Systems Microbiology

20.106J (1.084J) Lecture: *MW 9:30-11*

Prereq:5.111, 5.112 or 3.091; 7.012/7.013/7.014 Units: 3-0-9

Modern microbiology from a systems perspective

Professors David Schauer & Ed DeLong

Systems Microbiology

20.106 LOGISTICS

TEXT:

Biology of Microorganisms

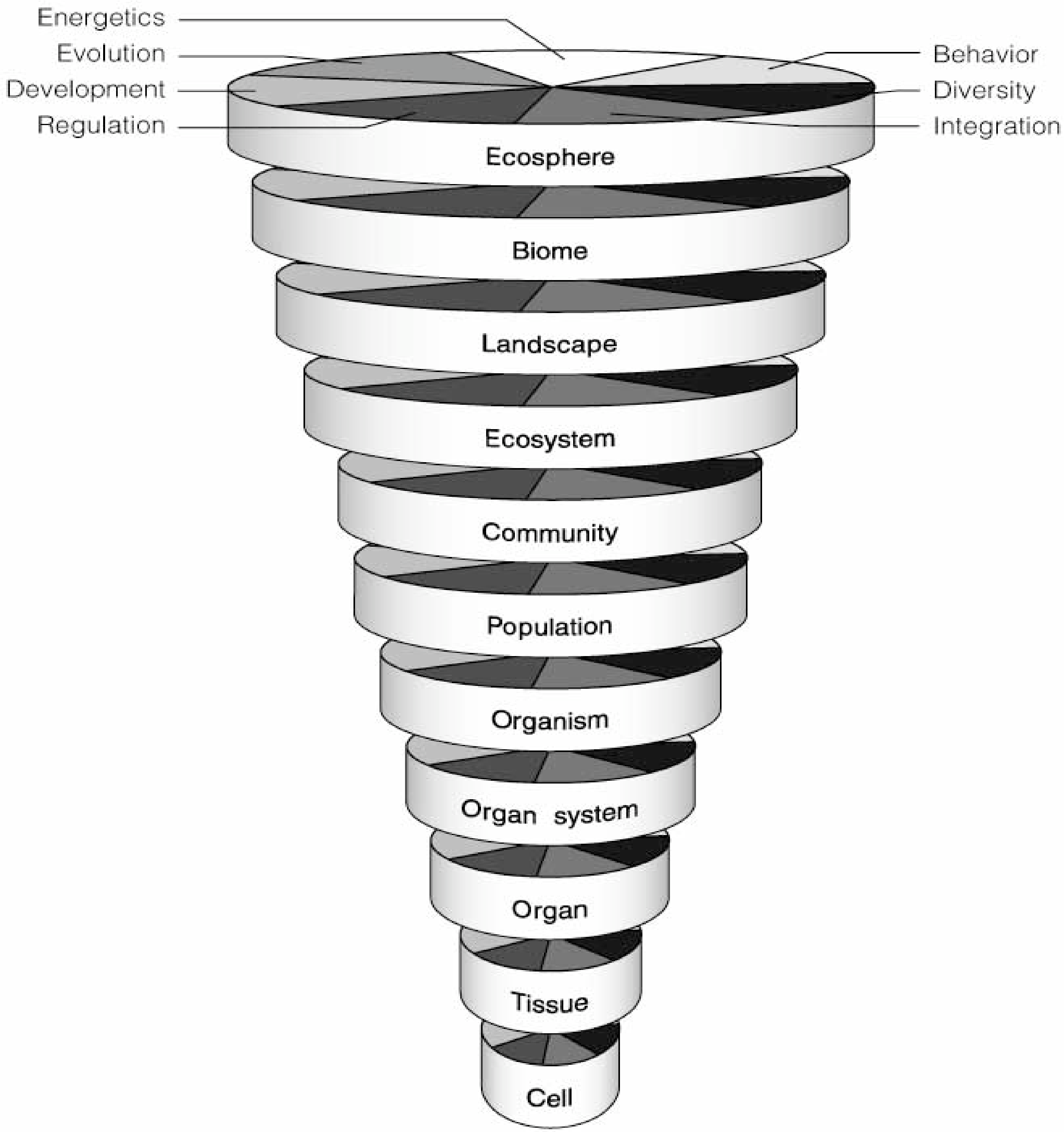
Mike Madigan and John Martinko

Grading based on:		Grade %
Problem sets :	~ 1 every 2 weeks	25 %
Midterms : I -	Monday October 17	20 %
II -	Monday, November 14	20 %
	Final Exam : Date TBD	35 %

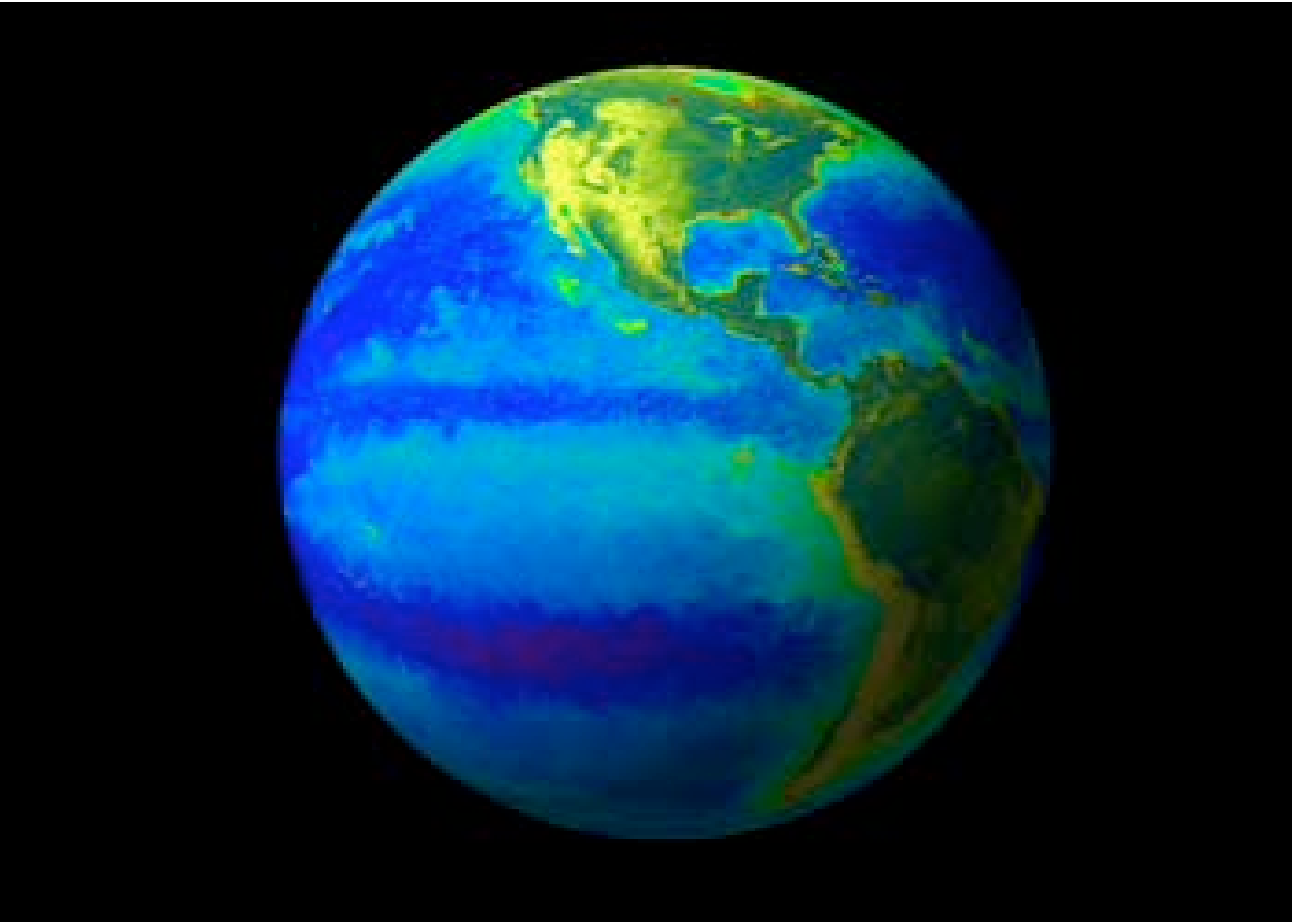
Microsopic photograph of microbes removed due to copyright restrictions.

MICROBIAL BIOLOGY

- MICROBIAL DIVERSITY & the BIOSPHERE
- ENERGY & ENVIRONMENT
- HUMAN HEALTH
- BIOLOGICAL ENGINEERING


Energetics
Evolution
Development
Regulation
Behavior
Diversity
Integration
Ecosphere
Biome
Landscape
Ecosystem
Community
Population
Organism
Organ system
Organ
Tissue
Cell

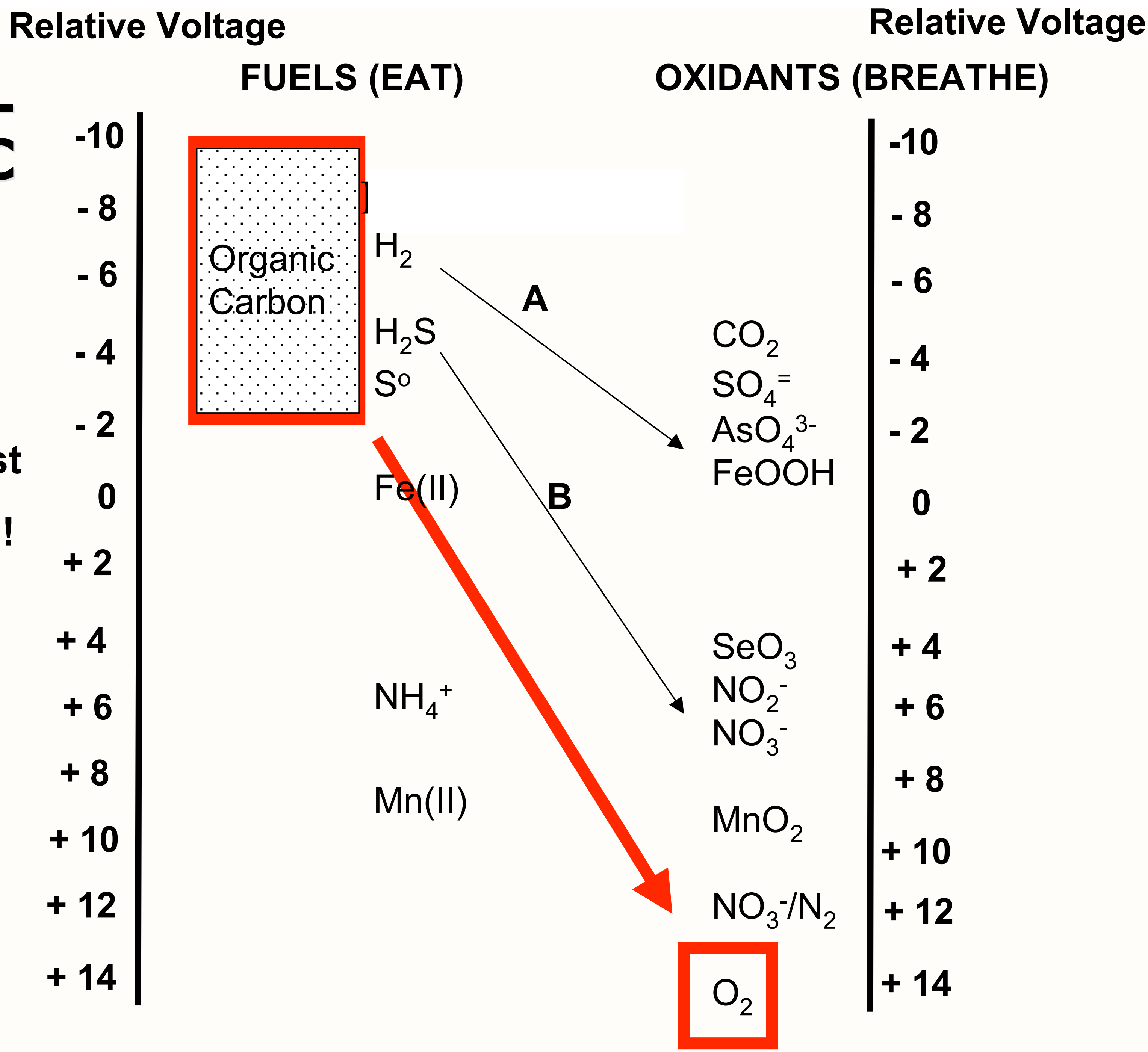
MICROBIAL DIVERSITY & THE BIOSPHERE



Photographs of extreme cold and warm microbial habitats removed due to copyright restrictions.

