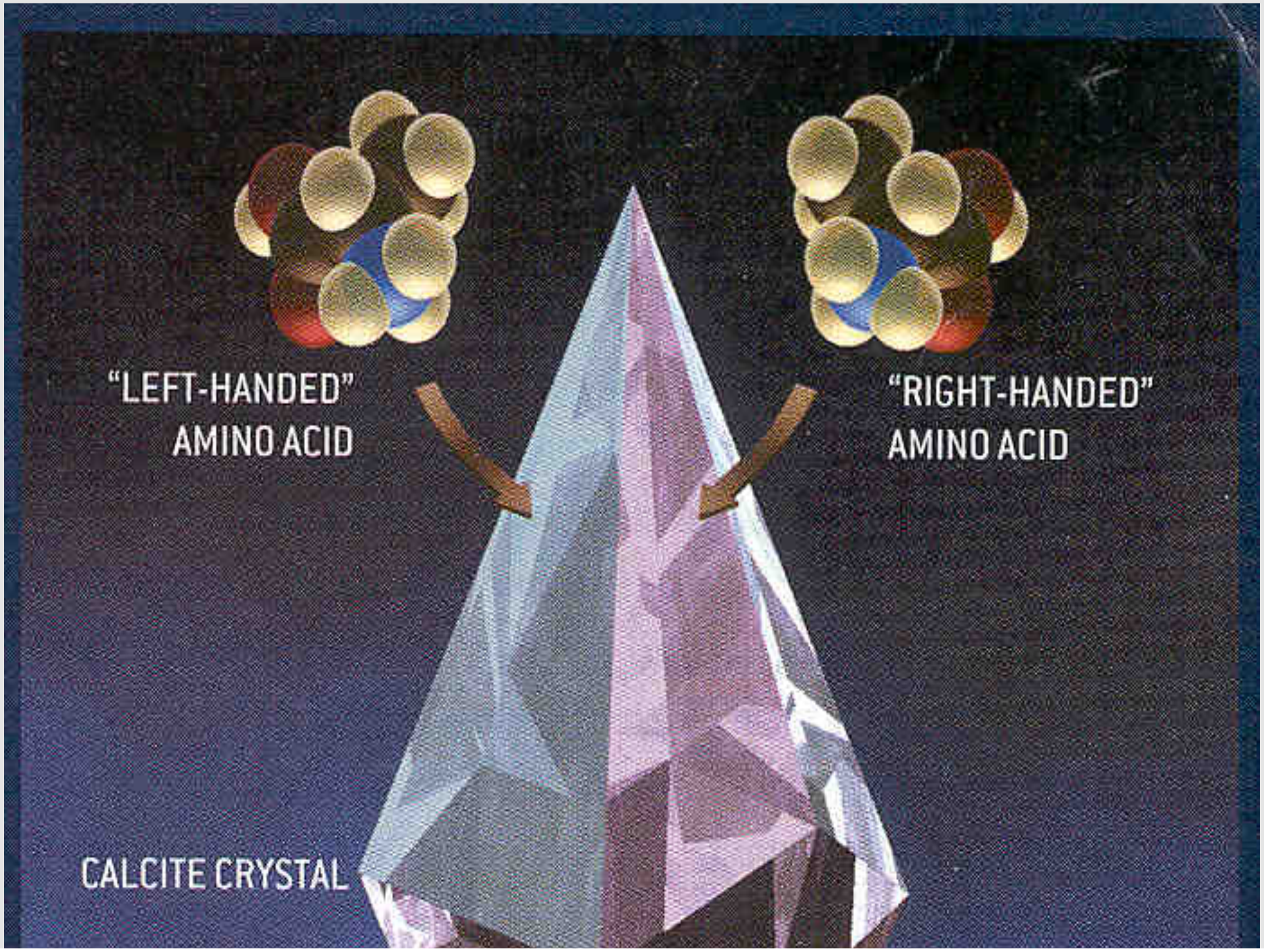
Marilyn Fogel

Self-Assembling Amphiphile Molecules




25 µ

Selection on Mineral Surfaces



Mineral surfaces select and concentrate small molecules

Biological Homochirality

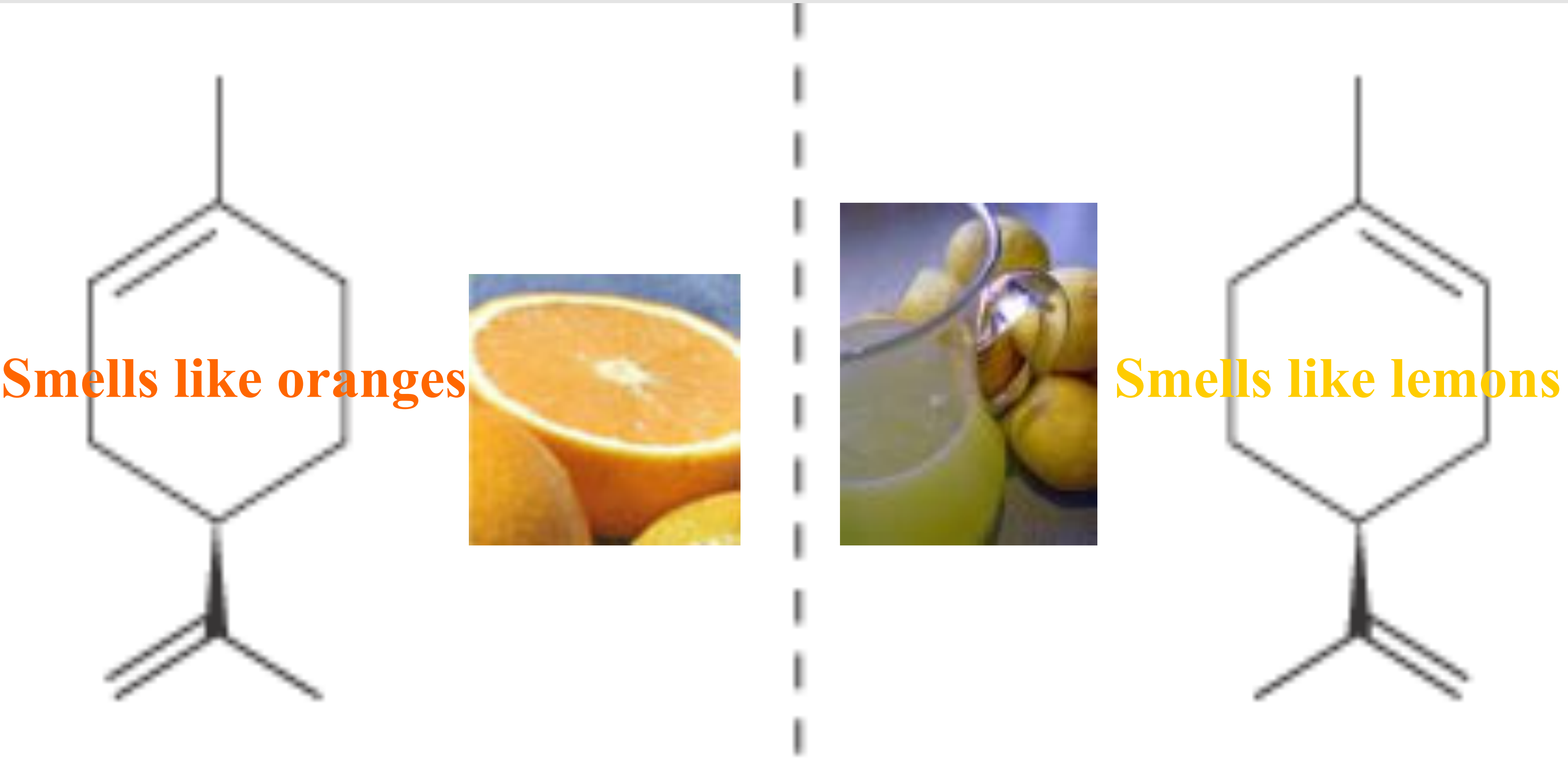
The most challenging aspect of molecular selection is handedness

(L)-enantiomer (R)-enantiomer

How did life on Earth become homochiral?

Annual sales of chiral pharmaceuticals approaches $200 billion.

Chiral Purity is Important



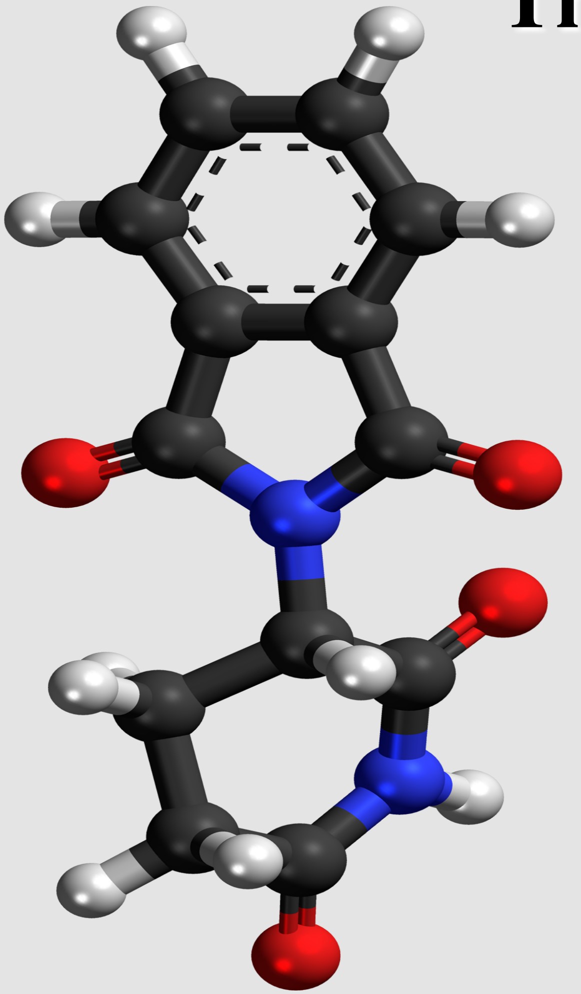
Smells like oranges

Smells like lemons

R-Limonene **Mirror** **L-Limonene**

Chiral Purity is Important

Thalidomide

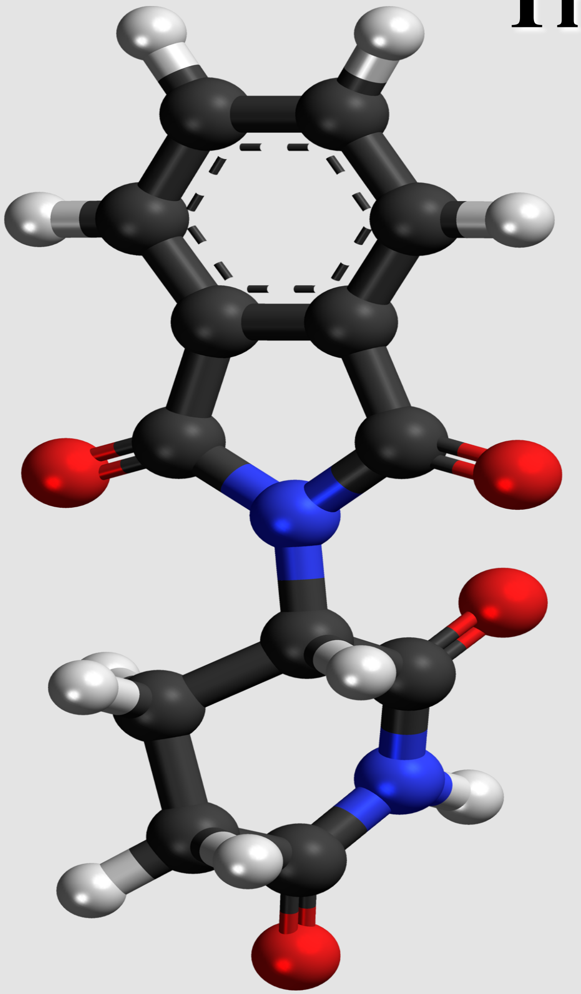


R-enantiomer

Analgesic (Good)

