Life: cascades of energy conversion and dissipation
Life: cascades of energy conversion and dissipation

- Photon
- Ion gradient
- ATP
- Life processes
- Dissipated energy

Not universal to all known forms of life.
“Such is life... an inserting itself, a drawing off to its advantage, a parasitizing of the downward course of energy, from its noble solar form to the degraded one of low-temperature heat. In this downward course, which leads to equilibrium and thus death, life draws a bend and nests in it.”

–Primo Levi, “Carbon”
(hat tip: Robin Snyder)
Other persistent nonequilibrium systems
Other persistent nonequilibrium systems

Big whorls have little whorls
Which feed on their velocity,
And little whorls have lesser whorls
And so on to viscosity.

- L.F. Richardson

Image: go.nasa.gov/2V5IzyC
Thermodynamics and the origin of life

All nonequilibrium processes on earth:

- air currents
- ocean currents
- plate tectonics
- life
Thermodynamics and the origin of life

All nonequilibrium processes on earth:

- air currents
- ocean currents
- plate tectonics
- life

are ultimately “plugged into” two major imbalances:

1. **solar**: time-varying distribution of photons incident on the surface
2. **geological**: heat released as core solidifies, decay of radioactive elements
Thermodynamics and the origin of life

**nonequilibrium stationary state:** \[ \dot{W} = P_{in} - P_{out} = T\dot{I} \equiv P_{diss} \]

Energy (units of \( k_B T_0 = 25.7 \text{ meV} \))

Frequency (GHz)

Power flux (arbitrary units)

Typical biochemical free energies

Transmembrane potential

ATP

Cost of irreversibility

Free energy requirement for the origin of life

Sun-like star 6000 K

Red dwarf star 3500 K

Hadean magma 1600 K

Water at critical temp. 647 K

Lightning

*Pascal et al.*  
Open Biol (2013)
Thermodynamics and the origin of life

nonequilibrium stationary state: \( \dot{W} = P_{\text{in}} - P_{\text{out}} = T\dot{i} \equiv P_{\text{diss}} \)

energy (units of \( k_B T_0 = 25.7 \text{ meV} \))

- water at critical temp. 647 K
- Hadean magma 1600 K
- red dwarf star 3500 K
- sun-like star 6000 K
- lightning

UV photons: persistent high-energy source

Pascal et al. Open Biol (2013)
Primordial soup: Miller-Urey experiment (1952)

Classic experiment synthesizing amino acids (protein building blocks) in a simple atmosphere using an influx of free energy (electrical spark = “lightning”).
Primordial soup: Miller-Urey experiment (1952)

Classic experiment synthesizing amino acids (protein building blocks) in a simple atmosphere using an influx of free energy (electrical spark = “lightning”).

Life also requires:

- **genetic material:** DNA/RNA nucleotides
- **containers:** lipids for membranes
- **metabolism:** ATP, etc.

Which came first?
Recent landmarks in prebiotic chemistry

2003: Clay can catalyze both the formation of lipid vesicles (containers) and RNA strands (genetic material) from “activated” (chemically modified) bases (A,U,C,G).

Where do you get the precursors (bases + lipids)?
2009: Activated bases can be synthesized from plausible prebiotic materials.
Recent landmarks in prebiotic chemistry

2015: Potentially resolved the chicken vs. egg problem:

Lipids, amino acids, and RNA bases can all be derived from a common chemistry based on HCN, H$_2$S, and UV light.

Recent landmarks in prebiotic chemistry

2015: Potentially resolved the chicken vs. egg problem: the answer is both!

Lipids, amino acids, and RNA bases can all be derived from a common chemistry based on HCN, H$_2$S, and UV light.

Common origins of RNA, protein and lipid precursors in a cyanosulfidic protometabolism

Bhavesh H. Patel, Claudia Percivalle, Dougal J. Ritson, Colm D. Duffy and John D. Sutherland*

A minimal cell can be thought of as comprising informational, compartment-forming and metabolic subsystems. To imagine the abiotic assembly of such an overall system, however, places great demands on hypothetical prebiotic chemistry. The perceived differences and incompatibilities between these subsystems have led to the widely held assumption that one or other subsystem must have preceded the others. Here we experimentally investigate the validity of this assumption by examining the assembly of various biomolecular building blocks from prebiotically plausible intermediates and one-carbon feedstock molecules. We show that precursors of ribonucleotides, amino acids and lipids can all be derived by the reductive homologation of hydrogen cyanide and some of its derivatives, and thus that all the cellular subsystems could have arisen simultaneously through common chemistry. The key reaction steps are driven by ultraviolet light, use hydrogen sulfide as the reductant and can be accelerated by Cu(II)–Cu(I) photoredox cycling.
Recent landmarks in prebiotic chemistry

**2015:** Potentially resolved the chicken vs. egg problem: the answer is both!

Lipids, amino acids, and RNA bases can all be derived from a common chemistry based on HCN, H₂S, and **UV light**.