MICROBIAL METABOLIC DIVERSITY

Microbes can eat & breathe just about anything !

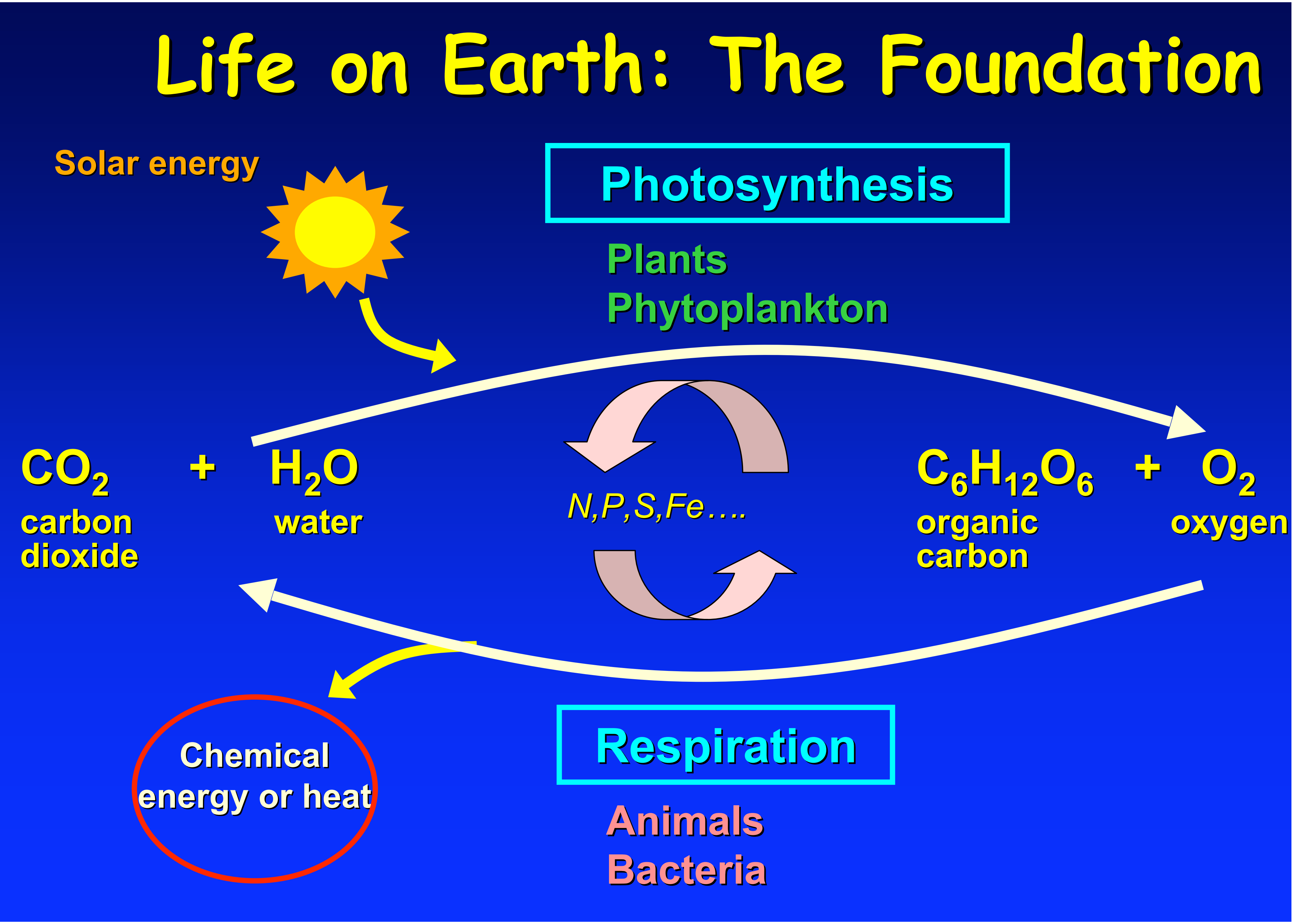


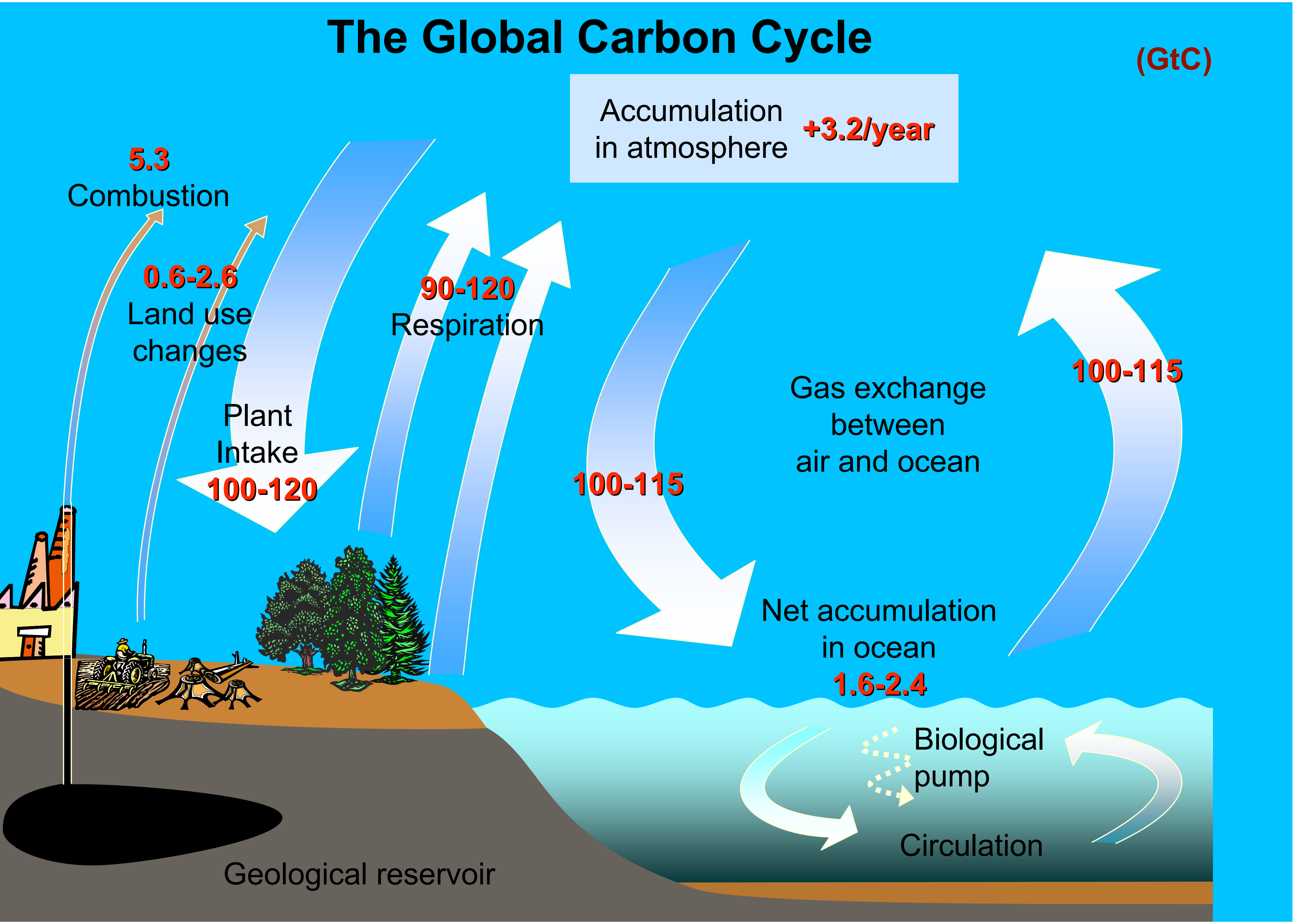
ENERGY AND THE ENVIRONMENT

The Global Importance of Microbes

- The only form of life on Earth for over 2-3 billion years
- Encompass most of the diversity of genes and biochemistry
- Represent > 50% of the biomass in the open ocean
- Control all elemental cycles that shape Earth's habitability
- They can live without us……

but we can't live without them


Life on Earth: The Foundation
Solar energy
Photosynthesis
Plants
Phytoplankton
CO_2 + H_2O
carbon dioxide
water
N,P,S,Fe….
$C_6H_{12}O_6$ + O_2
organic carbon
oxygen
Chemical energy or heat
Respiration
Animals
Bacteria

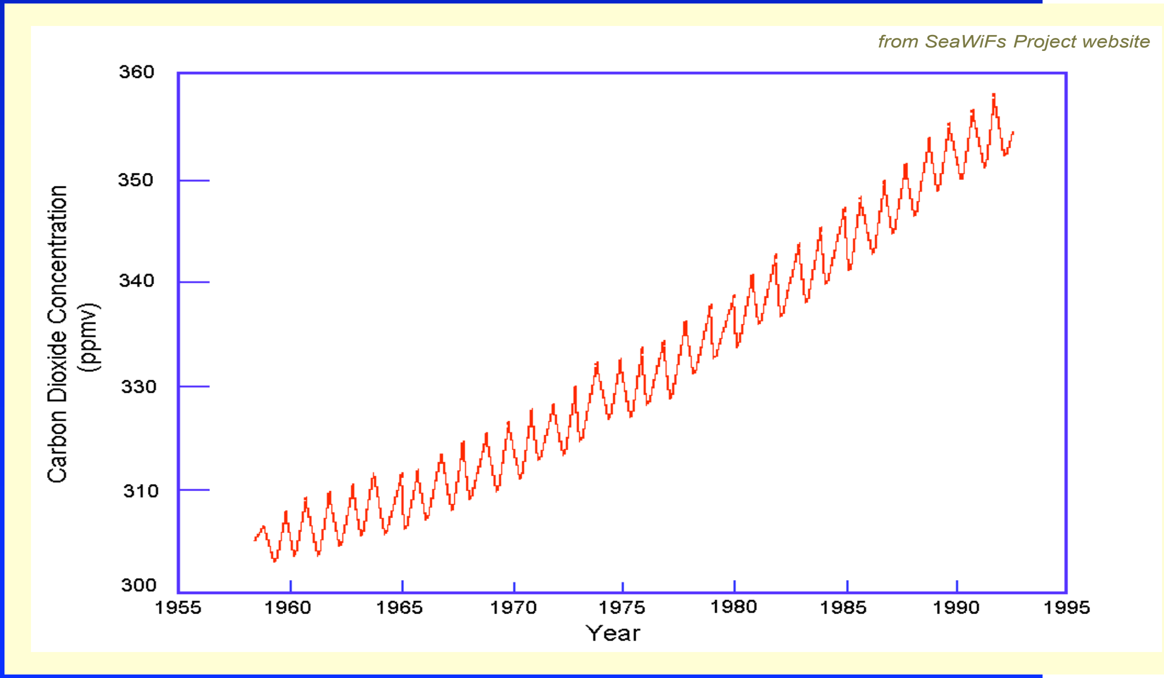

The Global Carbon Cycle
(GtC)
Accumulation in atmosphere
+3.2/year
5.3
Combustion
0.6-2.6
Land use changes
Plant Intake
100-120
90-120
Respiration
100-115
Gas exchange between air and ocean
100-115
Net accumulation in ocean
1.6-2.4
Biological pump
Circulation
Geological reservoir