Chiral Purity is Important

Thalidomide



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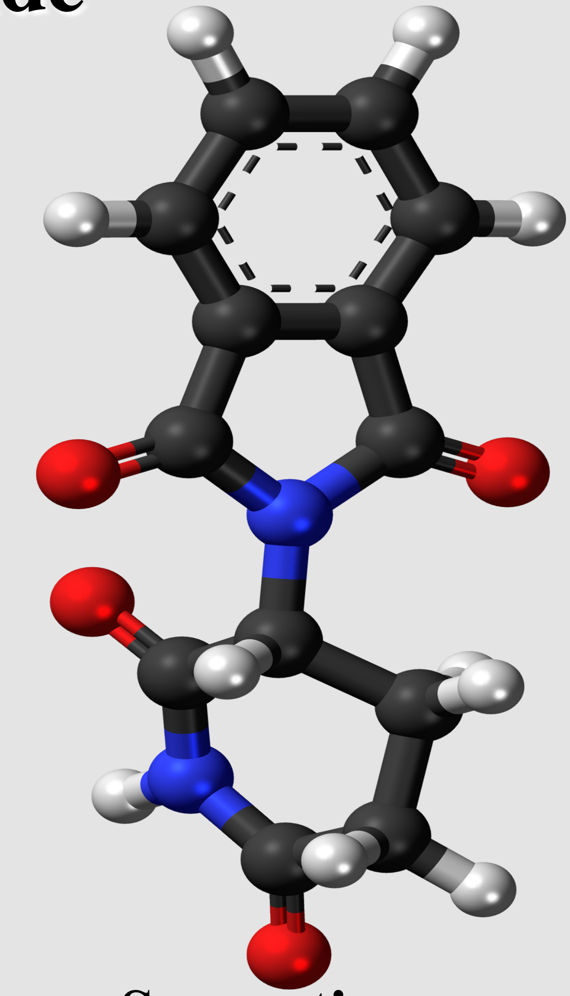


S-enantiomer

Teratogen (Bad)

Prebiotic Chiral Selection

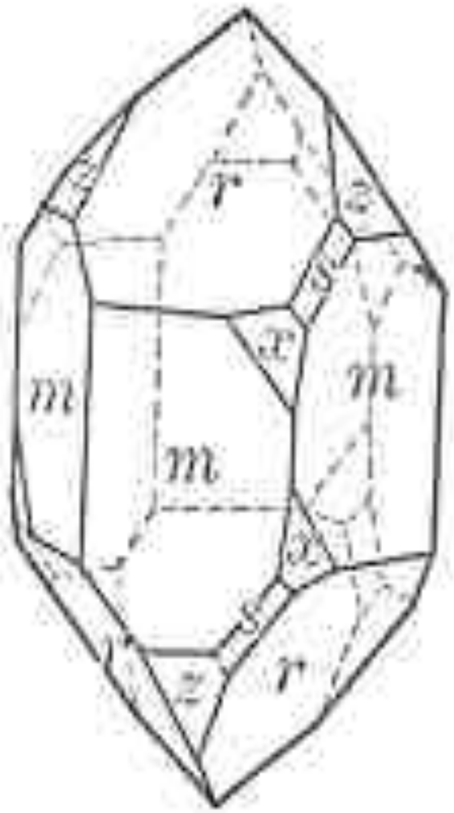
- Prebiotic synthesis processes produce mixtures of left and right molecules.

- But life demonstrates a remarkable degree of chiral selectivity.

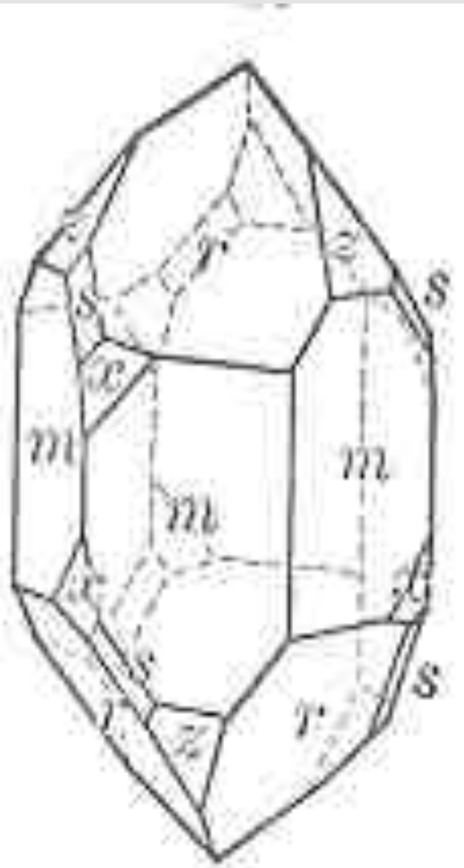
What is the mechanism of symmetry breaking?

