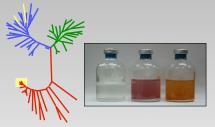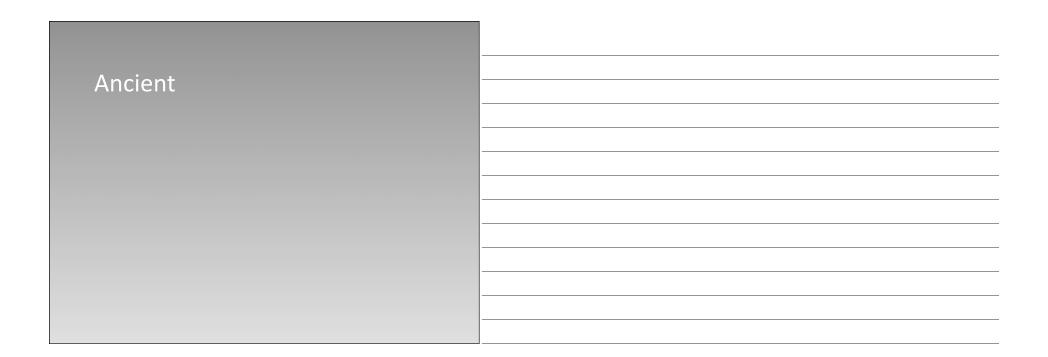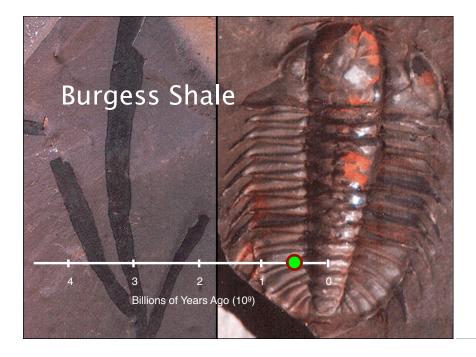# Microbial Diversity and Evolution
Part I: Overview

Professor Dianne Newman
Divisions of Biology and
Geological and Planetary Sciences
California Institute of Technology, and
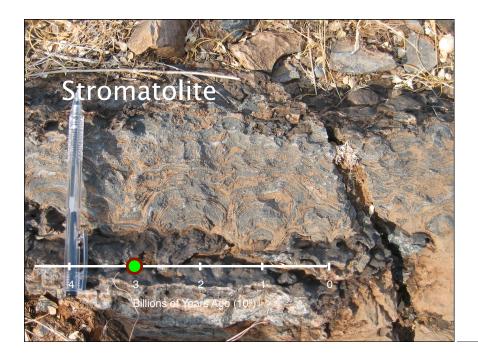Howard Hughes Medical Institute

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Ancient
Numerous
Ubiquitous
Diverse

Ancient

Burgess Shale

4   3   2   1   0

Billions of Years Ago (10^9)
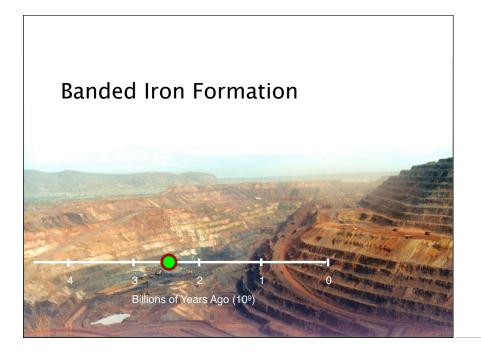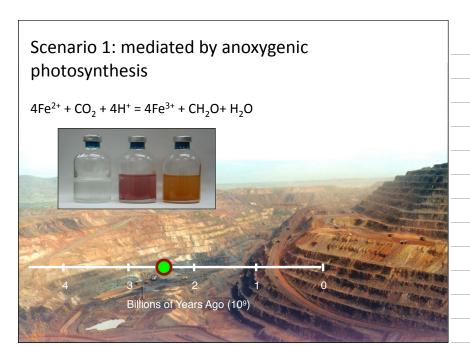
Cambrian Explosion
trilobite

Pongola, South Africa

Stromatolite

Billions of Years Ago (10^9)

Banded Iron Formation

Billions of Years Ago (10^9)
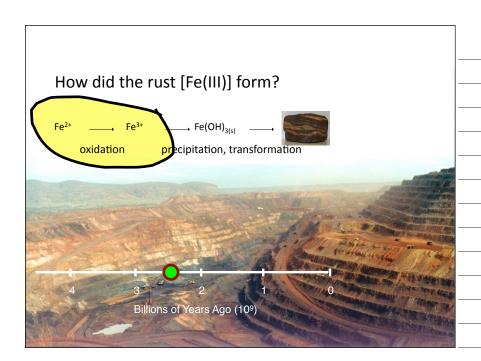
- Hammersley, Western Australia
- Characterized by laminations of Fe(III) minerals and chert (Si)
- ~>15 wt % Fe
- Account for 90% of the world's Fe

How did the rust [Fe(III)] form?