ENERGY

THE ANTHROPOCENTRIC PERSPECTIVE

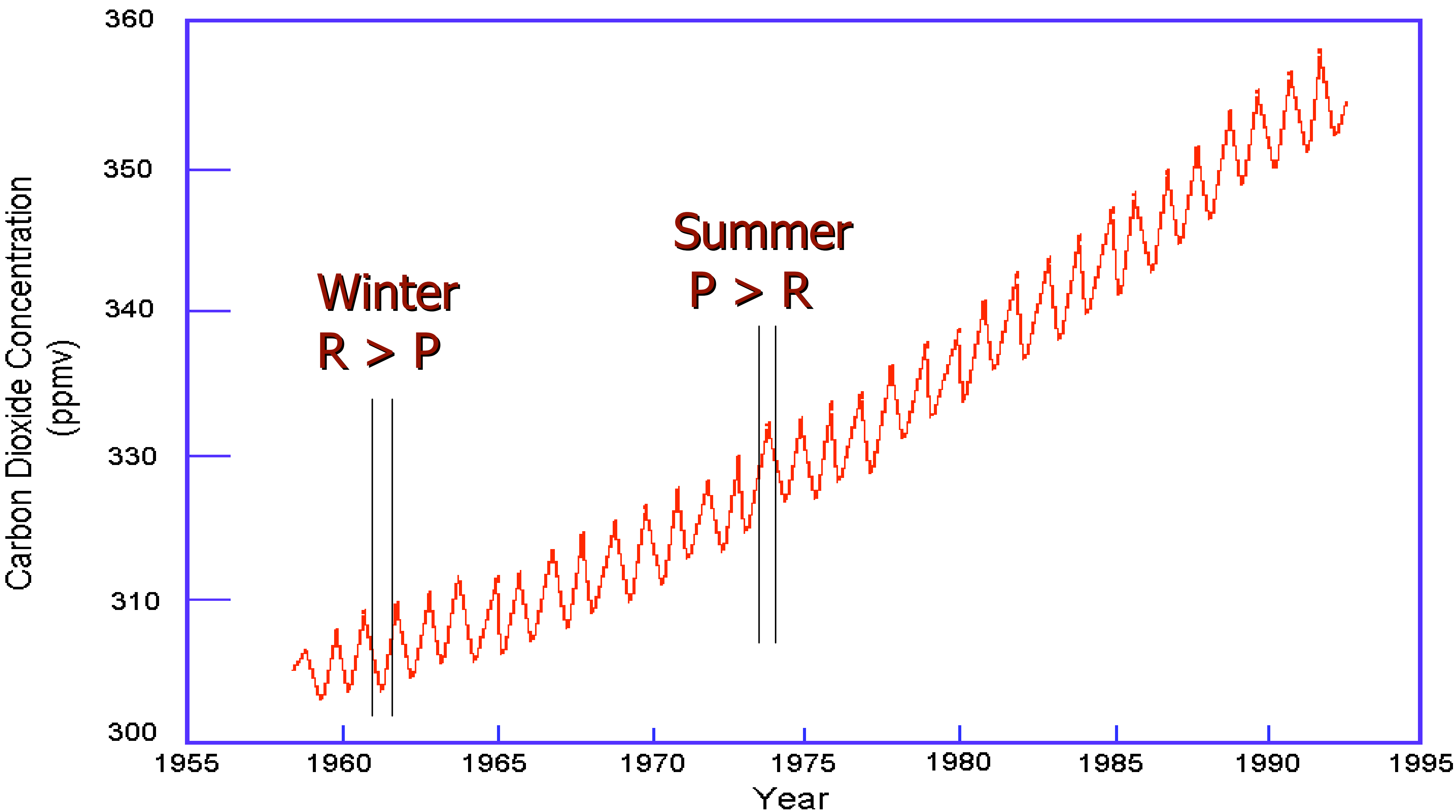
Photograph of an oil drill ship removed due to copyright restrictions.

PRODUCTS and OUTPUTS



Atmospheric Carbon Dioxide (Mauna Loa)

from SeaWiFs Project webs



MICROBES & HUMAN HEALTH

THE POPULAR VIEW OF "BUGS"

Flesh Bug Kills Drug Boss

Daily Record | Dec 26, 2003

ONE-EYED gangster Gerry "Cyclops" Carbin has died after being struck down by a flesh-eating bug.

Flesh-Eating Bananas from Costa Rica

Inside Costa Rica | Apr 15, 2005

Warning: Several shipments of bananas from Costa Rica have been infected with necrotizing fasciitis, otherwise known as flesh eating bacter

Flesh-Eating Bacteria Claims Teen's Leg

WJXT | Jan 4, 2005

A Central Florida teen is recovering Tuesday after a flesh-eating bacteria forced doctors to amputate most of his leg, according to WKMG-TV

Man Loses Battle With Gulf Bacteria

KPRC Houston | Aug 16, 2004

A Houston dentist has died after flesh-eating bacteria invaded a cut on his leg while he was fishing near Port O'Connor about a month ago

(*Streptococcus pyrogenes*. - > Necrotizing fasciitis)

Host-Bacterial Mutualism in the Human Intestine

Bäckhed,*Ley,*Sonnenburg, Peterson, Gordon SCIENCE 307:1915 (2005)

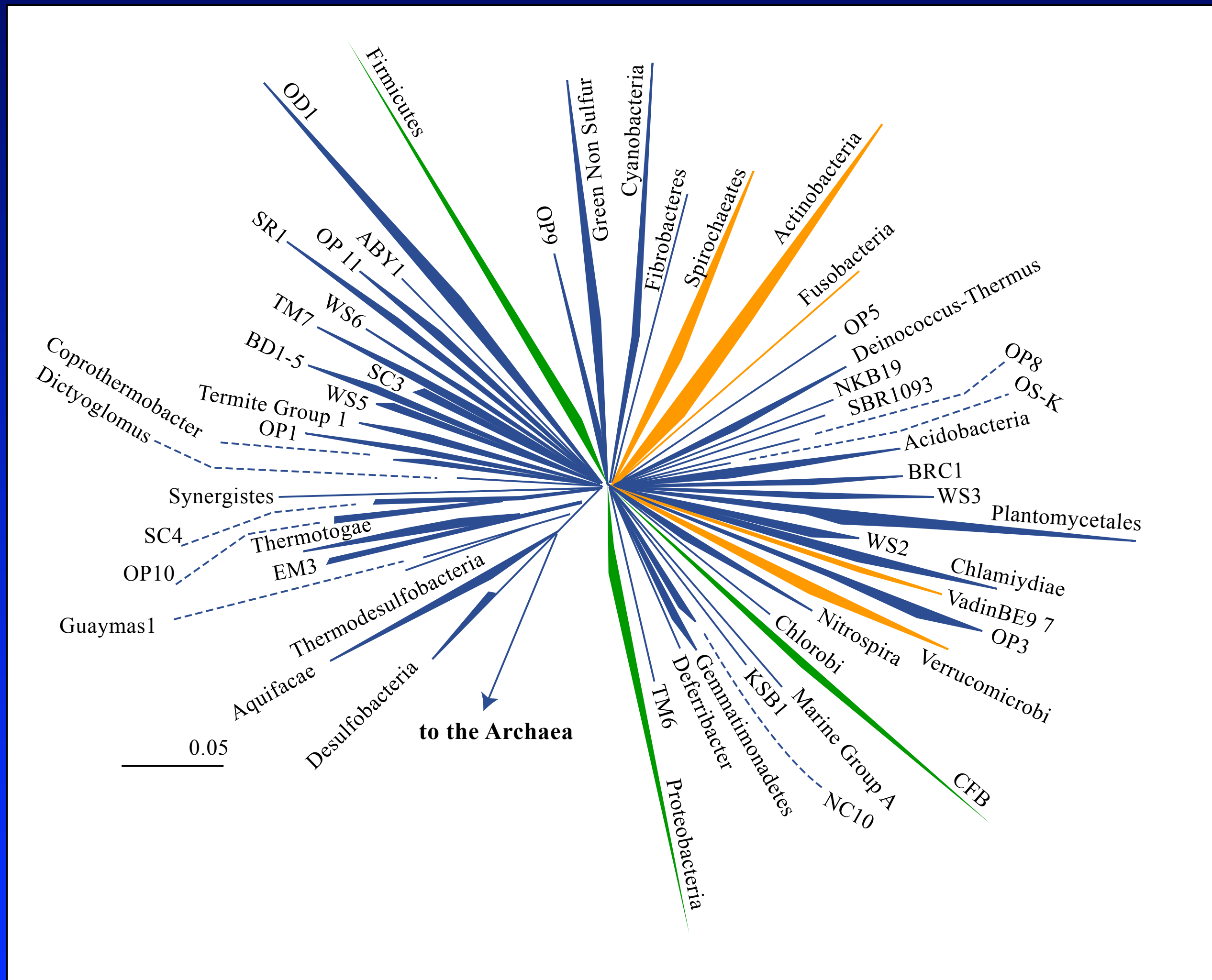
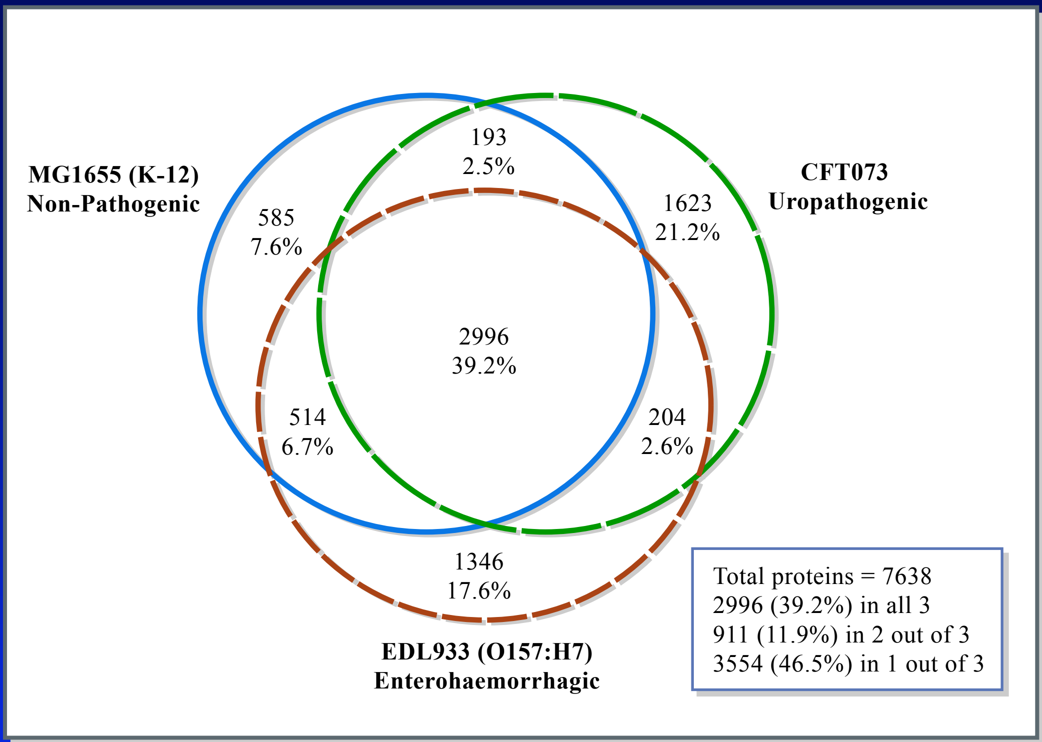
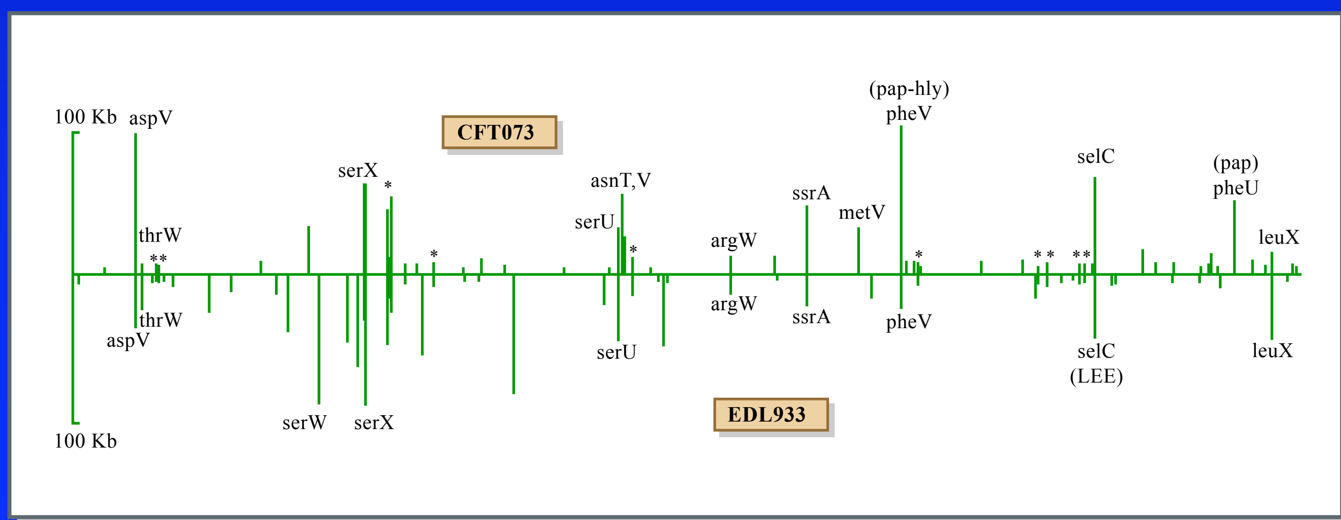


Figure by MIT OCW.