Quartz – SiO_2

Quartz is the only common chiral rock-forming mineral

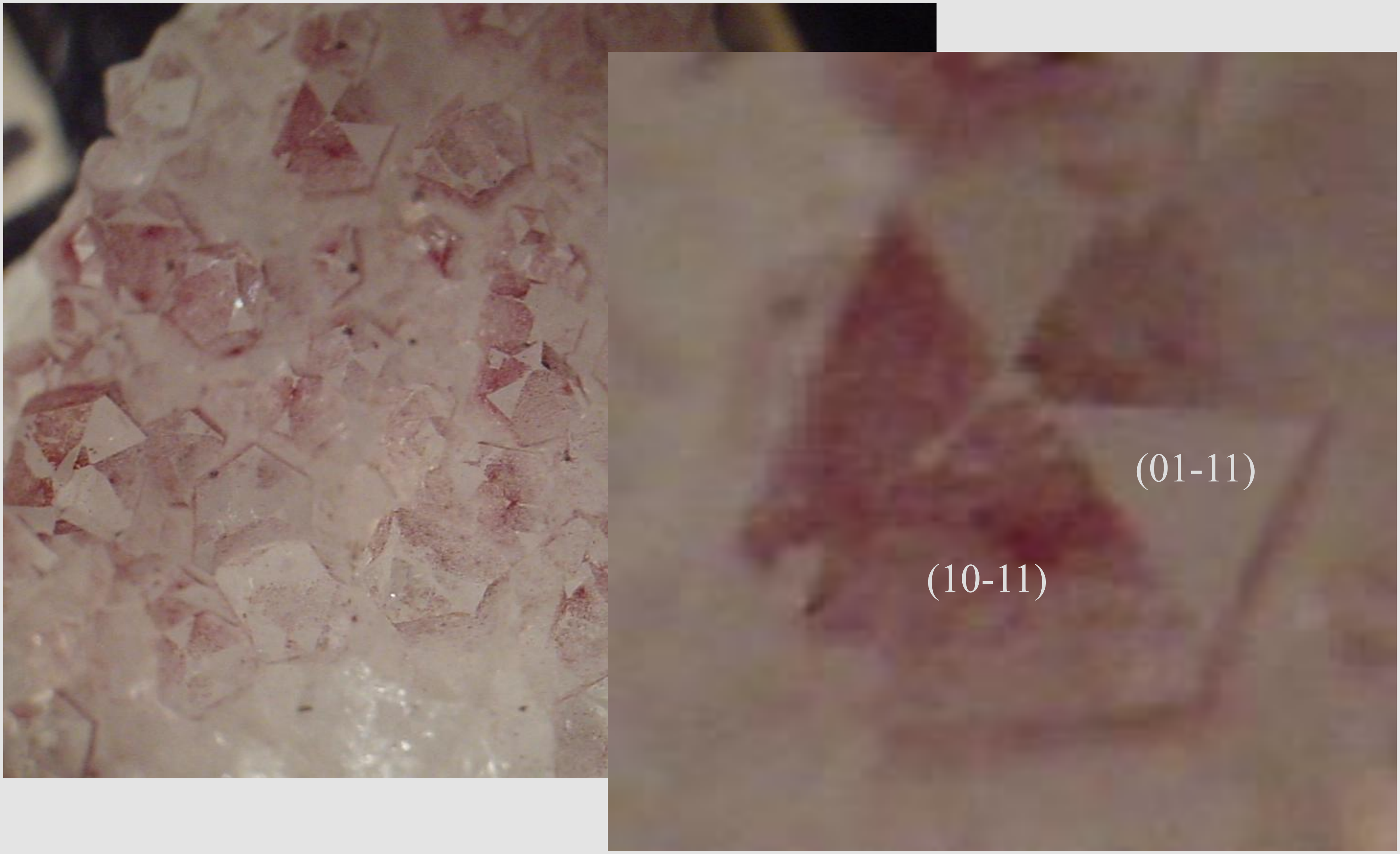


Right

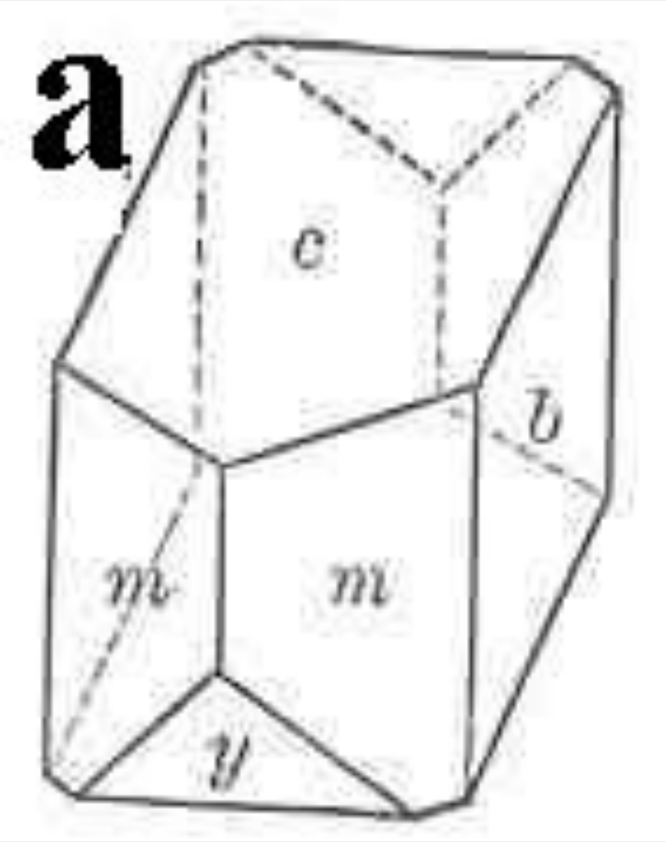


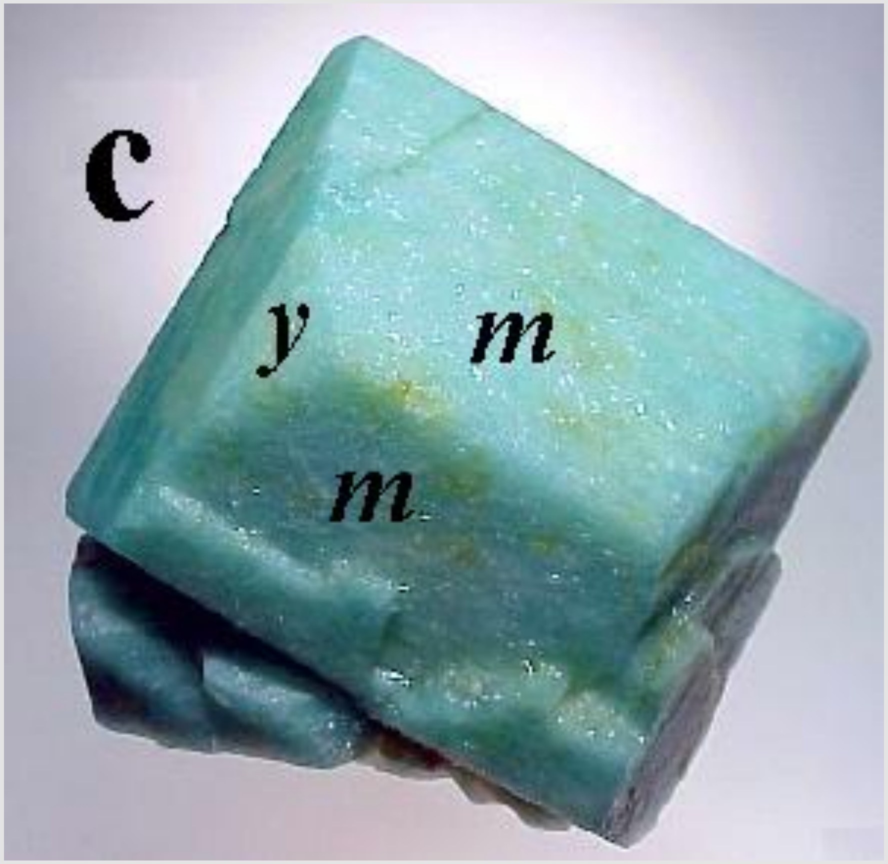
Left

Quartz: Face-Specific Adsorption

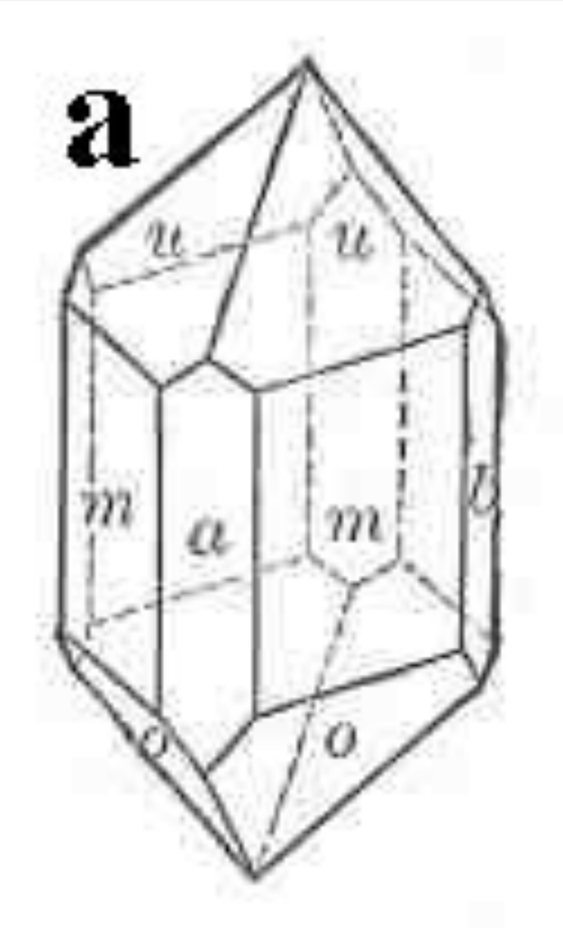


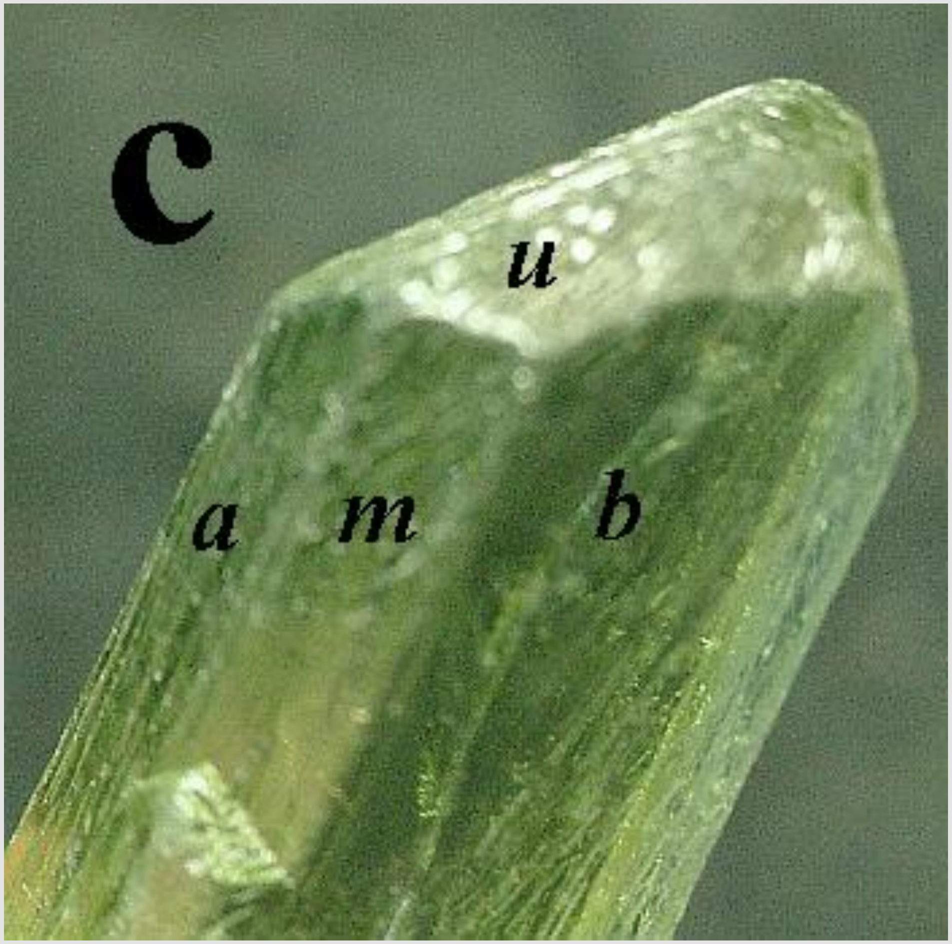
Feldspar (110)



