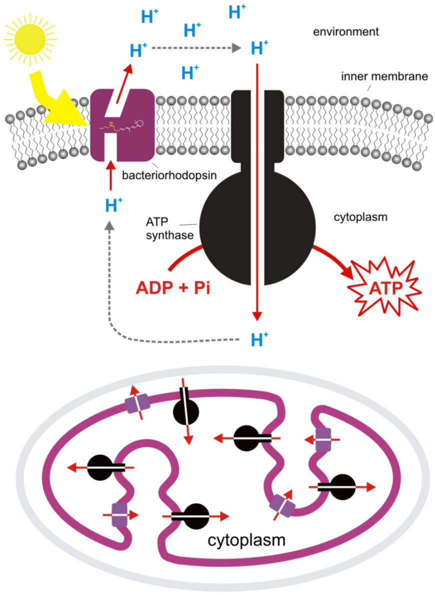
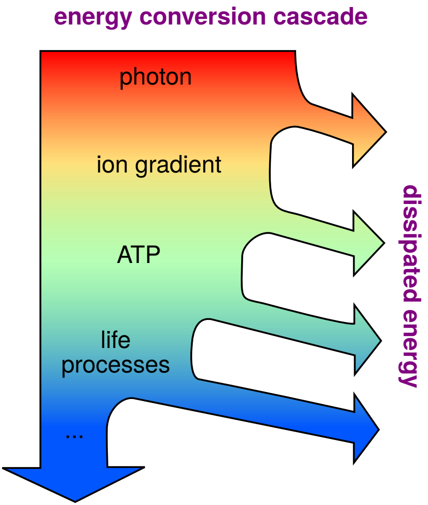
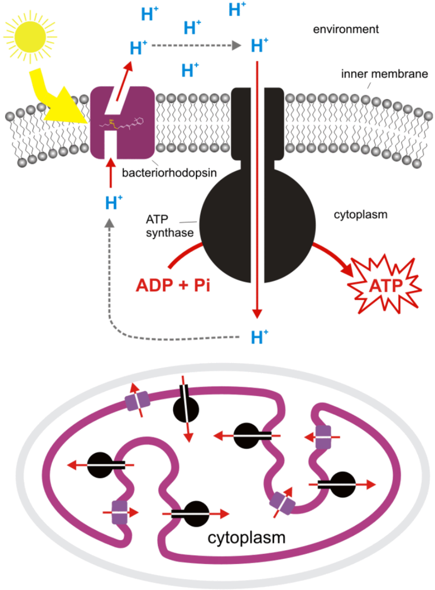
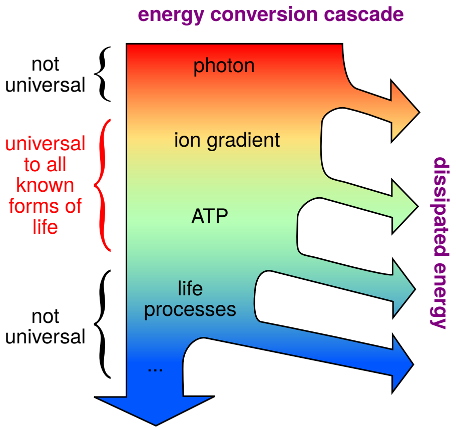
Life: cascades of energy conversion and dissipation