Diagram from Backhed, Ley, Sonnenburg, and Peterson removed due to copyright restrictions.

E. coli 0157:H7 = Jack in the Box food poisoning incident





Figures by MIT OCW.

UROPATHOGENIC & ENTEROHAEMORRHAGIC "HOT-SPOTS"

Welch, R. A. et al. (2002) Proc. Natl. Acad. Sci. USA 99, 17020-17024

Vibrio cholerae

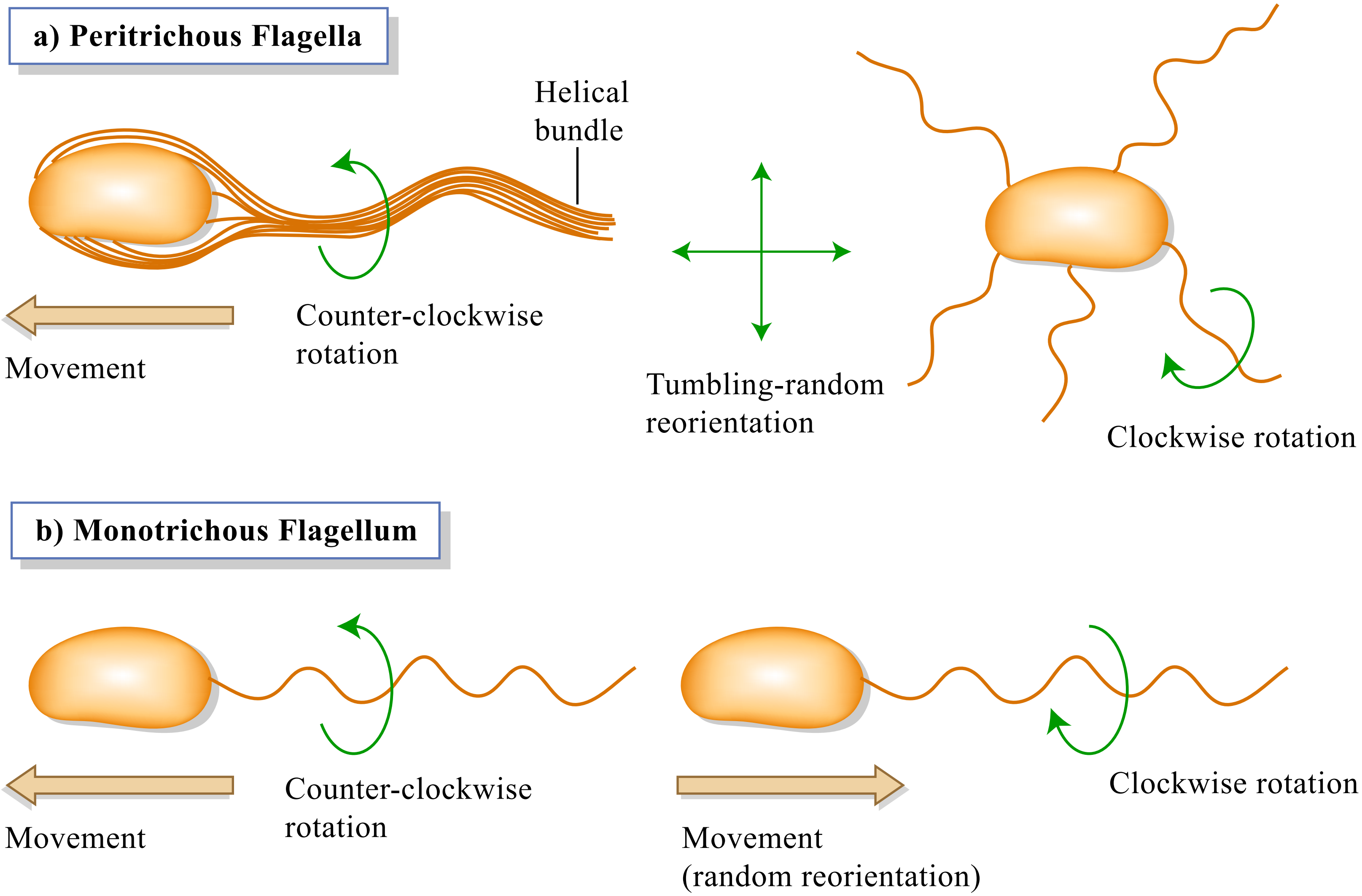


Figure by MIT OCW.

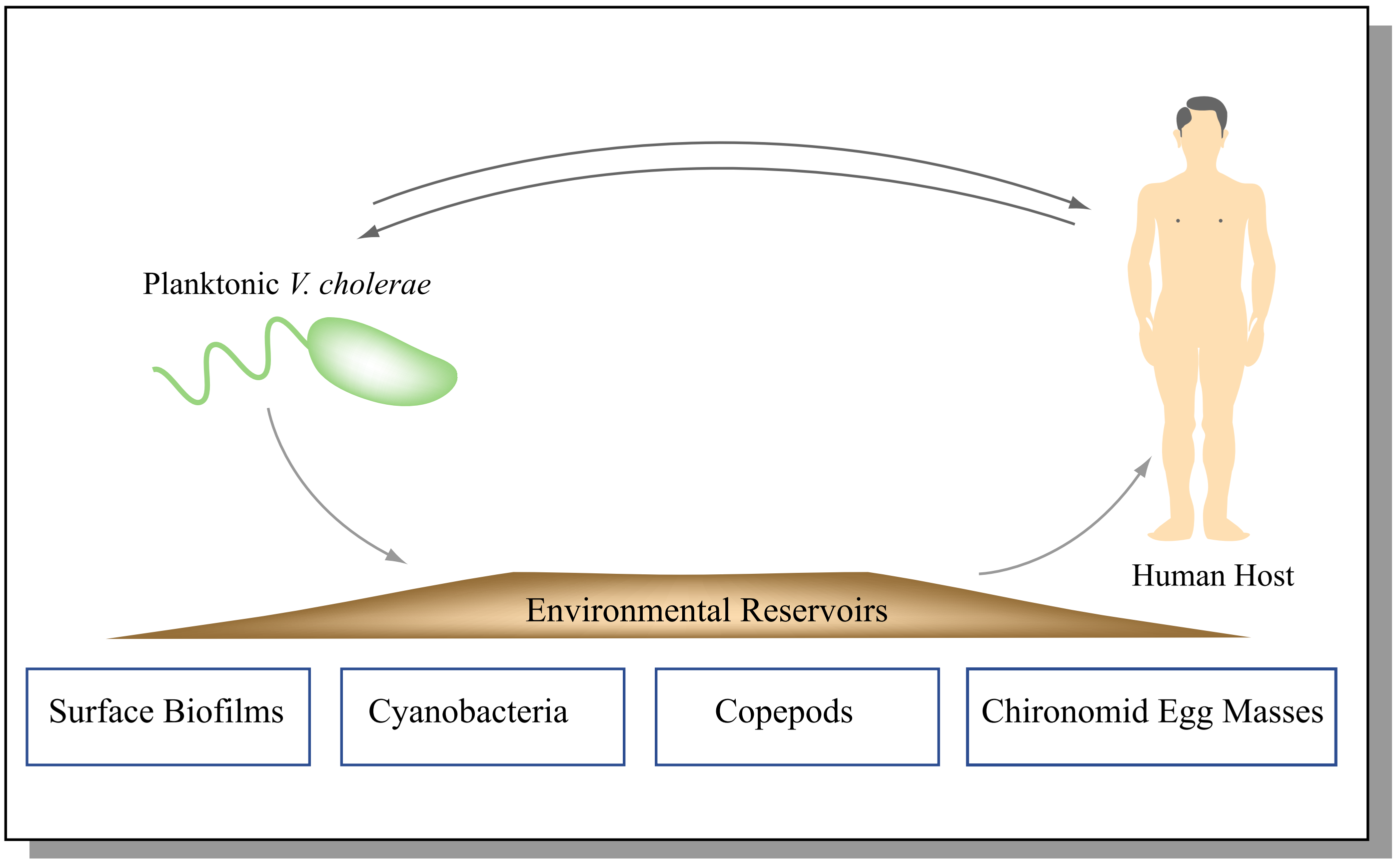


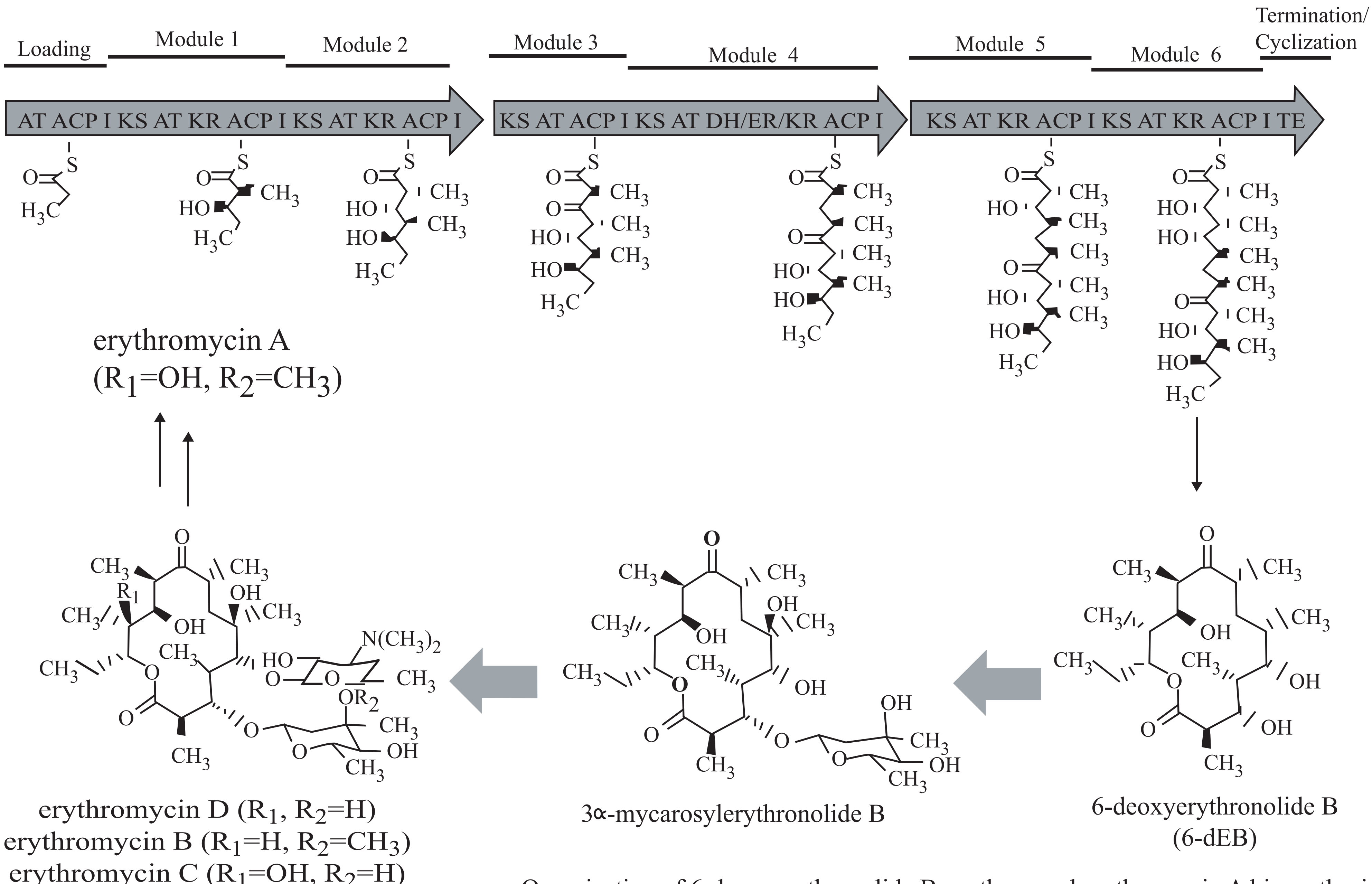
Figure by MIT OCW.