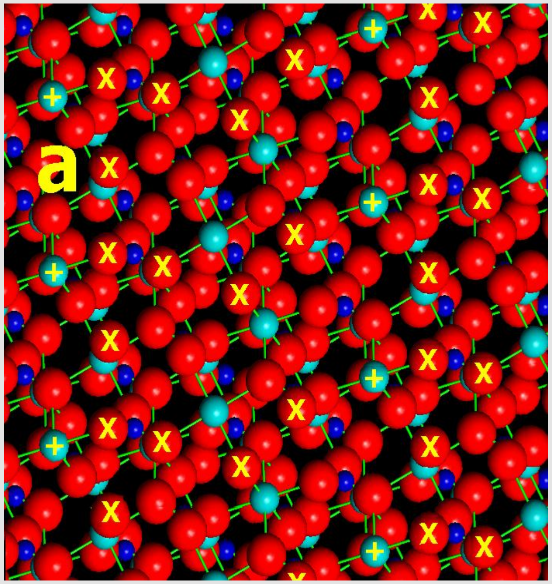


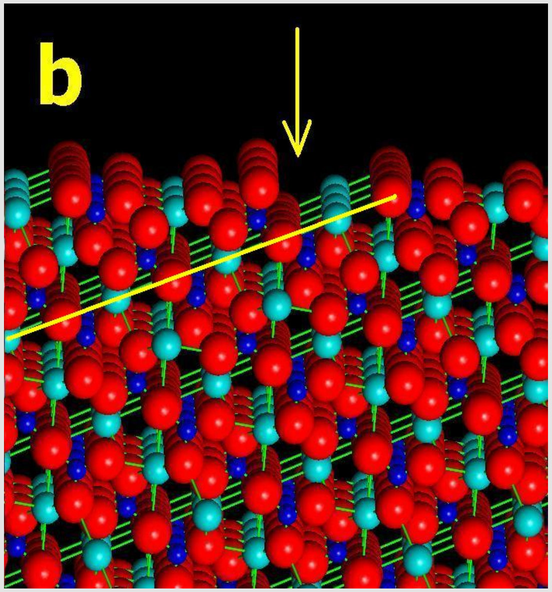
Diopside – (110) Face

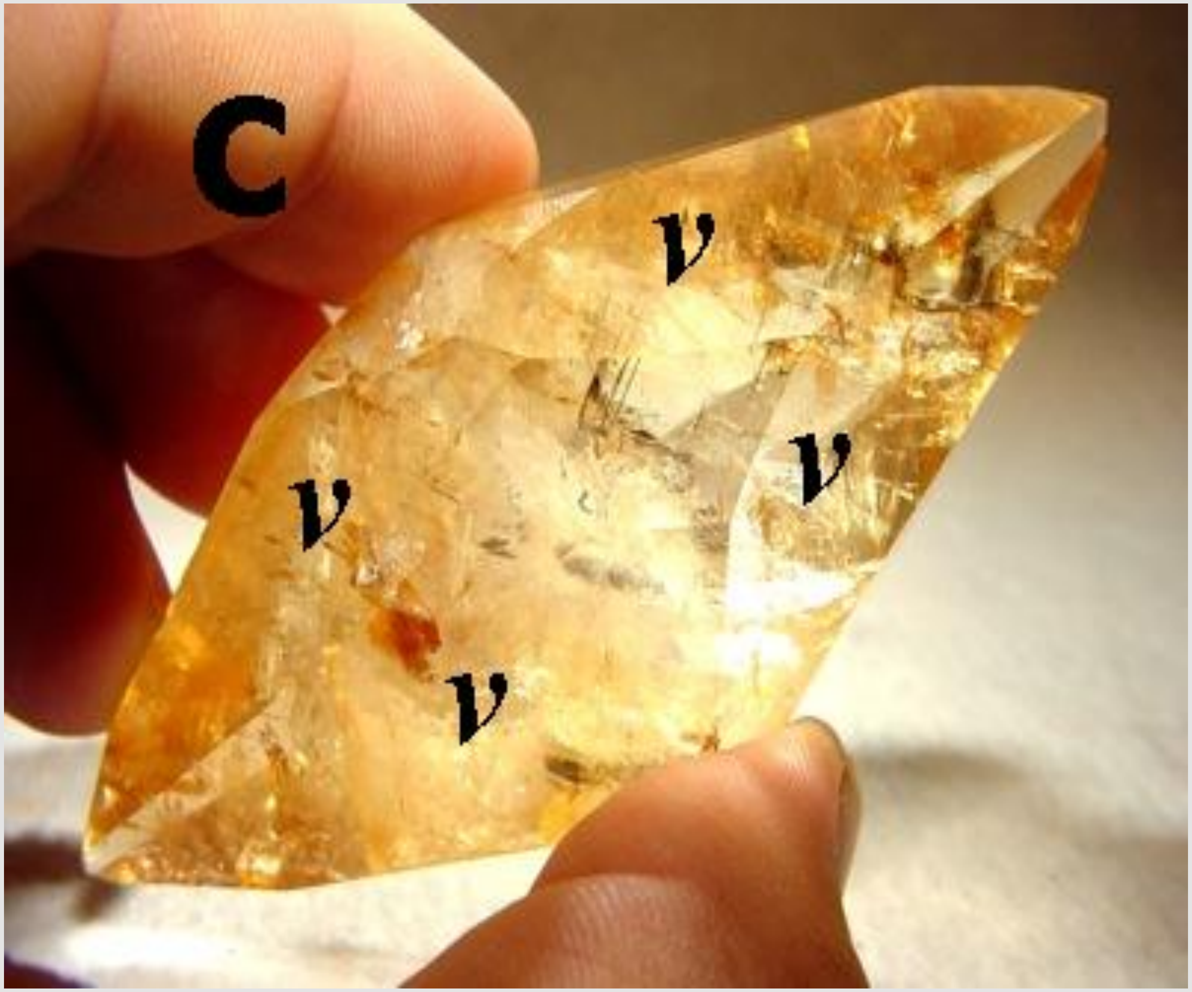




Calcite (214) Faces



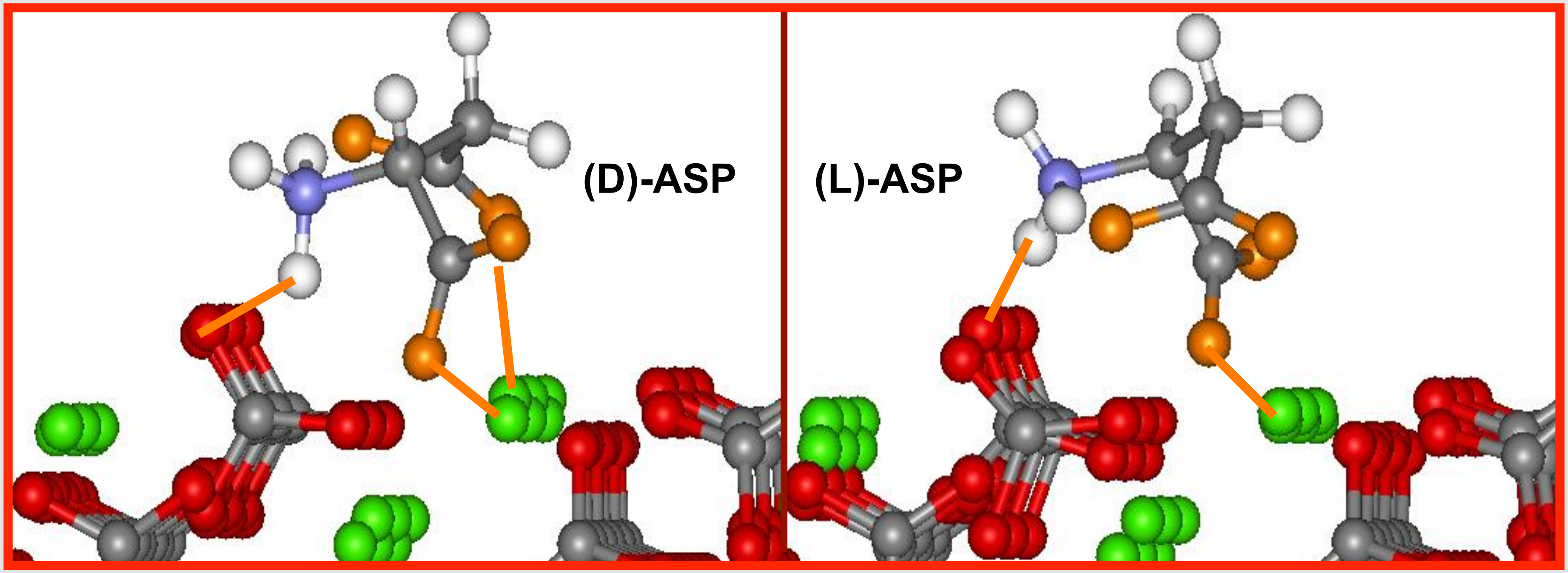




Minerals and Chiral Selection

Mineral surfaces select chiral amino acids

Aspartic Acid-Calcite (214) Interactions

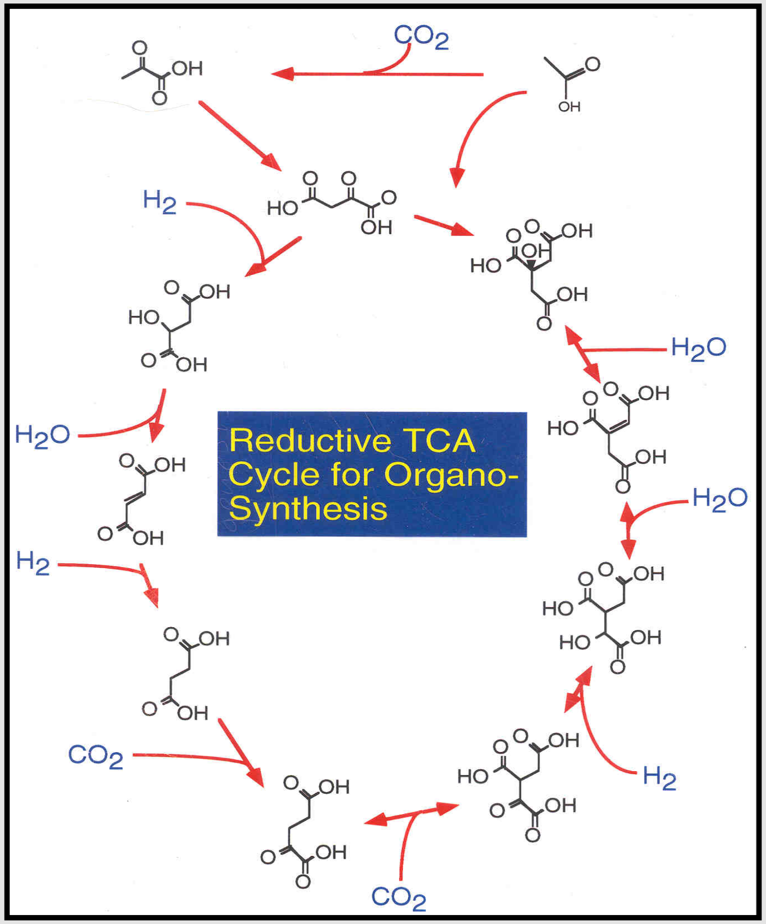


The most stable configuration found for D- and L-aspartic acid on calcite (214) surface. The D enantiomer is favored by 8 Kcal/mol.