Life: cascades of energy conversion and dissipation

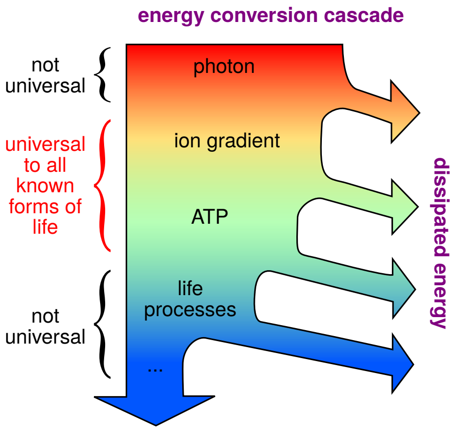




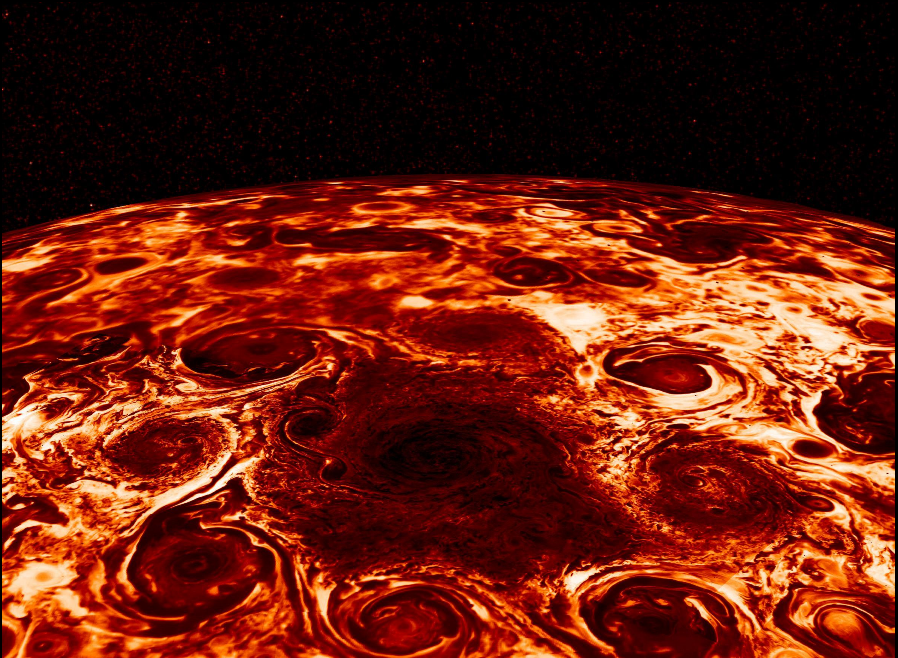
Life: cascades of energy conversion and dissipation

"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."

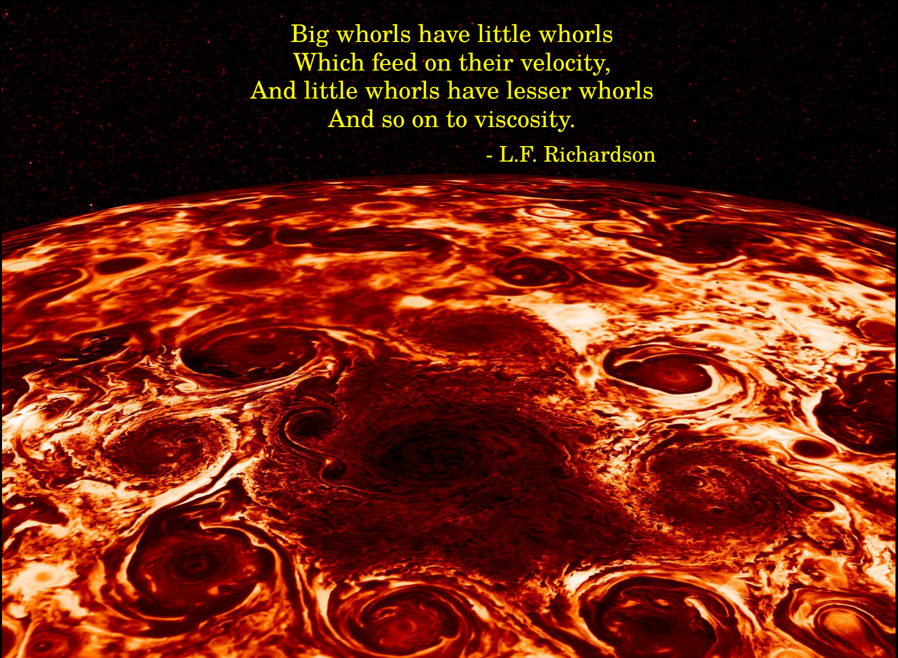
–Primo Levi, "Carbon"
(hat tip: Robin Snyder)