BIOTECHNOLOGY

&

BIOLOGICAL ENGINEERING

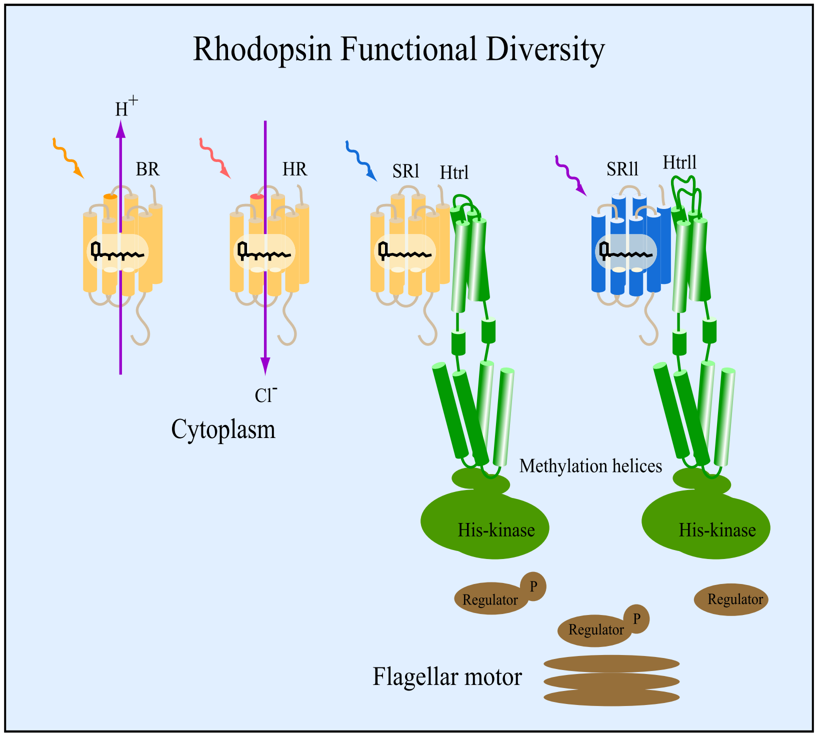
ANTIBIOTIC BIOSYNTHESIS

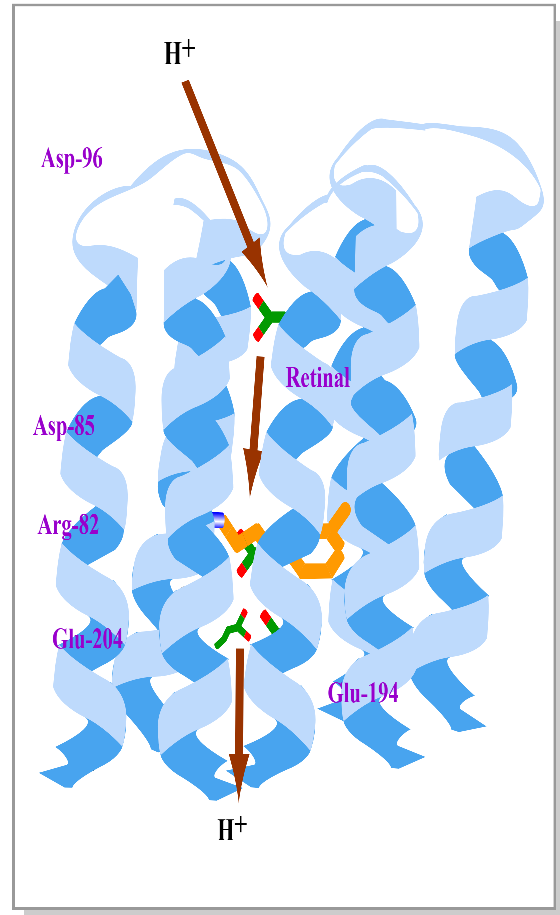


Organization of 6-deoxyerythronolide B synthase and erythromycin A biosynthesis

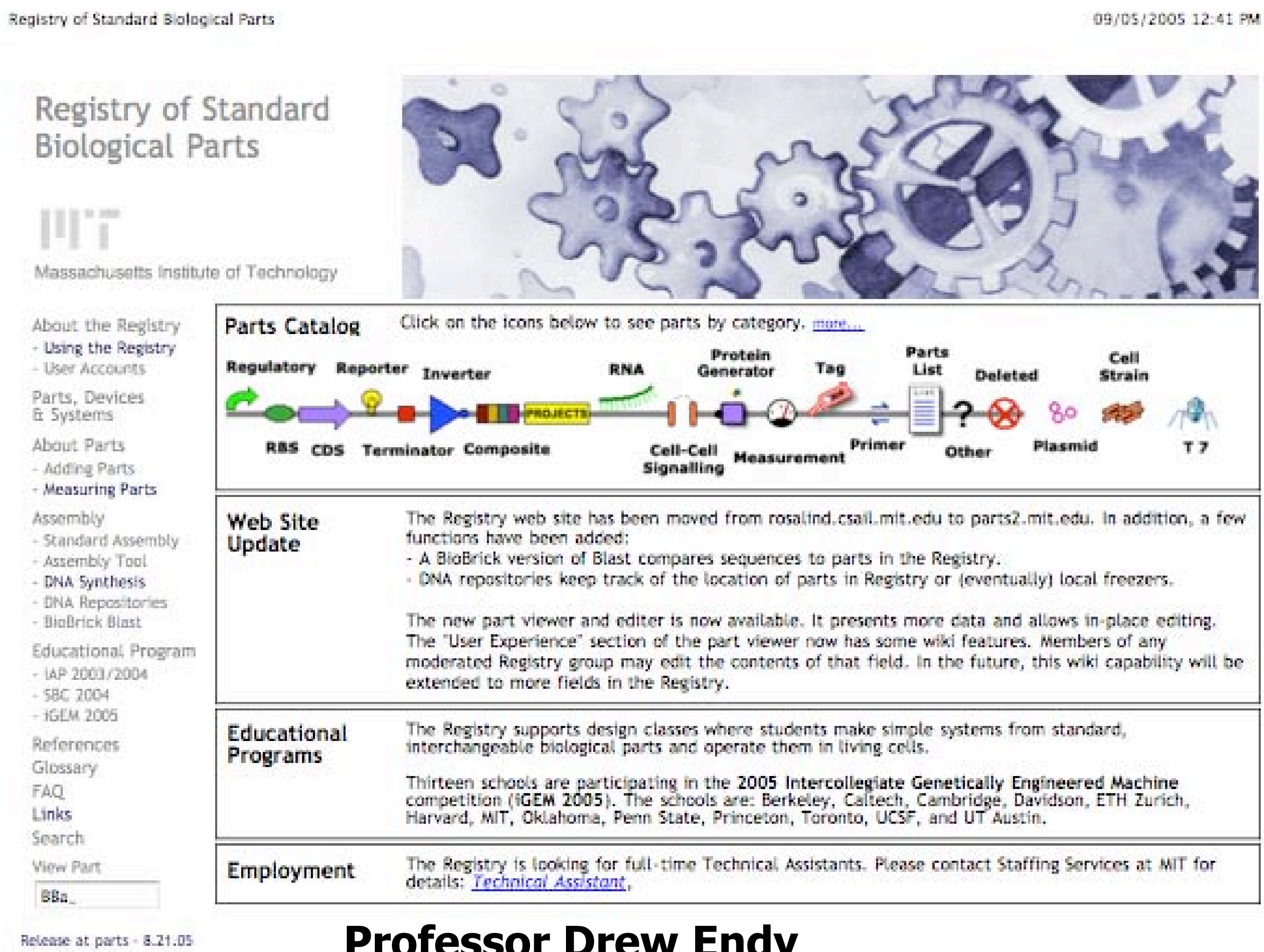
Figure by MIT OCW.

Rhodopsin functional diversity





Figures by MIT OCW.



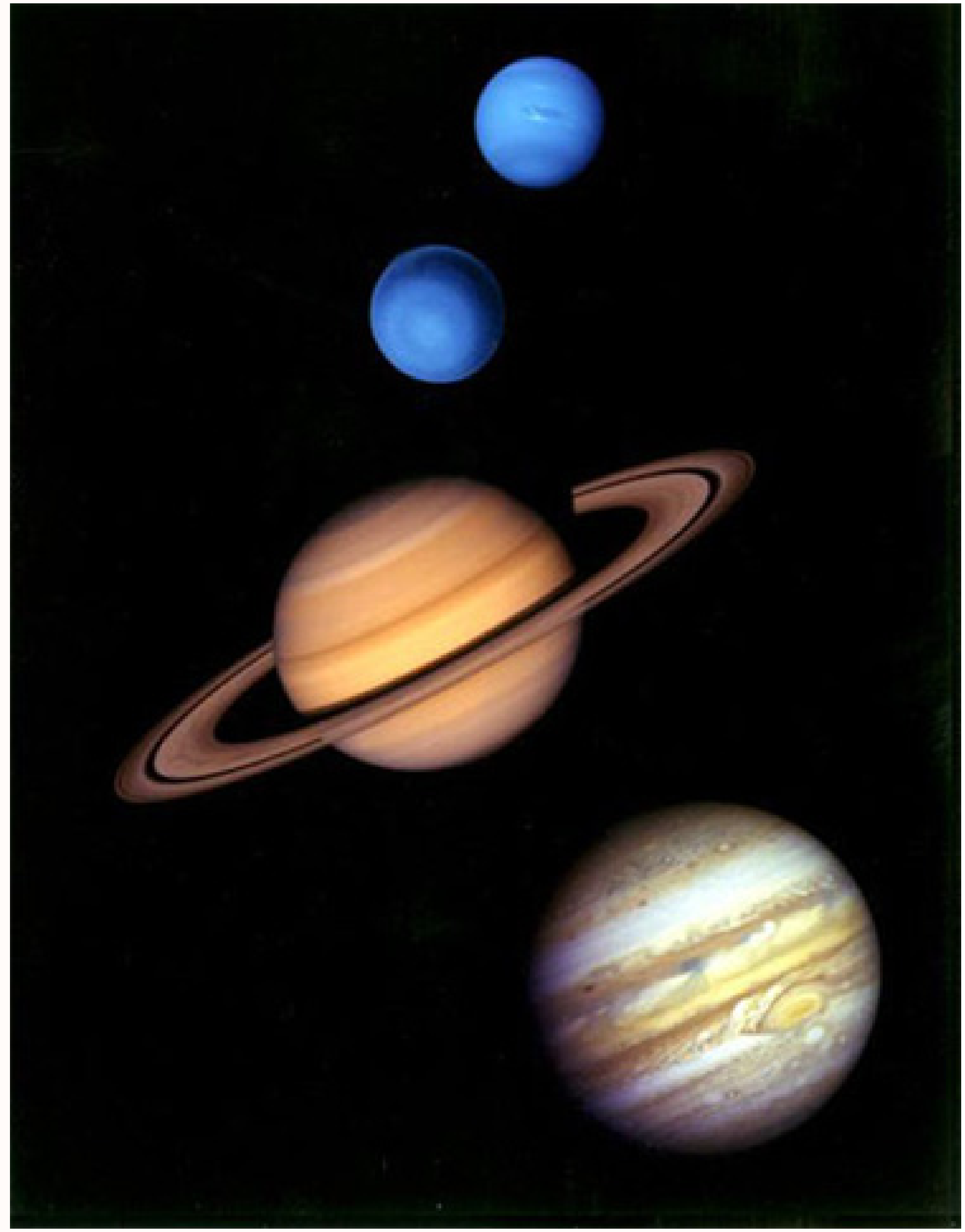
Professor Drew Endy

LIFE ON EARTH :

HOW DID WE GET FROM THERE,TO HERE?