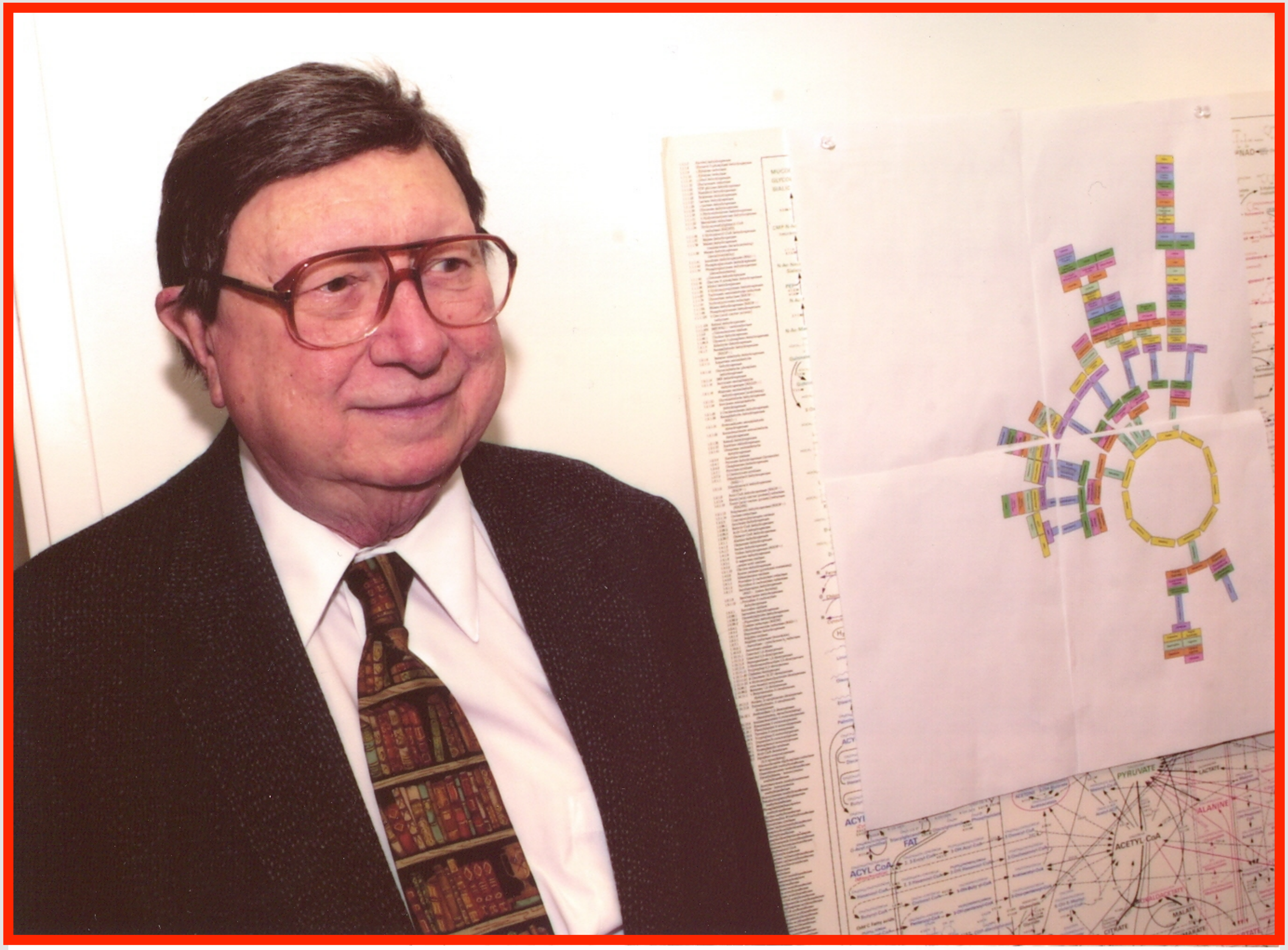
STEP 2:
CONCLUSIONS

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

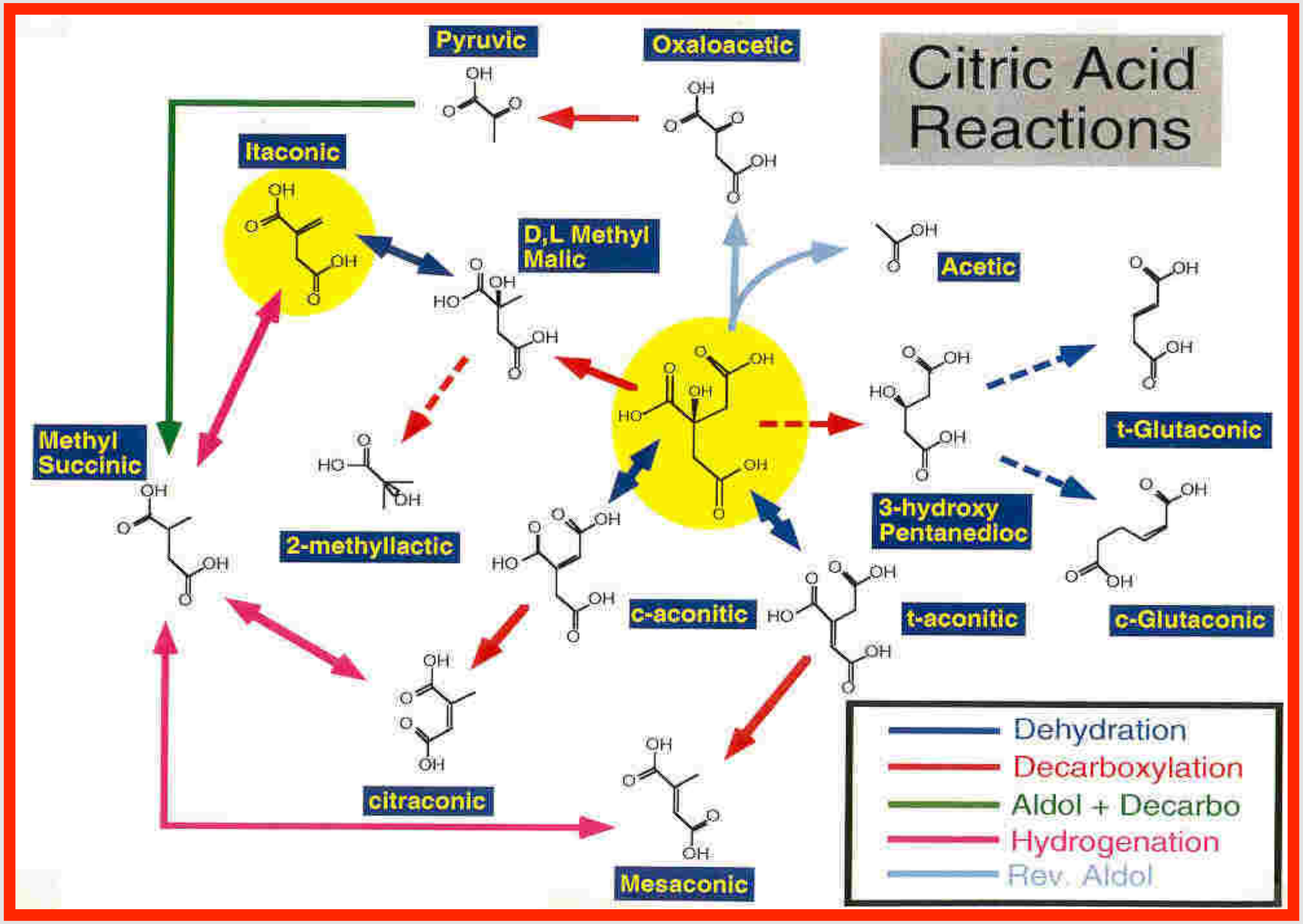


The abiotic synthesis of such a “metabolic” cycle represents a “Holy Grail” for our experimental program.

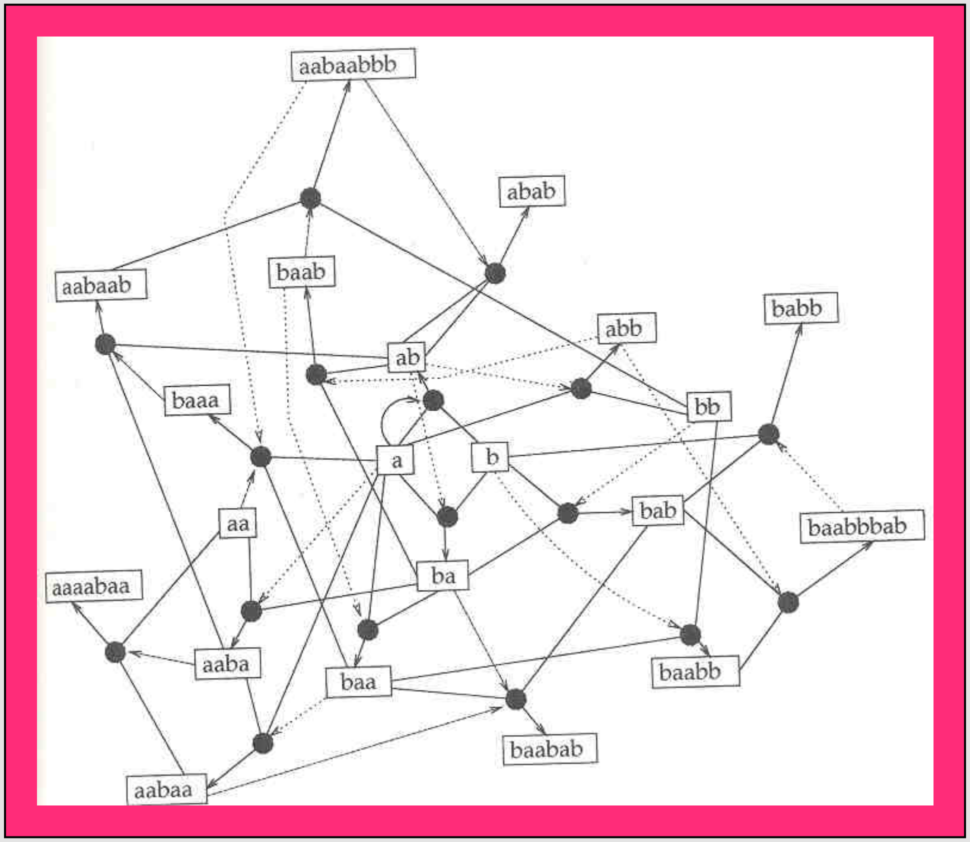


Harold J. Morowitz

The Emergence of Self-Replicating Molecular Cycles



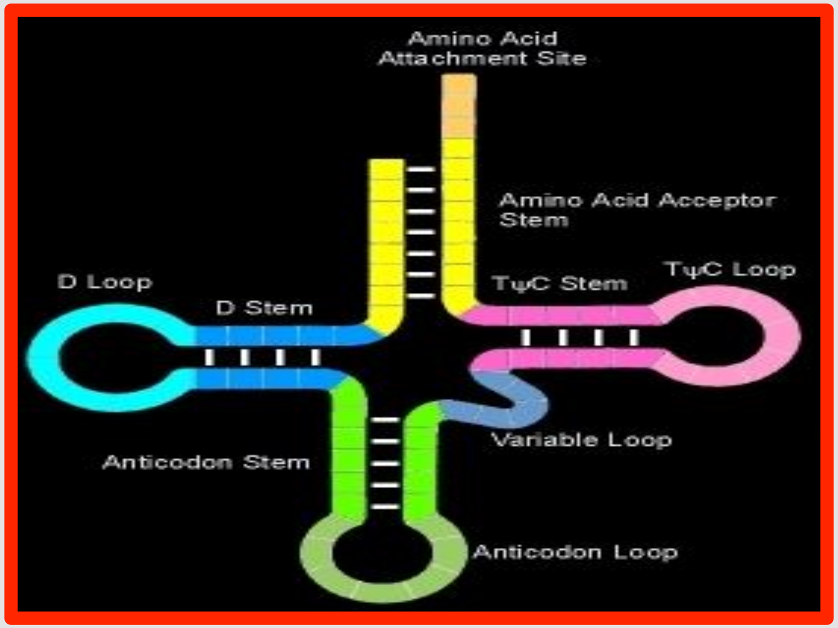
The Emergence of Self-Replicating Molecular Cycles



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?

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.

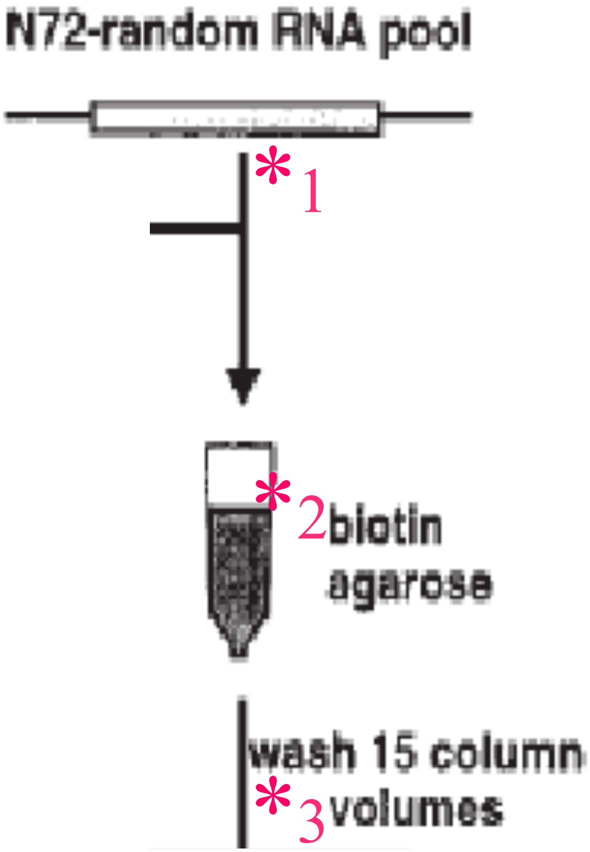
In such a system, competition and natural selection appear to be inevitable.

Molecular evolution has been demonstrated in the laboratory!