Other persistent nonequilibrium systems

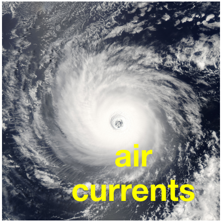


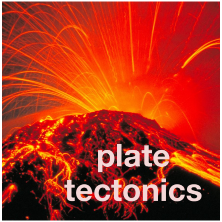
Other persistent nonequilibrium systems



Thermodynamics and the origin of life

All nonequilibrium processes on earth:





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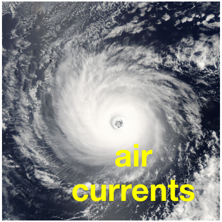
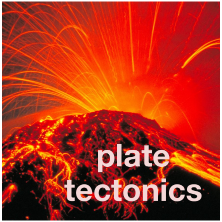
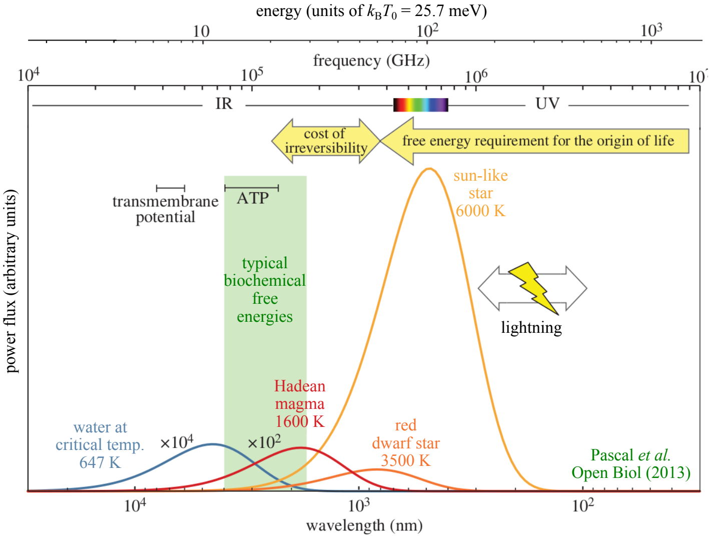




are ultimately “plugged into” two major imbalances:

Thermodynamics and the origin of life

nonequilibrium stationary state: $\dot{W} = P_{\text{out}} - P_{\text{in}} = -T\dot{I} \equiv P_{\text{diss}}$



Thermodynamics and the origin of life

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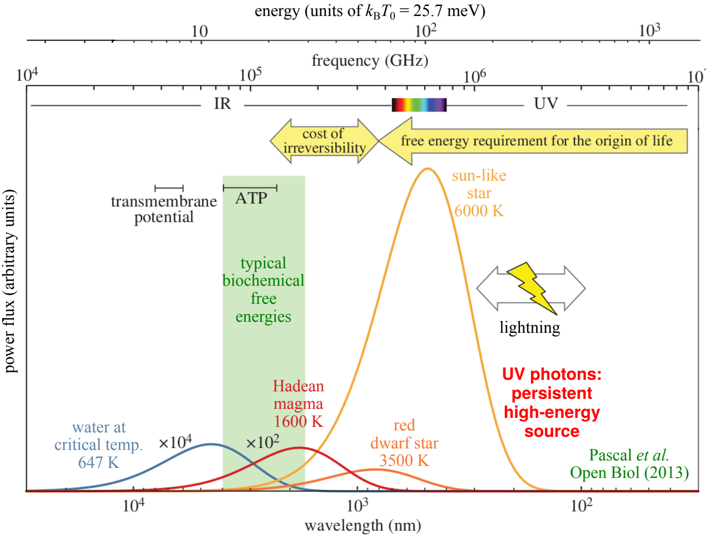
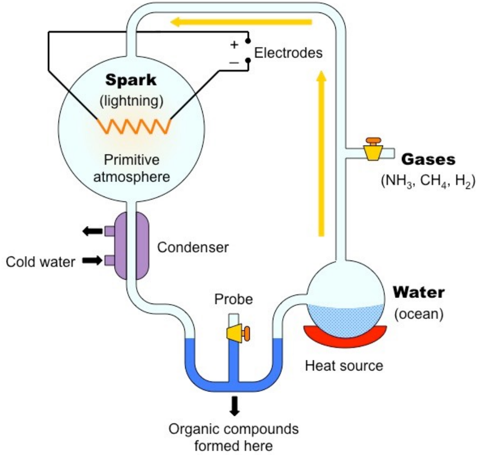
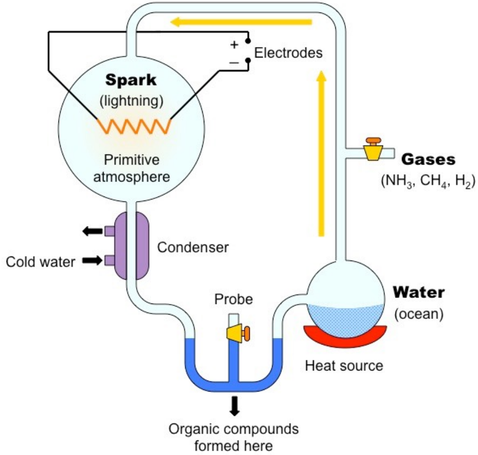