(OR, LESSONS IN GEOBIOLOGICAL ENGINEERING)

Microbes thrive at the extreme ranges of temperature, salinity, pH, pressure, water activity …..



<u>Whats needed for life</u>

Energy (light, oxidants, reductants)
Water (liquid)
Basic elements :
C, H, N, O, P, S + trace metals

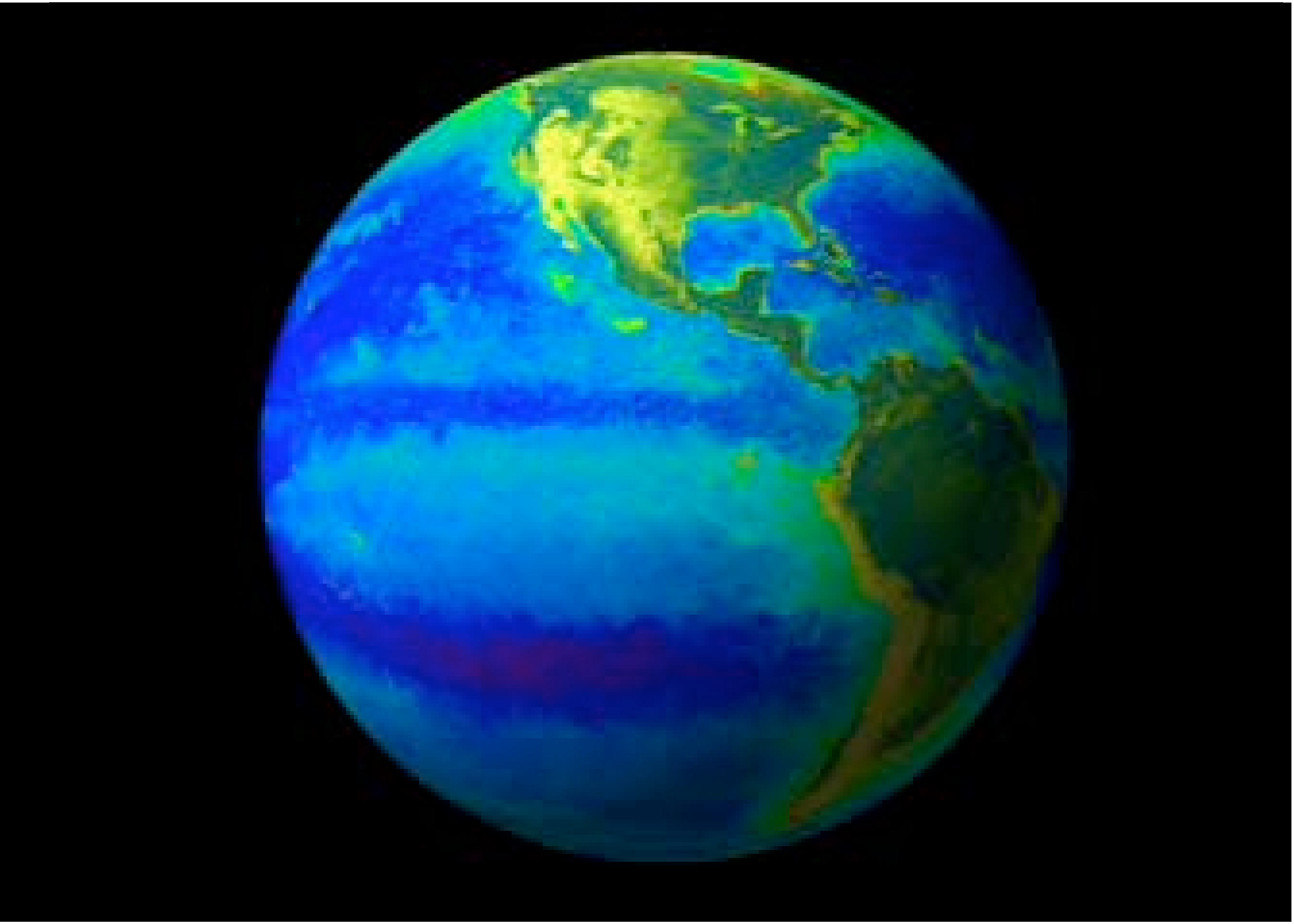
Microbial life thrives wherever these are found …

THE EARLY EARTH SYSTEM

1) The formation of the Earth
2) Early Earth physical and chemical conditions
3) Atmospheric and ocean “evolution”
4) The evolution of life
5) The evolution of photosynthesis

THE EVIDENCE

1) Isotopic record
2) Rocks and Microfossils
3) Organic Geochemical Record (“molecular fossils”)
4) Molecular Evolution



D. J. Des Marais

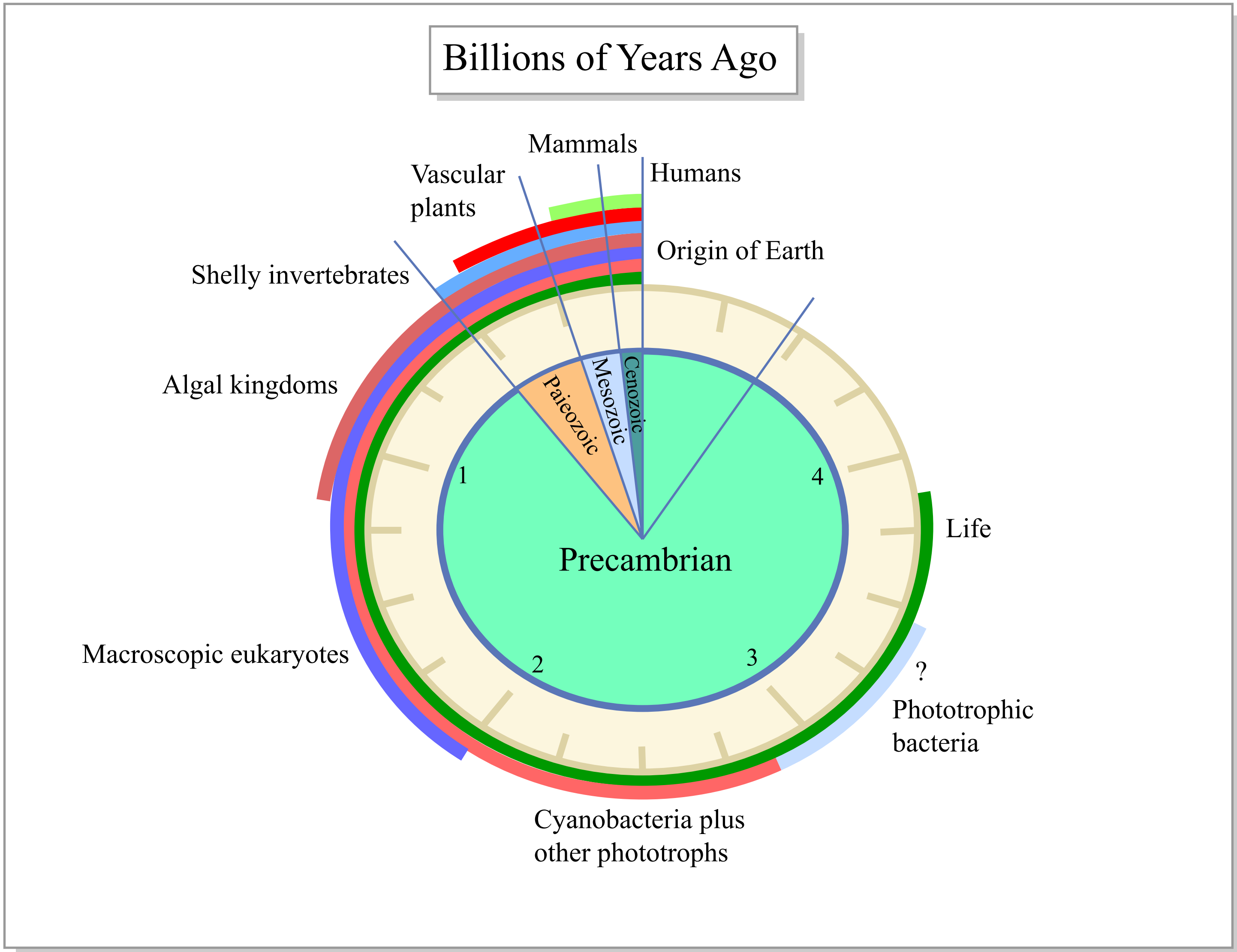


Figure by MIT OCW.

Science, Vol 289, Issue 5485, 1703-1705 , 8 September 2000

What was the early Earth really like ????

1) Was the early Earth hot or cold?
2) Was there lots of NH_3, hydrogen and methane in Earth's atmosphere?
3) What was the redox potential of the ocean and atm ?

Image removed due to copyright restrictions.

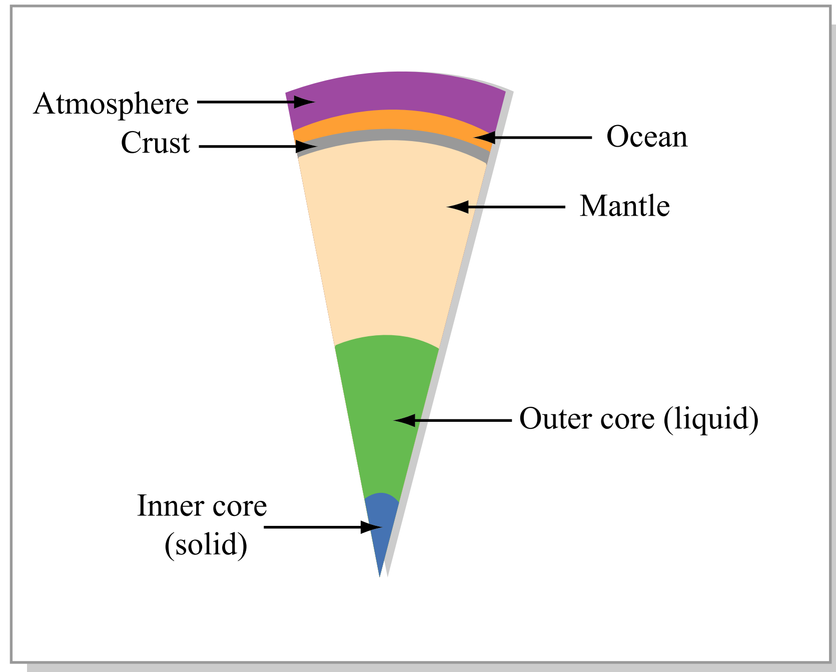


Figure by MIT OCW.

The Early days … (first few million years)

1. **Accretion**. Impacting bodies bombard the Earth and convert their energy of motion (kinetic energy) into heat. In recent years we also learned that an early collision with a very large object was responsible for the "extraction" of the Moon from Earth.

2. **Self-compression**. As the Earth gets bigger, the extra gravity forces the mass to contract into a smaller volume, producing heat (just like a bicycle pump gets hot on compression).

3. **Differentiation**. Conversion of gravitational potential energy to heat during core formation

3. **Short-lived radiogenic isotopes**. The surrounding material absorbs the energy released in radioactivity, heating up.