Jack Szostak, Harvard University
Experiments in Molecular Evolution

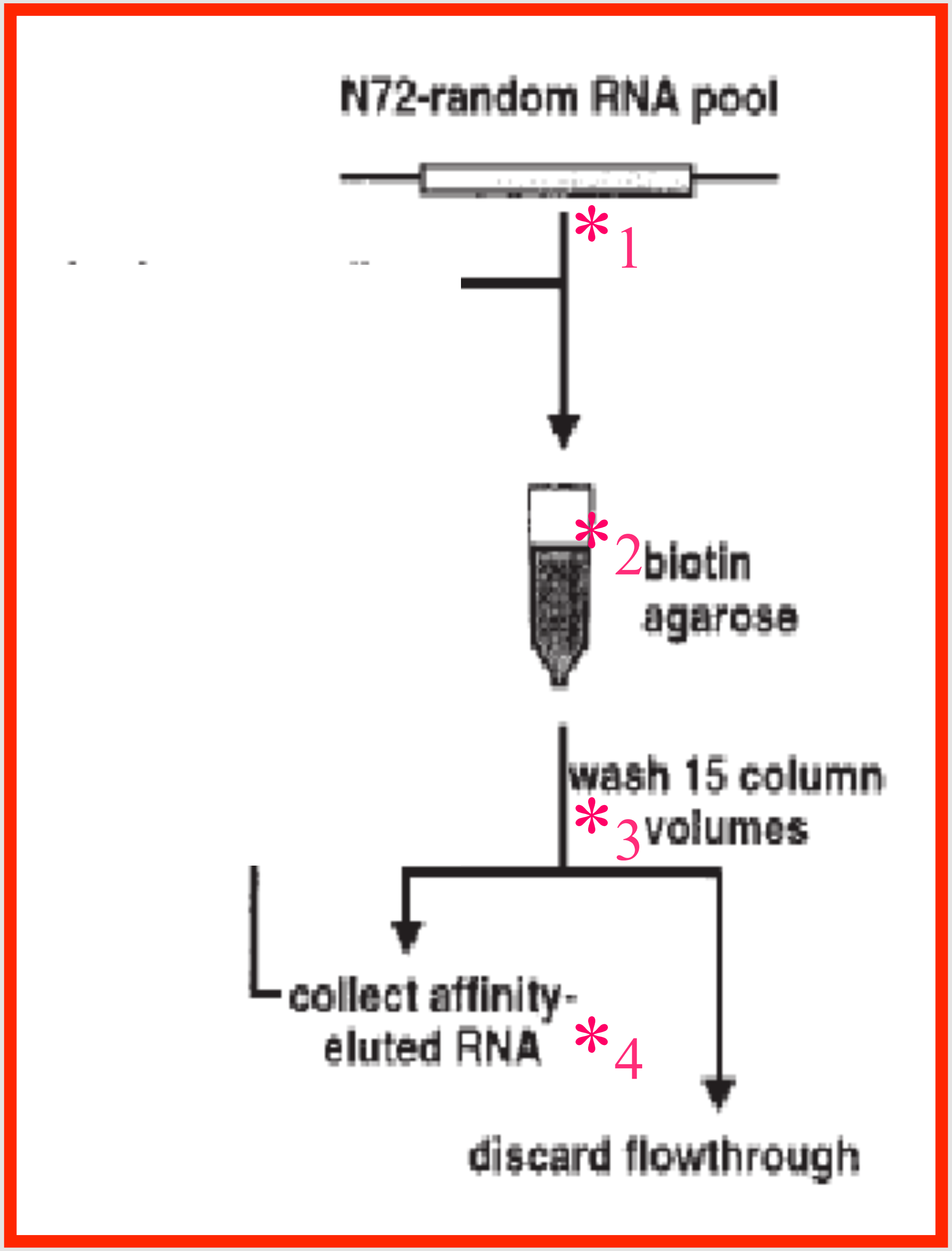
Szostak Lab: Aptamer Evolution

1. Random RNA pool



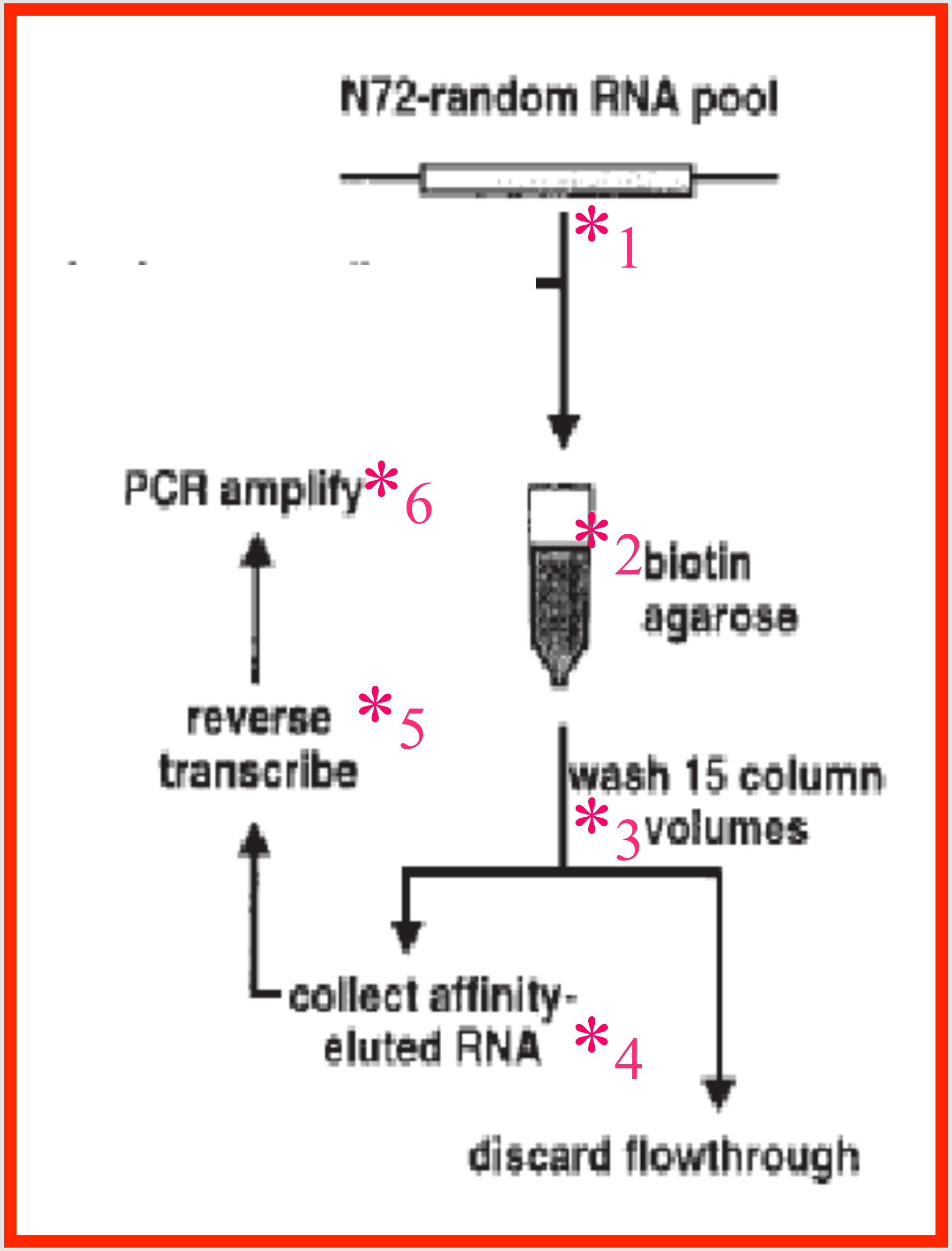
Szostak Lab: Aptamer Evolution

1. Random RNA pool
2. In vitro process
3. Remove nonbinding strands



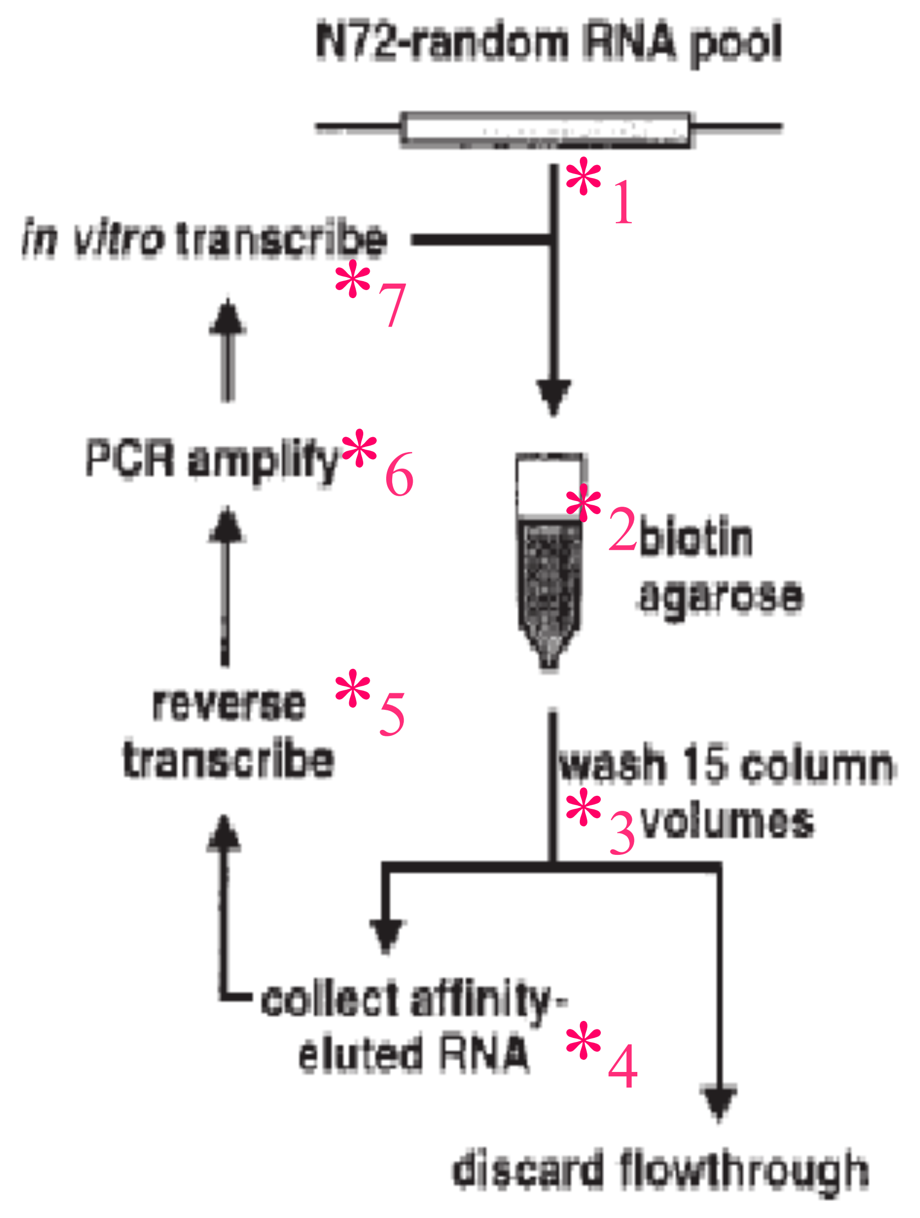
Szostak Lab: Aptamer Evolution

1. Random RNA pool
2. In vitro process
3. Remove nonbinding strands
4. Collect bound RNA



Szostak Lab: Aptamer Evolution

1. Random RNA pool
2. In vitro process
3. Remove nonbinding strands
4. Collect bound RNA
5. Reverse transcriptase
6. PCR amplify with errors