Primordial soup: Miller-Urey experiment (1952)



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)



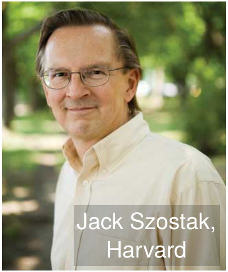
Classic experiment synthesizing amino acids (**protein** building blocks) in a simple atmosphere using an influx of free energy (electrical spark = “lightning”).

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)?

Recent landmarks in prebiotic chemistry

2009: Activated bases can be synthesized from plausible prebiotic materials.

Vol 459 | 14 May 2009 | **doi:10.1038/nature08013** nature

LETTERS

Synthesis of activated pyrimidine ribonucleotides in prebiotically plausible conditions

Matthew W. Powner[1], Béatrice Gerland[1] & John D. Sutherland[1]

At some stage in the origin of life, an informational polymer must have arisen by purely chemical means. According to one version of the 'RNA world' hypothesis[1–3] this polymer was RNA, but attempts to provide experimental support for this have failed[4,5]. In particular, although there has been some success demonstrating that 'activated' ribonucleotides can polymerize to form RNA[6,7], it is far from obvious how such ribonucleotides could have formed from their constituent parts (ribose and nucleobases). Ribose is difficult

we have discovered a short, highly efficient route to activated pyrimidine ribonucleotides from these same precursors that proceeds by way of alternative intermediates (Fig. 1, green arrows). By contrast with previously investigated routes to ribonucleotides, ours bypasses ribose and the free pyrimidine nucleobases. Mixed nitrogenous–oxygenous chemistry first results in the reaction of cyanamide **8** and glycolaldehyde **10**, giving 2-amino-oxazole **11**, and this heterocycle then adds to glyceraldehyde **9** to give the pentose amino-oxazolines including the

Recent landmarks in prebiotic chemistry

2015: Potentially resolved the **chicken vs. egg** problem:

Recent landmarks in prebiotic chemistry

John Sutherland, Cambridge

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_2S, and **UV light**.

nature chemistry | ARTICLES
PUBLISHED ONLINE: 16 MARCH 2015 | DOI: 10.1038/NCHEM.2202

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(I)–Cu(II) photoredox cycling.

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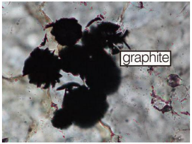
See: www.bbc.com/earth/story/20161026-the-secret-of-how-life-on-earth-began

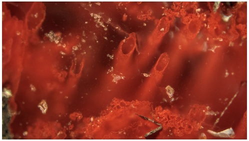
What about evidence from the fossil record?

A



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

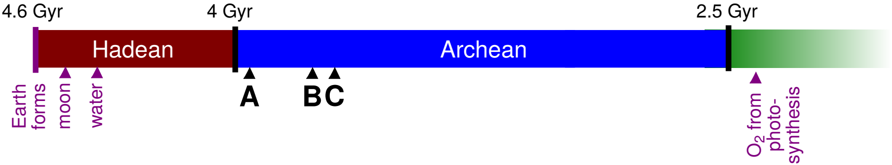
B



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):

nature
International journal of science

Letter | Published: 17 October 2018

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.