So, how did life originally arise on Earth ???

1) ***In situ*, or panspermia ???**

2) **Oparin ocean scenario, or hydrothermal vents ?**

3) **Geo-template, or solution chemistry ?**

Images removed due to copyright restrictions.

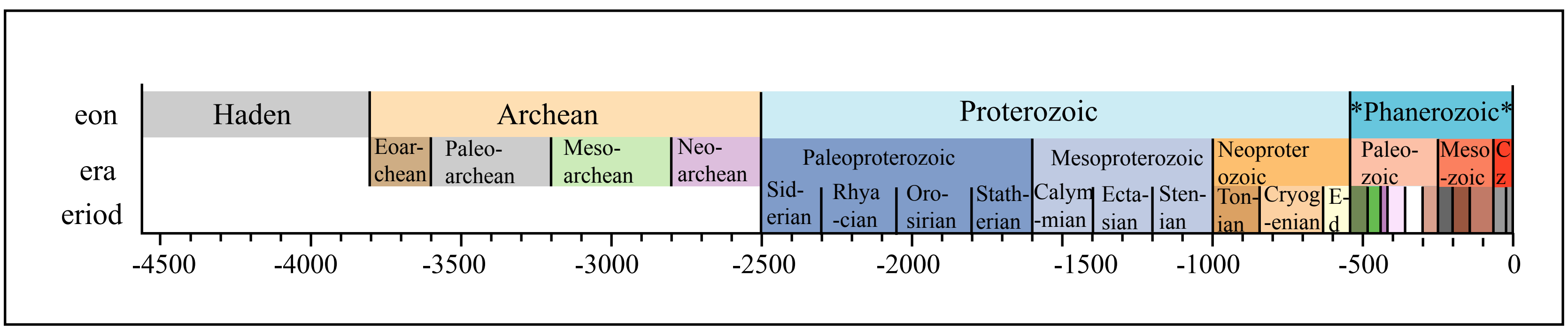


Figure by MIT OCW.

Atmospheric composition on the early Earth - still largely guesswork

Formation conditions

Initial Composition - Probably H_2, He These gases are relatively rare on Earth compared to other places in the universe and were probably lost to space early in Earth's history because Earth's gravity was not strong enough to hold lighter gases. Earth still did not have a differentiated core (solid inner/liquid outer core) which creates Earth's magnetic field (magnetosphere = Van Allen Belt) which deflects solar winds. Once the core differentiated the heavier gases could be retained.

"First" Atmosphere

Probably produced by volcanic out gassing. Gases produced were likely similar to those created by modern volcanoes (H_2O, CO_2, SO_2, CO, S_2, Cl_2, N_2, H_2) and NH_3 (ammonia) and CH_4 (methane).

Used to think mostly this in early atm ! But more of the other gases in volcanic Emmissions, and these detstroyed by UV & UV hydrolysis.

(Note: Mildly reducing, not strongly reducing …)

No free atmospheric O_2 in the Early Earth !!! (not found in volcanic gases)

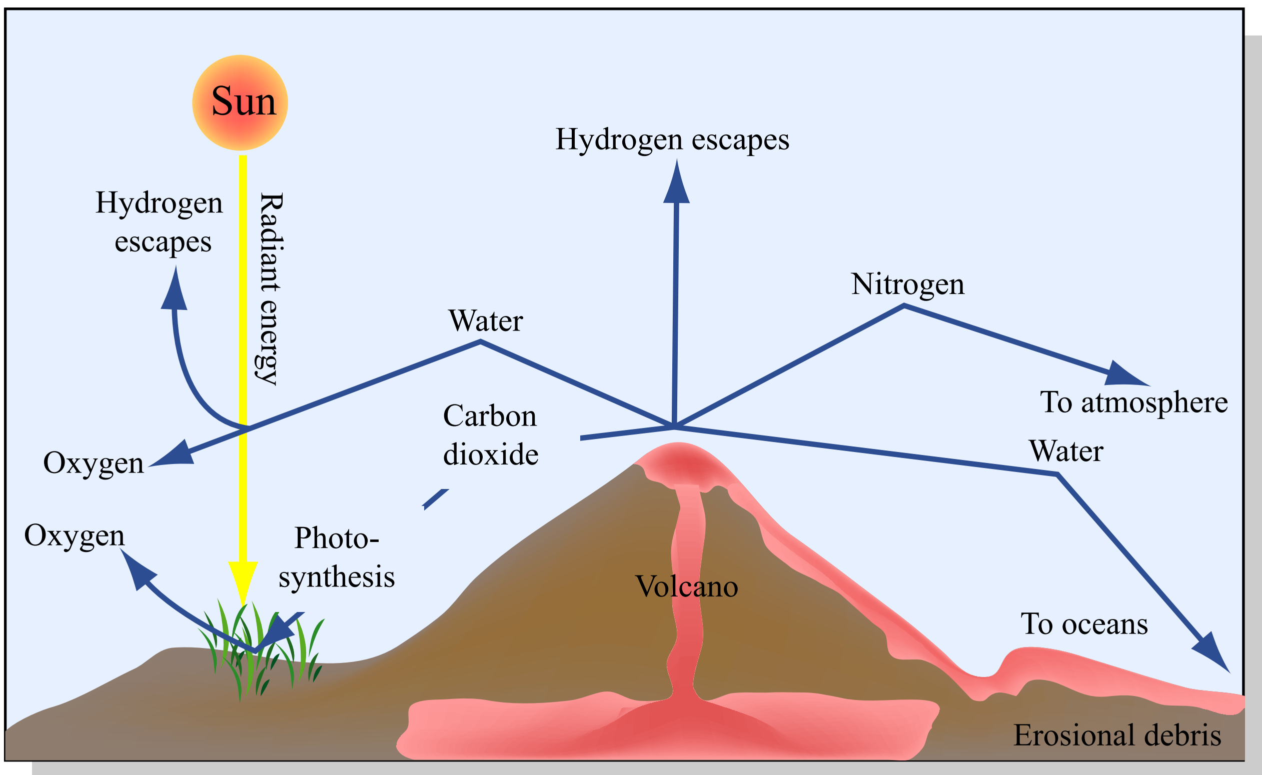


Figure by MIT OCW.

Present day volcanic gases

- **Water Vapor** 50--60%
- **Carbon Dioxide** 24%
- **Sulfur** 13%
- **Nitrogen** 5.7%
- **Argon** 0.3%
- **Chlorine** 0.1%

Atmosphere of Earth and its planetary neighbors - Why so different ?

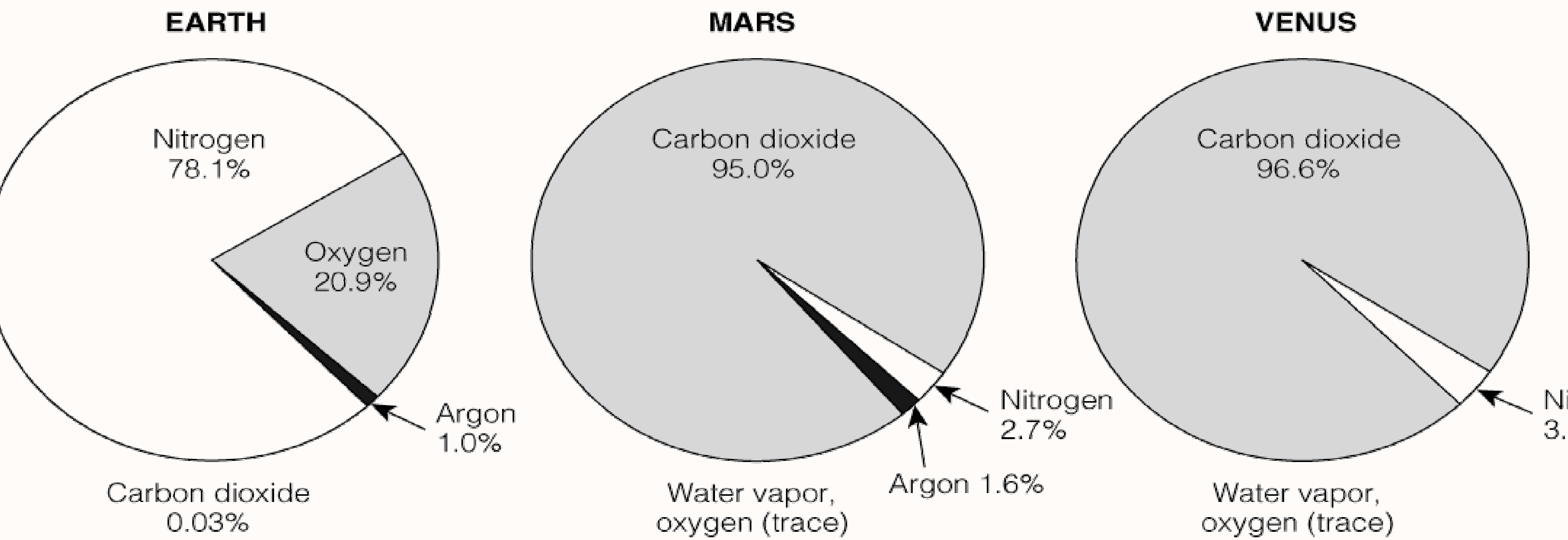


Table: the probable chemical composition of the atmosphere over time

Stage 1 (Early Earth)	*Stage 2 (~2 x 10^9 years ago)*	*Stage 3 (Today)*
Major components ($p > 10^{-2}$ atm)		
CO_2 (10 bar)		
N_2 (1 bar)	N_2	N_2
H_2 (?) / CH_4		O_2
CO		
Minor components ($10^{-2} > p > 10^{-6}$ atm)		
H_2 (?)	O_2 (?)	Argon
H_2O	H_2O	H_2O
H_2S	CO_2	CO_2 (10^{-3} bar)
NH_3	Argon	
Argon	(CO?)	
Trace components ($p < 10^{-6}$ atm)		
He	Ne	Ne
Ne	He	He
	CH_4	CH_4
	NH_3 (?)	CO
	SO_2	NO
O_2 (10^{-13} bar)	H_2S (?)	

Summary of data on the probable chemical composition of the atmosphere over time

Figure by MIT OCW.

Summary of some of the early Earth conditions

Lots of bolide impacts, volcanic activity

Much warmer average global temperature than today (80°C ?)

Mildly reducing conditions in the atmosphere (CO, CO_2, N_2, H_2O, CH_4)

Oceans formed > 3.8 bya (condensation from atm as Earth cooled)

No free oxygen (O_2) !!!

Image removed due to copyright restrictions

The Characteristics of the Ocean on Early Earth and Today

Proto-ocean (?)

pH = 2.0 (initial); T = 80°C

CO_2 and SO_2 not very soluble

HCL provides acidity

Initially weak content of cations, but increasing to Ca^{2+}, 115 mM; Mg^{2+}, 95 mM; Na^+, 120 mM; K^+, 60 mM

Redox potential around - 0.5 to 0.0 volts

Early Ocean

pH = 8.0; T = 55°C

HCO_3^- (CO_2) high; SO_4^{2-} low; H_2S high

$Ca^{2+} \geqslant 10$ mM

Fe^{2+}, 1 mM; $Zn^{2+} \leqslant 10^{-10}$ M

Redox potential > 0.0 rising to < 0.4volts

Late Ocean (today)

pH = 8.0; T = 25°C

HCO_3^- (CO_2) high, and SO_4^{2-} (not H_2S) present

Average concentrations of cations are Ca^{2+}, 10 mM; Mg^{2+}, 105 mM; Na^+, 470 mM; K^+, 10mM

Redox potential up to 0.80 volts at surface (O_2)
Fe^{3+}, 10^{-17}M

Figure by MIT OCW.

*Some Trace Elements In The Early Sea**

Elements Present

Fe^{2+}, Mn^{2+}, (Mo^{6+}), V^{4+}, (Ni^{2+}), W^{6+}, (Co^{2+}), Se as H_2Se

Elements Largely Absent

Cu^{2+}, Cd^{2+}, Zn^{2+}, Cr^{3+}, Ti^{3+}

**The assumption is that the pH > 5 and the amount of H_2S kept the sea as a reducing medium. The concentration of Mo^{6+} may have been lower than that of W^{6+} as Mo is precipitated as MoS_2 at low pH.*

Figure by MIT OCW.