What about evidence from the fossil record?

A  September 2017: Tashiro et al., Nature
biogenic graphite from 3.95 Gyr ago
found in Labrador, Canada rocks

B  March 2017: Dodd et al., Nature
hematite tube "microfossils" from 3.77 Gyr
found in Quebec, Canada rocks (possibly
from seafloor hydrothermal vents)

C  August 2016: Nutman et al., Nature
Stromatolite (fossilized microbial colony)
from 3.7 Gyr in Greenland: earliest evidence
of anoxygenic photosynthesis?
Stromatolite controversy

The 3.7 Gyr stromatolites recently called into question by Abigail Allwood and coworkers, who discovered the previous record holder (3.45 Gyr stromatolites in Western Australia):

Reassessing evidence of life in 3,700-million-year-old rocks of Greenland

Abigail C. Allwood, Minik T. Rosing, David T. Flannery, Joel A. Hurowitz & Christopher M. Heirwegh

Nature (2018) | Download Citation
Stromatolite controversy

The debate is a crucial rehearsal for the Mars 2020 rover mission, where potential Martian stromatolites will be a major target.

SCIENCE

Can Abigail Allwood Find Life on Mars?

She made her name identifying the earliest accepted proof of life on Earth. Now NASA is counting on her to repeat the trick.
Stromatolites

Living stromatolites are rare: undisturbed colonies of photosynthetic cyanobacteria in hypersaline shallow waters inhospitable to other life.

Major part of fossil record until $\sim 1$ Gyr ago, when they fell victim to grazing by higher lifeforms.
Stromatolites

Thanks to the generosity of Ashley Manning-Berg, we have samples from:

Laguna Negra, Argentina: 5000 yr old sample
Stromatolites

Thanks to the generosity of Ashley Manning-Berg, we have samples from:

Baffin Island, Canada:
~1 Gyr old samples
Intrepid crew gathering stromatolites at Lake Salda, Turkey
Intrepid crew gathering stromatolites at Lake Salda, Turkey
Intrepid crew gathering stromatolites at Lake Salda, Turkey
SEM images of Lake Salda stromatolites

Shirokova et al., Aquat Geochem (2013)
The competing hypothesis: geochemical origins

Hypothesis 1:
photons are the original power source

Hypothesis 2:
geochemical ion gradients are the original power source
Meet Luca, the Ancestor of All Living Things

By NICHOLAS WADE | JULY 25, 2016
Meet Luca, the Ancestor of All Living Things

By NICHOLAS WADE    JULY 25, 2016

The physiology and habitat of the last universal common ancestor

Madeline C. Weiss†, Filipa L. Sousa†, Natalia Mrnjavac, Sinje Neukirchen, Mayo Roettger, Shijulal Nelson-Sathi and William F. Martin*
Most likely habitat of LUCA

Researchers identified 355 LUCA protein families, hinting at an organism that thrived somewhere:

- hot: temperatures $> 60^\circ\text{C}$
- rich in H$_2$, CO$_2$, and iron
Researchers identified 355 LUCA protein families, hinting at an organism that thrived somewhere:

- hot: temperatures $> 60^\circ C$
- rich in $H_2$, $CO_2$, and iron

A similar modern environment: alkaline hydrothermal vents, such as exist today at the Lost City vent field, discovered in 2000.
Lost city hydrothermal vents

See movie on course website.
A geochemical “power outlet”

\[ \text{peridotite} + \text{seawater} \rightarrow \text{serpentinite} + \text{heat} + \text{fluid depleted of H}^+ \text{ ions} \]
Porous structure of the rock chimneys at the vents
A plausible hypothesis: Lane and Martin, Cell (2012)

Long-term (> $10^4$ yr) imbalances of $H^+$ ions persist at the boundaries of rock pores and seawater.
A nonequilibrium playground for the birth of biochemistry

A plausible hypothesis: Lane and Martin, Cell (2012)

Long-term ($>10^4$ yr) imbalances of H$^+$ ions persist at the boundaries of rock pores and seawater.

The pore walls could have provided the scaffolding for the development of membranes, membrane-bound proteins like ATP synthase, and other biological components.