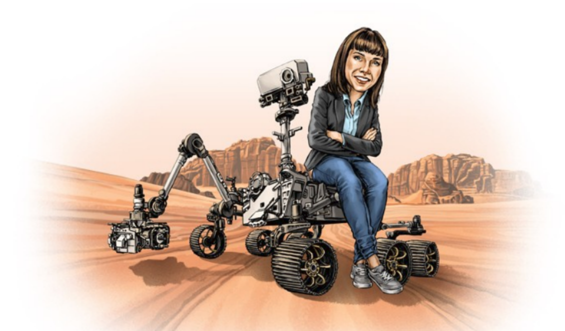
The Atlantic   Popular   Latest   Sections   Magazine   More

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.

LAURA PARKER JUNE 2018 ISSUE



MORE STORIES

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BEN HEALY

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SARAH ELIZABETH ADLER

The Most Honest Book About Climate Change Yet
NATHANIEL RICH

When Animals Take the

Stromatolites

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


Shark Bay, Western Australia

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

Stromatolites

Thanks to the generosity of **Ashley Berg** (arm272@case.edu), we have samples from:

Check out her course for spring 2019: EEPS 310, Habitability and Astrobiology in the Solar System

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Intrepid crew gathering stromatolites at Lake Salda, Turkey

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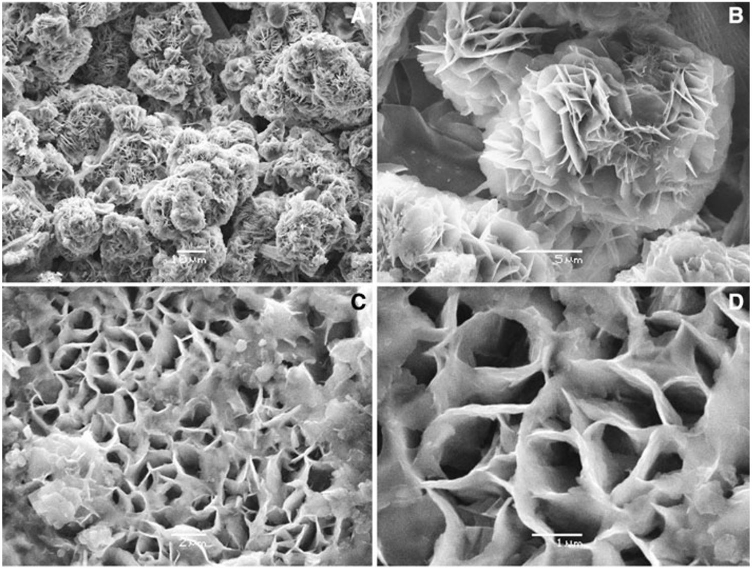
SEM images of Lake Salda stromatolites



Shirokova *et al.*, Aquat Geochem (2013)

Extremophile environments

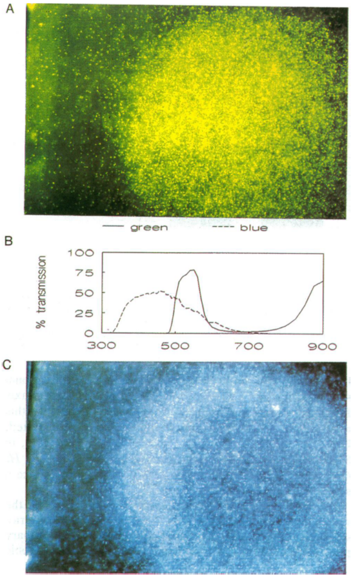
Hypersaline lakes are good places to search for “primitive” model organisms.

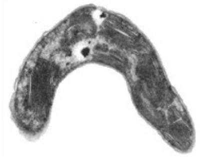
Wadi Natrun, Egypt. Inhospitable for most life: pH 10.5, 36% salt [wt/vol]

Probably pining for the fjords

Good for mummification thanks to high quantities of natron (soda ash and salt mixture), an excellent desiccating agent. Photo credit: Nick Brandt.