$Fe^{2+} \longrightarrow Fe^{3+} \longrightarrow Fe(OH)_{3(s)} \longrightarrow$

oxidation   precipitation, transformation

4   3   2   1   0

Billions of Years Ago (10^9)

Scenario 1: mediated by anoxygenic photosynthesis

$4Fe^{2+} + CO_2 + 4H^+ = 4Fe^{3+} + CH_2O + H_2O$

4   3   2   1   0

Billions of Years Ago (10^9)

Scenario 2: mediated by oxygenic photosynthesis

i.) $H_2O + CO_2 = CH_2O + O_2$
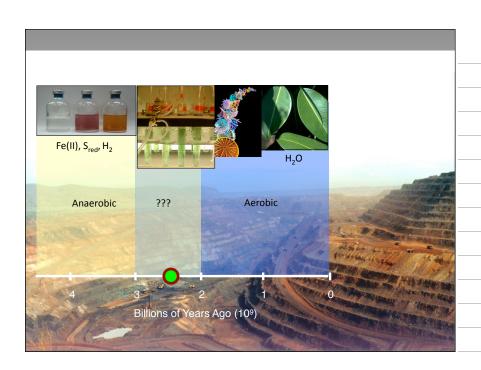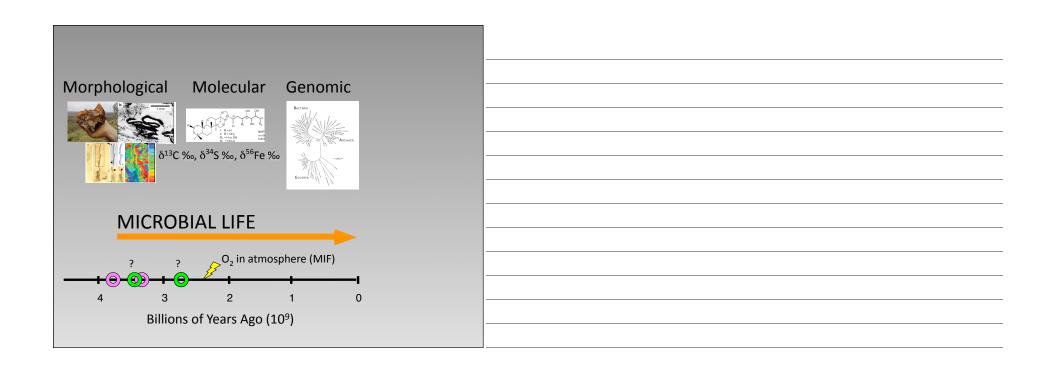
ii.) $4Fe^{2+} + O_2 + 4H^+ = 4Fe^{3+} + 2H_2O$

4   3   2   1   0
Billions of Years Ago (10^9)

Fe(II), S_{red}, H_2

H_2O

Anaerobic   ???   Aerobic

4   3   2   1   0
Billions of Years Ago (10^9)

Morphological   Molecular   Genomic

$\delta^{13}C$ ‰, $\delta^{34}S$ ‰, $\delta^{56}Fe$ ‰

MICROBIAL LIFE

O_2 in atmosphere (MIF)

?   ?

4   3   2   1   0

Billions of Years Ago (10^9)

Ancient
Numerous

How many microbes are there on Earth?

Human Population:

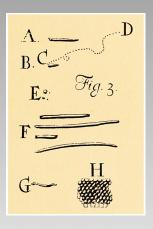|		
Los Angeles	10,000,000	10×10^6
California	35,000,000	35×10^6
United States	290,000,000	290×10^6
World	6,300,000,000	6×10^9

Microbial Population:

5,000,000,000,000,000,000,000,000,000,000

$$5 \times 10^{30}$$

Microbes = 200 trillion (10^{12}) Earth-Sun distances

"Prokaryotes: the Unseen Majority", PNAS, 95:6578-6583 (1998)

Where do they live?

Antony van Leeuwenhoek
1684

Where do they live?