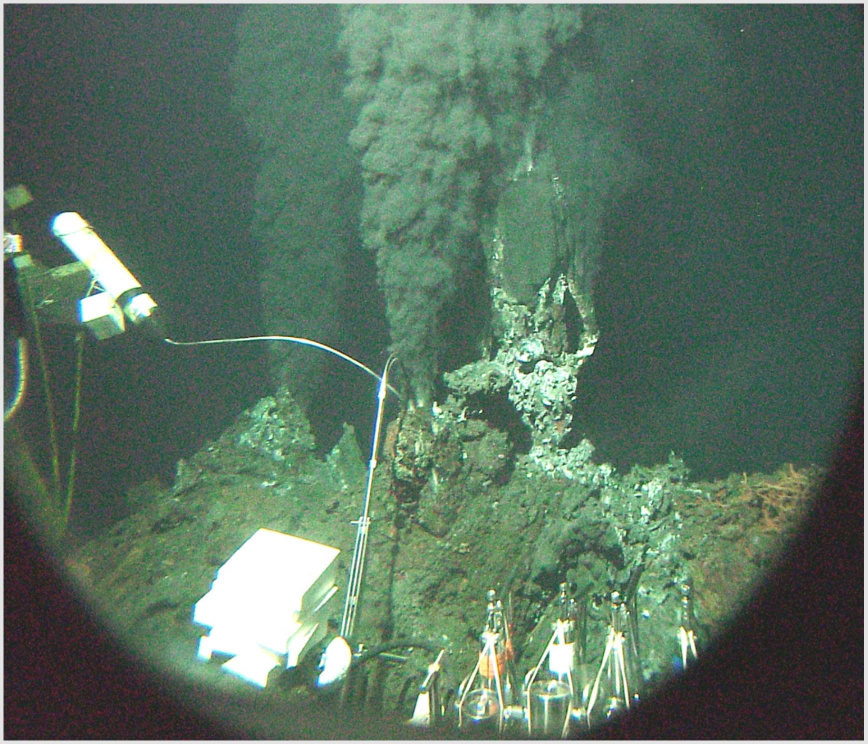


Szostak Lab:
Aptamer Evolution

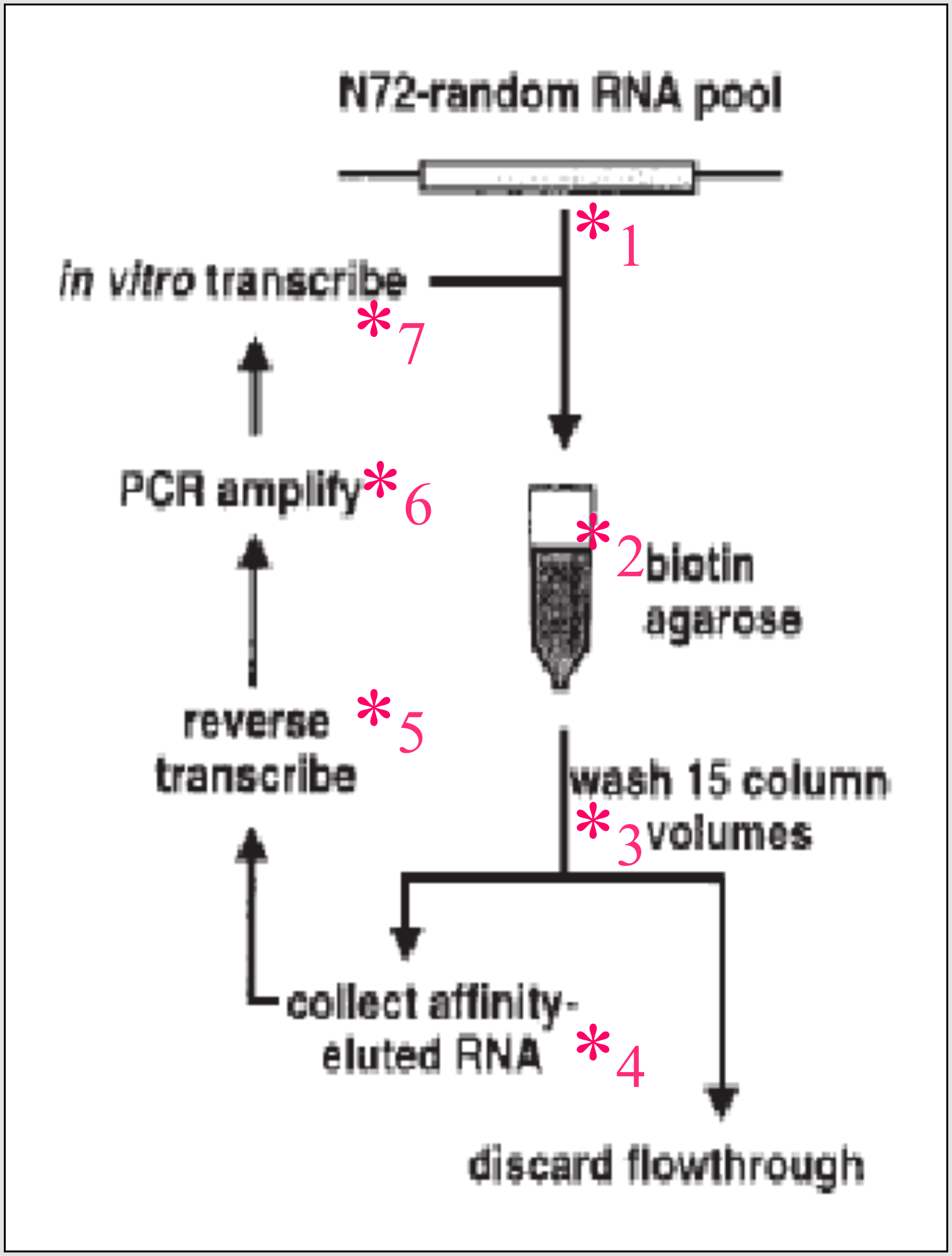
1. **Random RNA pool**
2. **In vitro process**
3. **Remove nonbinding strands**
4. **Collect bound RNA**
5. **Reverse transcriptase**
6. **PCR amplify with errors**
7. **Transcribe DNA to new RNA strands**
8. **Repeat 1 thru 7**

Key Conclusion: Life cannot evolve in a static environment

Geochemical complexities are key to understanding life's origins:



- Gradients
- Cycles
- Fluxes
- Interfaces
- Chemical complexity



Aptamer Evolution

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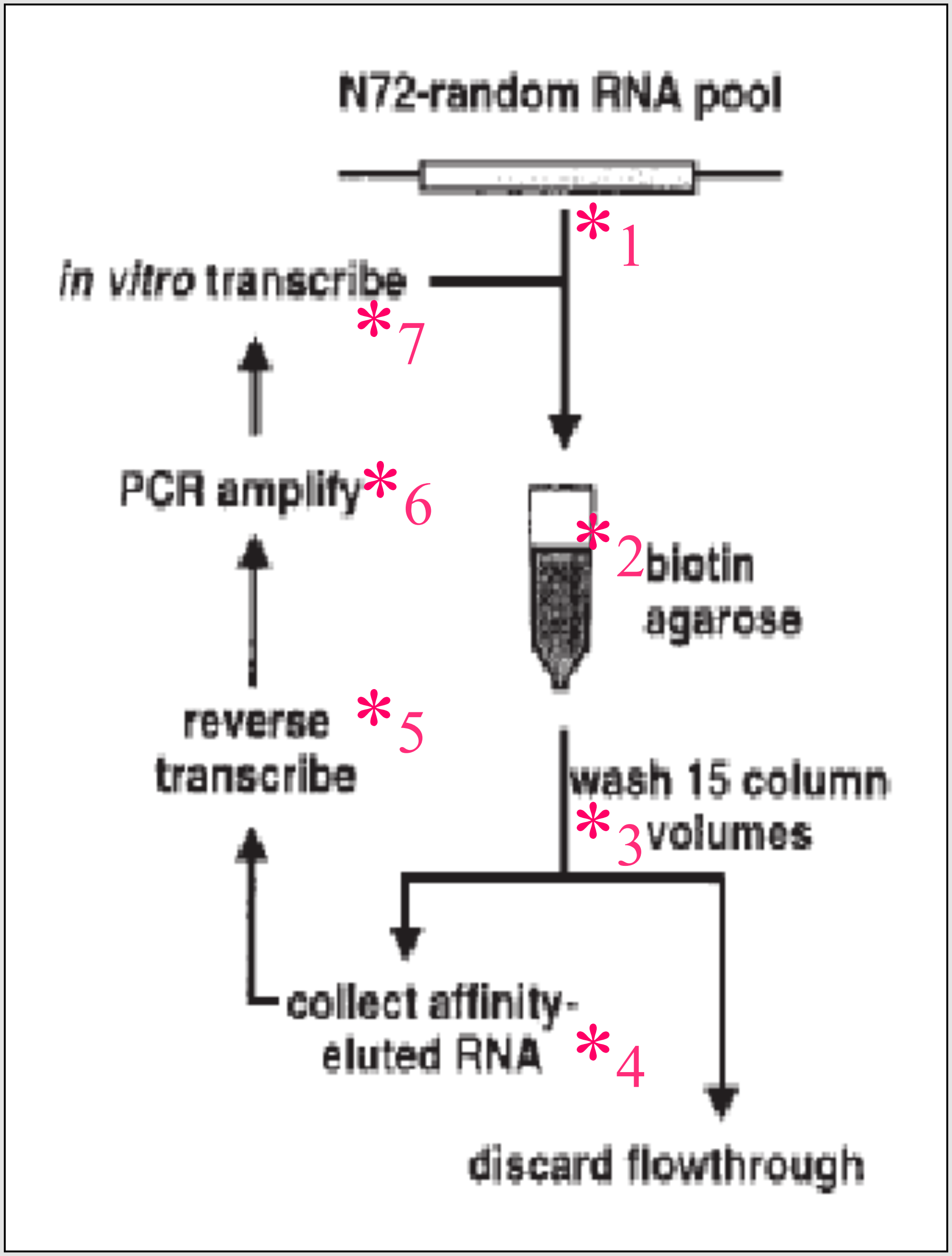

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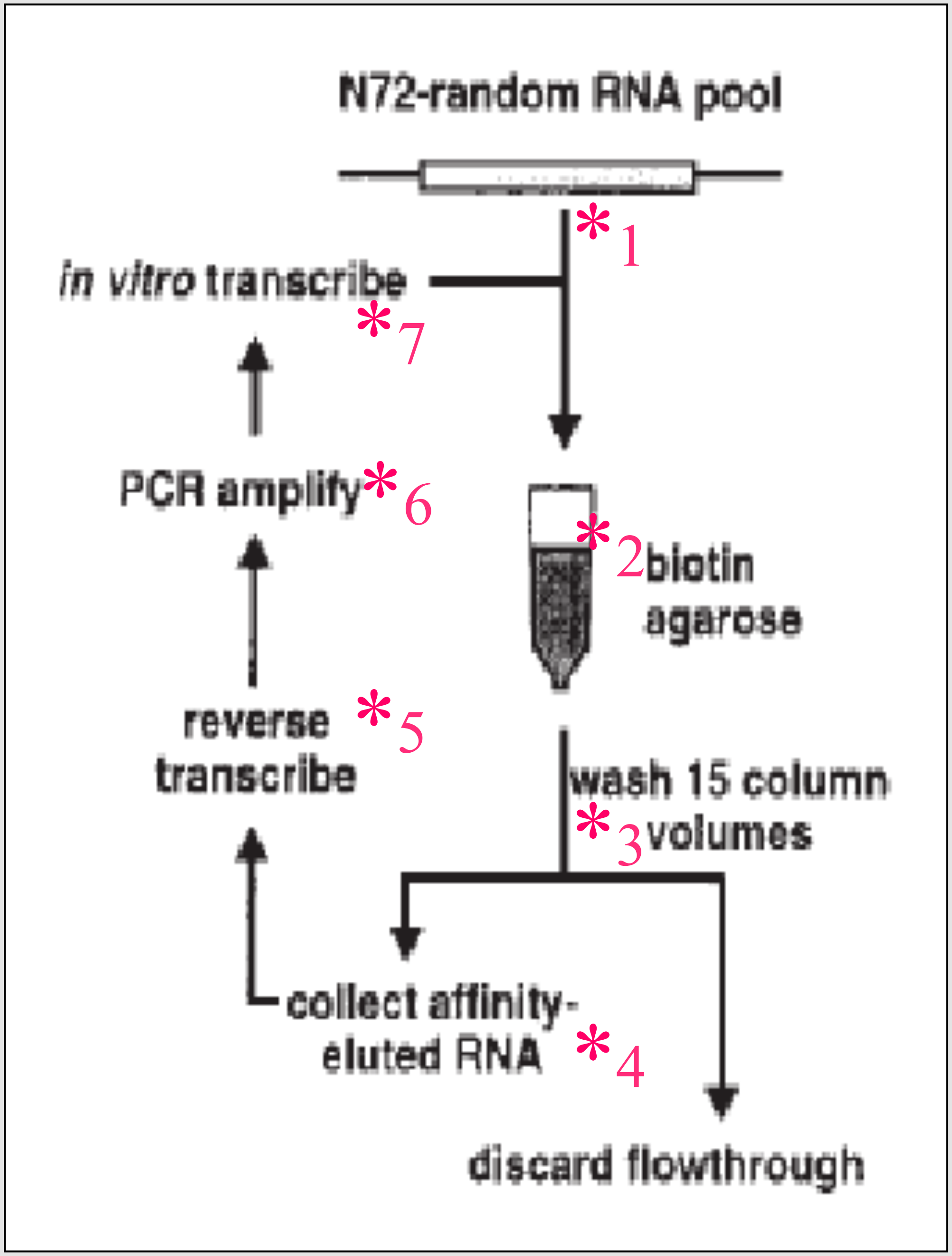