Home of extremophile bacteria *H. halophila*





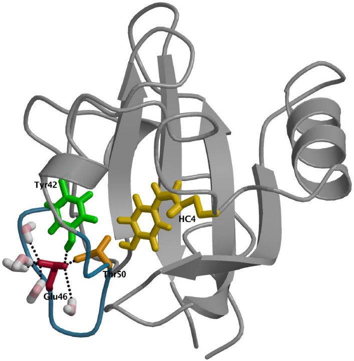
Sprenger *et al.*, J. Bacteriol. (1993):

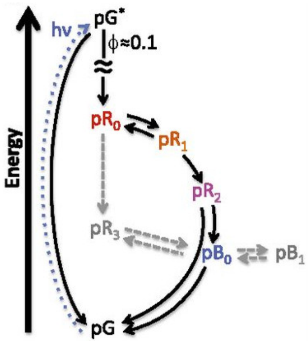
These bacteria have a mechanism to swim toward green light, a photon frequency useful for photosynthesis.

They swim away from large intensities of blue light, possibly because exposure to higher energy photons ($>$ 2.5 eV or 100 $k_B T$) may be damaging.

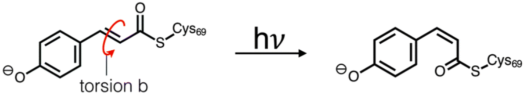
Photoactive yellow protein (PYP)

The bacterial flight response from blue photons is due to PYP, which has become a model system for photosensitive proteins.



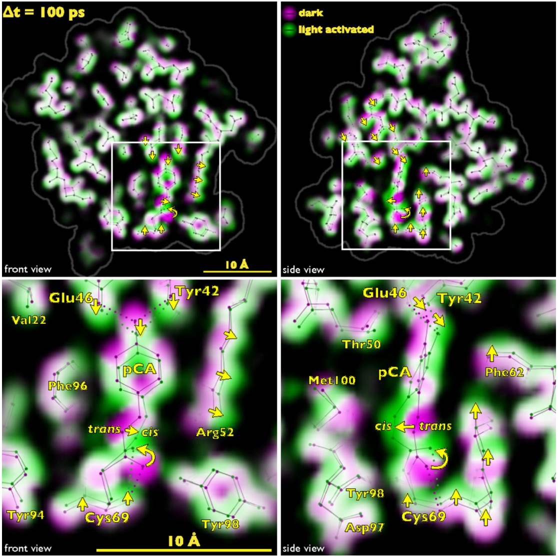


Change in *p*-coumeric acid on absorption of blue photon:



Visualizing the photon-induced protein motions

Time-resolved x-ray diffraction: seeing atomic-scale motions at 100 ps time steps, from $t = 100$ ps -1 s [Schotte *et al.*, PNAS (2012)].

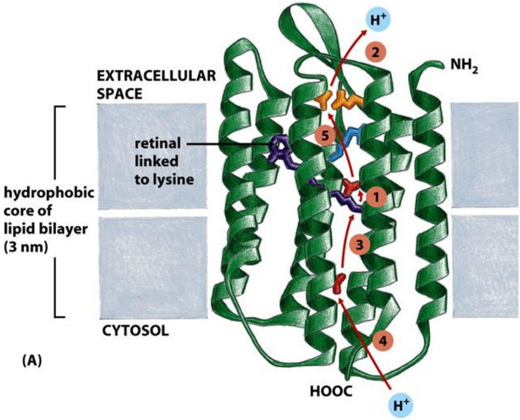


PYP in action

See movie file on course website.

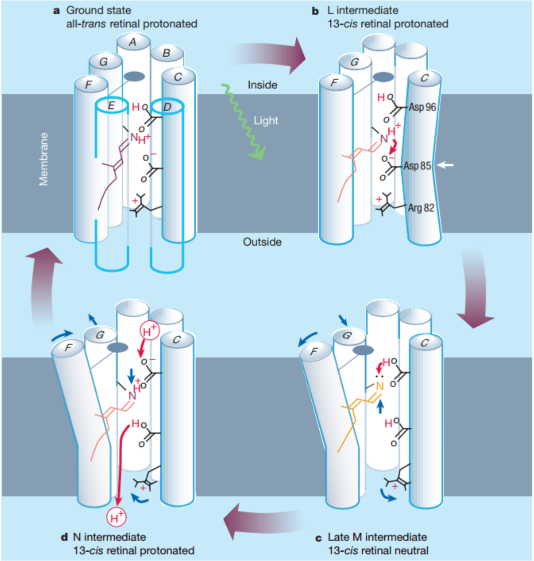
What can you do with photo-induced protein motions?