Antony van Leeuwenhoek
1684

"...Tho my teeth are
kept usually very clean,
nevertheless when I view
them in a magnifying glass,
I find growing between them
white matter as thick as a
wetted flower...
...The number of these
animals in the scurf of a
mans teeth, are so many that
I believe they exceed the
number of men in a kingdom."

Where do they live?

On Humans:

Skin:	$5\text{-}50 \times 10^3$/sq. inch
Groin, Axillia:	5×10^6/sq. inch
Teeth	$5\text{-}50 \times 10^6$/sq. inch
Colon:	300×10^9/g

Total per person: (70 trillion, 70×10^{12})

~10X number of
human cells
Gut microbiome >100X
human genome!

"Prokaryotes: the Unseen Majority", PNAS, 95:6578-6583 (1998)

Where do they live?

Air:
  Detected as high as 34-46 mi 5.0×10^{19}

Animals:
  All Humans 4.0×10^{23}
  Domestic animals, Termites 5.0×10^{24}

Soils:
  Forests, Grassland, Desert,
    Tundra, Swamps 2.5×10^{29}

Aquatic:
  Marine and Freshwater
            10^6-10^7 cells/ounce 1.0×10^{29}

Subsurface:
    Terrestrial and Deep Ocean
    Detected as deep as 2 mi. 3.8×10^{30}

"Prokaryotes: the Unseen Majority", PNAS, 95:6578-6583 (1998)

Ancient
Numerous
Ubiquitous

Ponds

Oxygenic/anoxygenic phototrophs
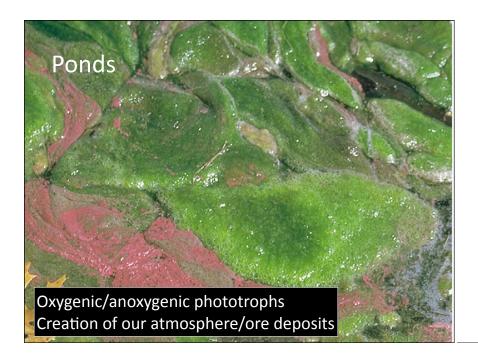Creation of our atmosphere/ore deposits

Figure: 12-005

Caption:
Blooms of purple sulfur bacteria. (a) Thiopedia roseopersicinia, in a sulfide spring in Madison, Wisconsin. The bacteria grow near the bottom of the spring pool and float to the top (by virtue of their gas vesicles) when disturbed. The green color is from cells of the eukaryotic alga Spirogyra.
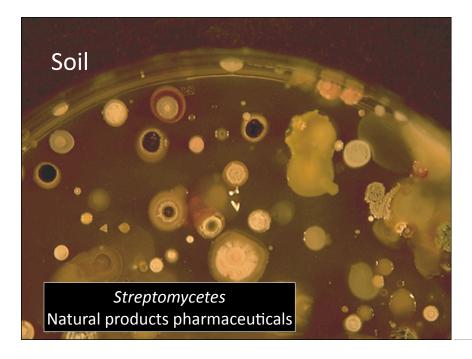

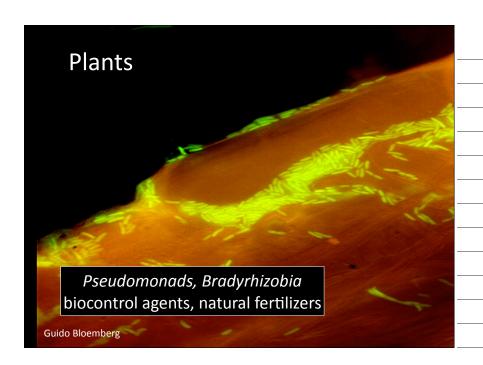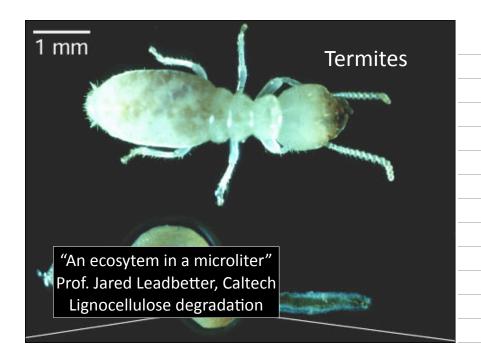**Soil**