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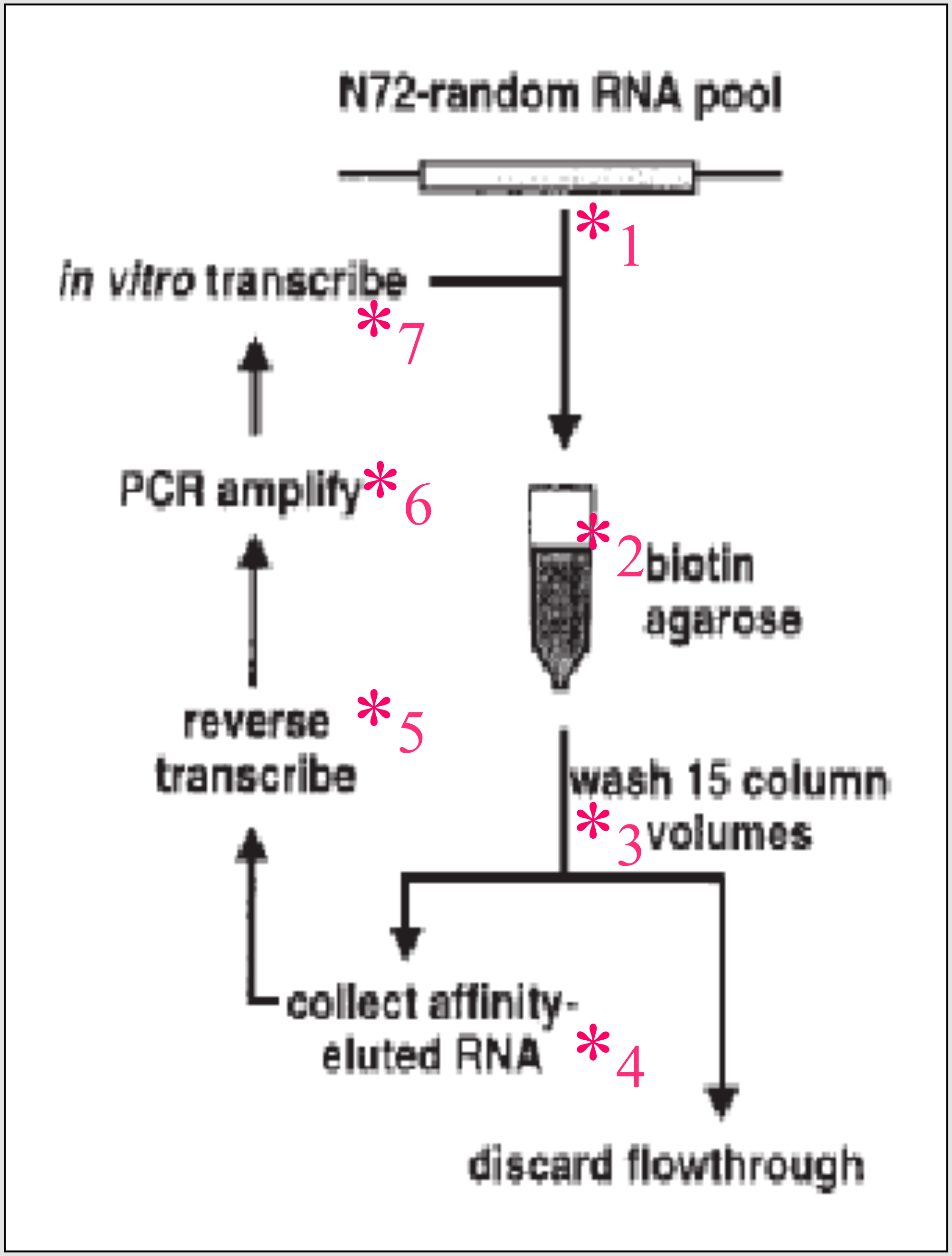

Aptamer Evolution

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Life’s Origins: Four Steps

1. Synthesis of biomolecules

2. Biomolecular selection

? ? ↓ ? ?

3. Self-replicating molecular systems

4. Molecular natural selection

Hazen (2005) *Genesis.* Joseph Henry Press: Washington

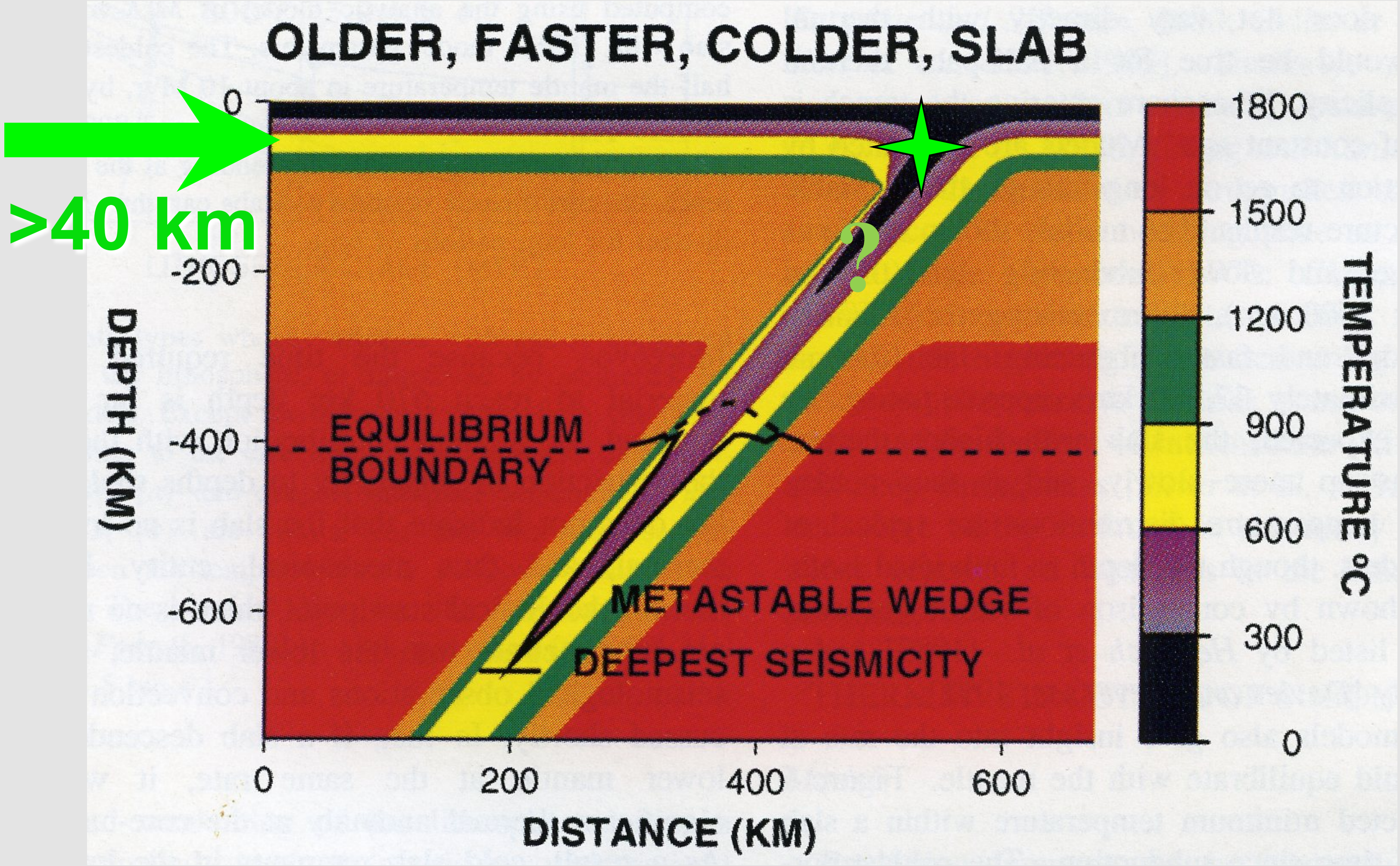
Something New: Another Approach

Is there a “shadow biosphere” that might point to an early domain of life?

New data from deep drilling hint at a new domain of life >150°C

©IODP/JAMSTEC

Deep "Ur-Life"



Is there a deep domain of "life" that does not rely on DNA and proteins?

For more information go to the Deep Carbon Observatory website:

http://deepcarbon.net

Deep Carbon Observatory

ALFRED P. SLOAN FOUNDATION
1934

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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.

Deep Carbon Observatory

NSF

NASA

With thanks to:

NASA Astrobiology Institute
National Science Foundation
Alfred P. Sloan Foundation
Carnegie Institution, Geophysical Lab

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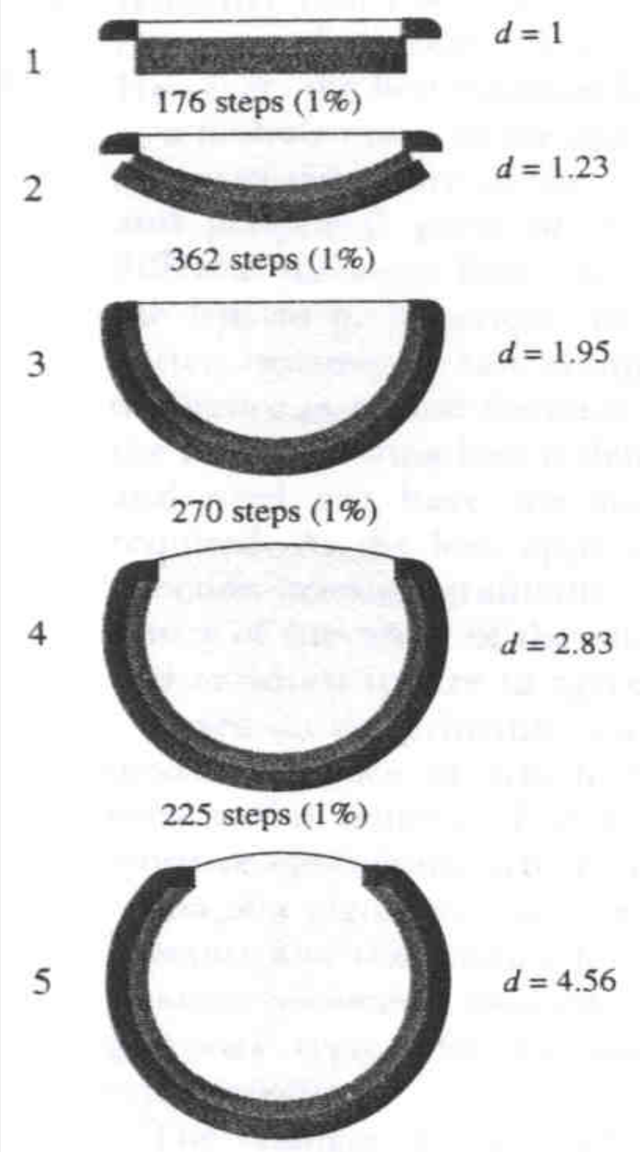
Feedback: Eye Evolution

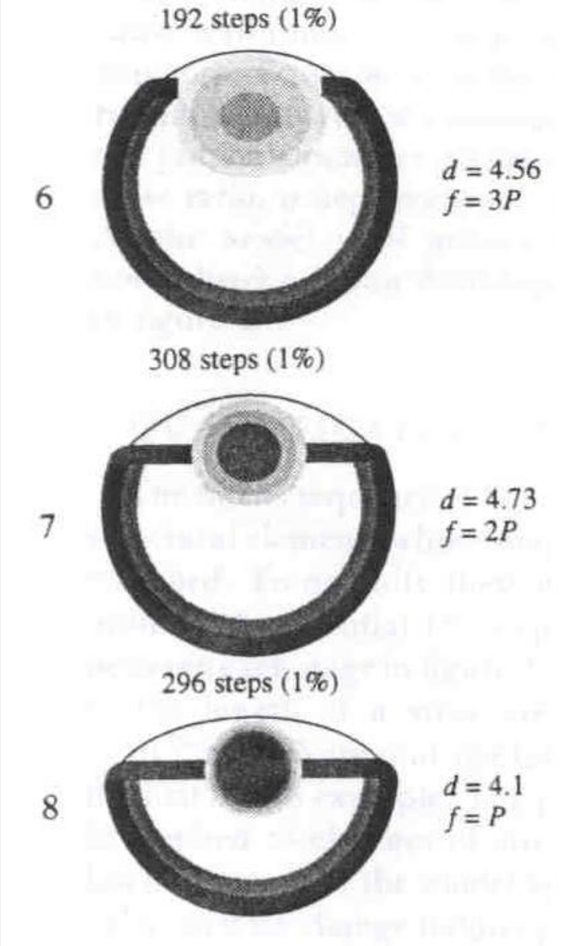
D. Nilsson & S. Pelger, "A pessimistic estimate for the time required for an eye to evolve." *Proc. R. Soc. Lond. B* 256, 53-58 (1994).

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.