Another example from a simple, salt-loving organism: **bacteriorhodopsin** from Halobacteria (a class of Archaea)



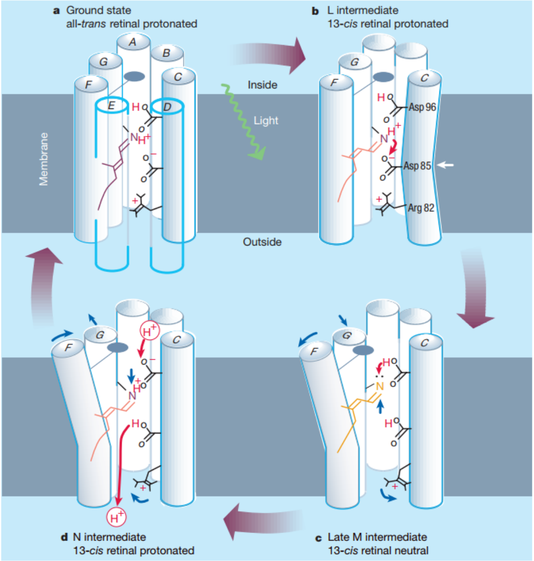
Similar in structure to the photoreceptors in our eyes. Can cover up to 50% of the surface of the archael cell.

Bacteriorhodopsin pumps protons out of cell



Key question for later: what is the advantage of pumping protons?

Bacteriorhodopsin pumps protons out of cell



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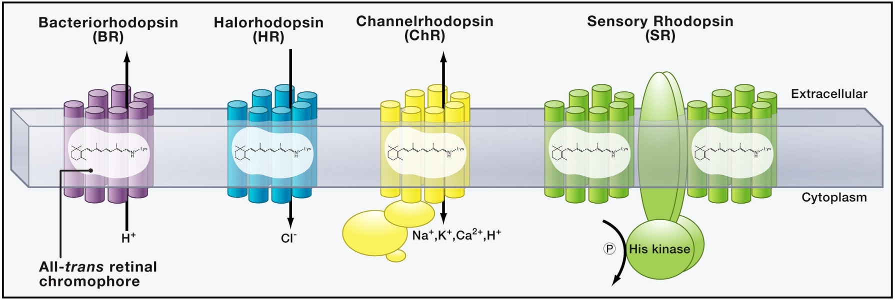
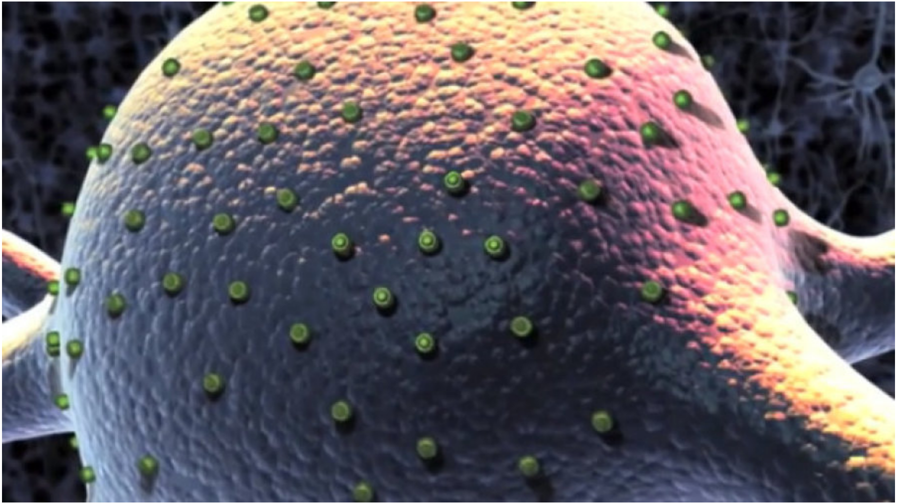
The broad family of microbial rhodopsins

Many variants have been discovered, specialized for different functions:



The broad family of microbial rhodopsins

Artifically embedded in neurons of higher organisms, they allow for **optogenetic** manipulation of behavior.



Optogenetics

See movie file on course website.

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See movie file on course website.