Diagram removed due to copyright restrictions.

See Figure 11-8 in Madigan, Michael, and John Martinko. *Brock Biology of Microorganisms*. 11th ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2006. ISBN: 0131443291.

THE EARLY EARTH SYSTEM

1) The formation of the Earth
2) Early Earth physical and chemical conditions
3) Atmospheric and ocean "evolution"
4) The evolution of life
5) The evolution of photosynthesis

THE EVIDENCE

1) Isotopic record
2) Rocks and Microfossils
3) Organic Geochemical Record ("molecular fossils")
4) Molecular Evolution

1920s. **The Oparin-Haldane model**

Under strongly reducing conditions (theorized to have been present in the atmosphere of the early earth), inorganic molecules could spontaneously form organic molecules (simple sugars and amino acids).

Inorganic materials - > organic materials

Strongly reducing gases

CH_4, H_2, NH_4, H_20

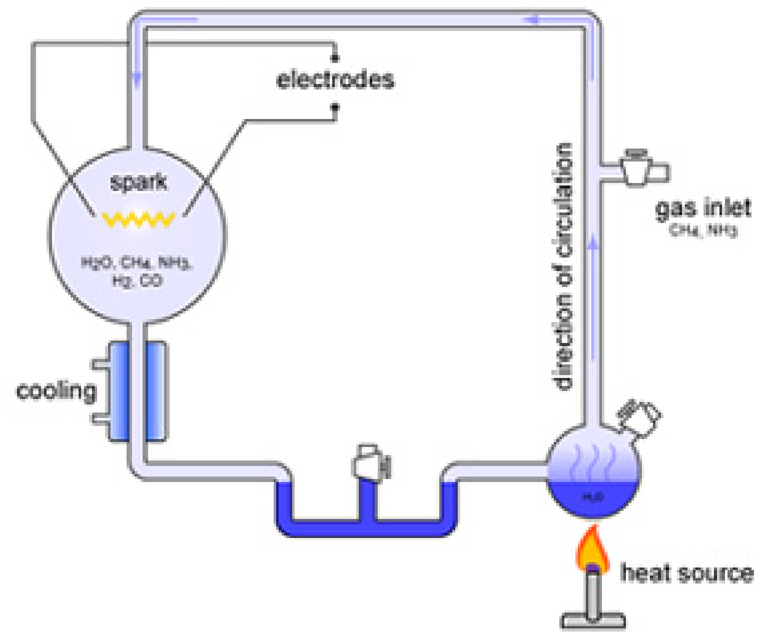
↓ *E*

CH3−CH(NH2)−COOH

amino acids,

sugars, etc …å

Miller Urey experiment



Diagrams removed due to copyright restrictions.

See Figures 11-11 and 11-5 in Madigan, Michael, and John Martinko. *Brock Biology of Microorganisms*. 11th ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2006. ISBN: 0131443291.

THE EARLY EARTH SYSTEM

1) The formation of the Earth
2) Early Earth physical and chemical conditions
3) Atmospheric and ocean "evolution"
4) The evolution of life
5) The evolution of photosynthesis

THE EVIDENCE

1) Isotopic record
2) Rocks and Microfossils
3) Organic Geochemical Record ("molecular fossils")
4) Molecular Evolution

THE EVIDENCE

Microfossils

Microfossils of the Early Archean Apex Chert: New Evidence of the Antiquity of Life

J. William Schopf *Science*, New Series, Vol. 260, No. 5108. (Apr. 30, 1993), pp. 640-646

Diagram removed due to copyright restrictions.

Image removed due to copyright restrictions.

See Figure 11-3 in Madigan, Michael, and John Martinko. *Brock Biology of Microorganisms*. 11th ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2006. ISBN: 0131443291.

Images of "macrofossils" removed due to copyright restrictions.

Ozark Precambrian

Microbes that make "macrofossils"

Stromatolites

STROMATOLITES

Stromatolites are formed through the activity of primitive unicellular organisms: cyanobacteria (which used to be called blue-green algae) and other algae. These grow through sediment and sand, binding the sedimentary particles together, resulting in successive layers which, over a long period of time, harden to form rock. For at least three-quarters of the earth's history stromatolites were the main reef building organisms, constructing large masses of calcium carbonate.

Images of stromatolites removed due to copyright restrictions.
See Figure 11-2 in Madigan, Michael, and John Martinko. *Brock Biology of Microorganisms*.
1th ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2006. ISBN: 0131443291.

STABLE ISOTOPE ANALYSIS, ORGANIC GEOCHEMISTRY, AND THE HISTORY OF LIFE ON EARTH

Internal structure of an atom

Z = number of protons, the number of electrons, the “atomic number”
N = number of neutrons, the “neutron number”

A = Z + N the “mass number”

Ex:

mass number

$^{14}_{6}C$ has 6 protons, 6 electrons, and 14-6=8 neutrons

atomic number

Ad-hoc definition of atomic weights

^{12}C has 6 protons and 6 neutrons = 12 subatomic particles with appreciable mass

So … one atom ^{12}C = 12.000000 amu

1 atomic mass unit (amu) = 1/12 the mass of ^{12}C

And … one mole of ^{12}C = 12.000000 g, one mole = 6.022e23 atoms

Stable isotope abundances

ELEMENT	ISOTOPE	ATOMIC WEIGHT (amu)	ABUNDANCE (atom %)
HYDROGEN		1.0079	
(Z=l)	^{1}H (Protium)	1.007825	99.985
	^{2}H (D, for Deuteriun	2.014102	0.015
CARBON		12.011	
(Z=6)	^{12}C	12	98.9
	^{13}C	13.00335	1.1
NITROGEN		14.0067	
(Z=7)	^{14}N	14.003074	99.63
	^{15}N	15.00109	0.37
OXYGEN		15.9994	
(Z=8)	^{16}O	15.994915	99.76
	^{17}O	16.999131	0.04
	^{18}O	17.99916	0.2

From Walker et al. (1989) Nuclides and Isotopes

ISOTOPE RATIOS, R

ALWAYS: R = HEAVY ISOTOPE/ LIGHT ISOTOPE

THAT IS: R = RARE ISOTOPE / ABUNDANT ISOTOPE

e.g. D/H, $^{13}C/^{12}C$, $^{15}N/^{14}N$, $^{18}O/^{16}O$, $^{34}S/^{32}S$

The delta value δ – comparing isotope ratios

In practice, stable isotope measurements are made by mass spectroscopy, comparing isotopic ratios of a given sample to those of a known standard.

Hence use δ-value:-

$$\delta_x = 1000\left(\frac{R_x - R_{std}}{R_{std}}\right)$$

‰ (permil)

Written δD (δ^2H), $\delta^{13}C$, $\delta^{15}N$ etc.

$\delta_x > 0 \Rightarrow R_x$ "heavier" than R_{std} ($\delta_x < 0 \Rightarrow R_x$ "lighter" than R_{std})

Non-Equilibrium Fractionation
Kinetic Isotope Effects

Bonds involving “light” isotopes break more readily than those involving “heavy” isotopes.

Rate determining step which includes breaking of bond dictates isotopic fractionation of entire process

Typical of processes which are unidirectional and irreversible

Biological Fractionation !

Example: Breathing - we use ^{16}O preferentially for respiration, so ^{17}O and ^{18}O become progressively more abundant in lung air and exhaled air)

Example: During photosynthesis, green plants "fix" CO_2

1. Primary step is diffusion of CO_2 atm into stomata

Photograph of stomata removed due to copyright restrictions.

2. Preferential utilization of "light" carbon by CO_2-fixing enzymes
   Preferential incorporation of ^{12}C in CO2 fixing plants - passed on to herbivores and up the food chain

Isotope Fractionation during Photosynthesis, ε_P

In photosynthesis $^{12}CO_2$ is preferentially taken up relative to $^{13}CO_2$. There are two stages when kinetic isotope effects can occur:

1. Transport (diffusion) processes

- Gas phase diffusion (*i.e.* Atmospheric $CO_2 \rightarrow$ dissolved CO_2 in leaf)
  - Approx. fractionation factor: 4.4 ‰ (i.e., depletion = -4.4 ‰)
  - Only important for emergent (vascular) plants where air/leaf interaction occurs.
- Liquid phase diffusion of CO_2 or HCO_3^-
  - Approx fractionation factor: 0.8 ‰ (relatively minor)

2. Chemical (Enzymatic) processes

- Four pathways:
  - (i) C_3 (Calvin-Benson)
  - (ii) C_4 (Hatch-Slack)
  - (iii) CAM
  - (iv) Bacterial

Photosynthetic microbial mats in the 3,416-Myr-old ocean

MICHAEL M. TICE AND DONALD R. LOWE

Nature **431**, 549 - 552 (30 September 2004)

Buck Reef Chert

a) 3.4 billion years old

b) Laminated mat-like structures

c) Stable carbon isotope signature suggests CO_2 fixation : $\delta\ ^{13}C = -35\ ^{o}/_{oo}$

d) Normal marine sediment
(not hydrothermal)
$\delta\ ^{13}C = -35\ ^{o}/_{oo}$

d) Evidence for photosynthesis
> 3.4 Bya ???

Images removed due to copyright restrictions.

“Molecular fossils” - organic geochemical markers

Archaean Molecular Fossils and the Early Rise of Eukaryotes

Jochen J. Brocks, Graham A. Logan, Roger Buick, Roger E. Summons (EAPS @ MIT)

Science, Vol 285, Issue 5430, 1033-1036 , 13 August 1999

Organic biomarkers from 2.7 billion year old shales

A) Steranes (cholestane) - eukaryotes

B) 2-methyl hopanes - cyanobacteria

Lots of care has to be taken
To ensure organics are derived
from the rock was buried - and
not contaminating material.
Hard stuff to do !!!

Graphs removed due to copyright restrictions.

BANDED IRON FORMATIONS

Geochemical evidence

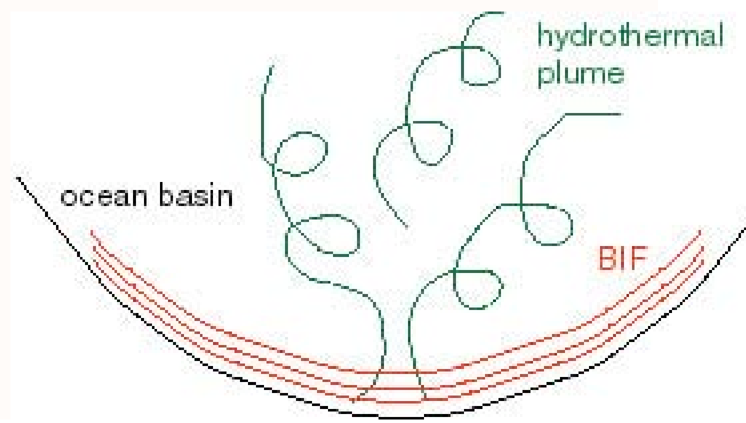
Photographs removed due to copyright restrictions.

Banded iron formations are very large bodies of sedimentary rock laid down some 2.5 - 1.8 billion years ago.

BIF formation seems to require anoxic deep waters for formation. Thus, if deep-sea O_2 became abundant, it could inhibit BIF formation (By formation of Fe-oxyhyriddes, and removal of Fe2+ from solution, precluding its transport to BIF formation zones.)

(BUT, alternative theory suggests Fe-sulfides can also highly insoluble. Was it oxygen or sulfide, that ended BIF deposition ??????)

Fe^{2+} very soluble
Fe^{3+} **insoluble**, precipitates from solution



Something BIG happened ~2.5 bya !!!

Photographs removed due to copyright restrictions.

"Red beds"

900 Ma - 150 Ma

$$FeSiO_4 \text{ (fayalite)} + 0.5O_2 \rightarrow \propto\text{-}Fe_2O_3 \text{ (haematite)} + SiO_2 \text{ (quartz)}$$

ife’s History on Earth