Streptomycetes
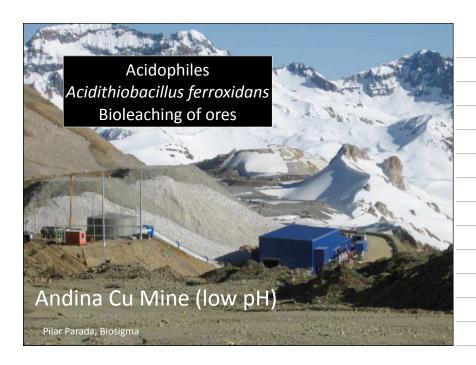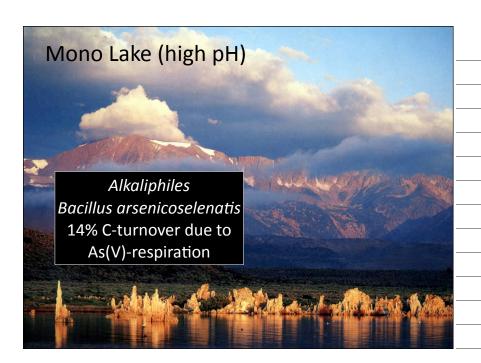Natural products pharmaceuticals

Figure: 12-076

Caption:
Streptomyces. (a) Colonies of Streptomyces and other soil bacteria derived from spreading a soil dilution on a casein-starch agar plate. The Streptomyces colonies are of various colors (several black Streptomyces colonies are in the foreground) but can easily be identified by their opaque, rough, nonspreading morphology.

Plants

Pseudomonads, Bradyrhizobia
biocontrol agents, natural fertilizers

Guido Bloemberg

Termites

1 mm

"An ecosytem in a microliter"
Prof. Jared Leadbetter, Caltech
Lignocellulose degradation

Sediments

Methanogens
Shaped early Earth's atmosphere

Microbial Diversity Course, Woods Hole

Acidophiles
Acidithiobacillus ferroxidans
Bioleaching of ores

Andina Cu Mine (low pH)

Pilar Parada, Biosigma

Mono Lake (high pH)

Alkaliphiles
Bacillus arsenicoselenatis
14% C-turnover due to
As(V)-respiration

Dead Sea (28% salt)

Halophilic archaea use
special photopigments to grow
(why salt flats appear purple)

Antarctica

Psychrophiles
Nutrients from aeolian dust

Black Smokers

Shanna Goffredi

Barophiles
Live at extreme pressures
Symbioses fed by sulfide sustain
abundant marine life (>1000 atm)
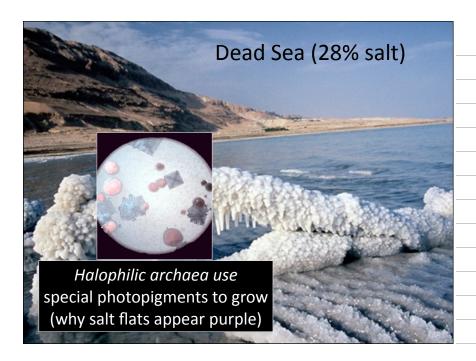
Geysers
High temperature

Thermophiles
Thermus aquaticus
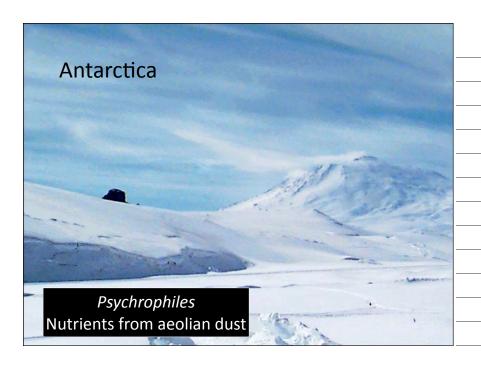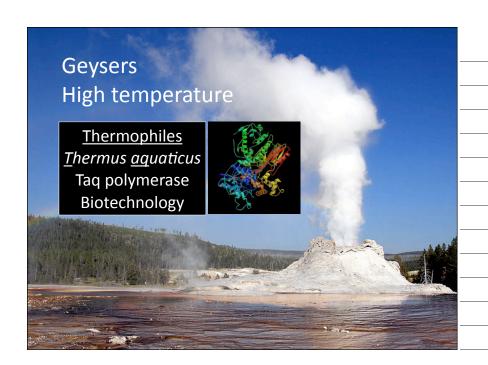Taq polymerase
Biotechnology

Ancient
Numerous
Ubiquitous
Diverse

Ancient
Numerous
Ubiquitous
Diverse

Phylogenetic diversity

Bacteria

Mitochondrion

Chloroplast

Archaea

Eucarya
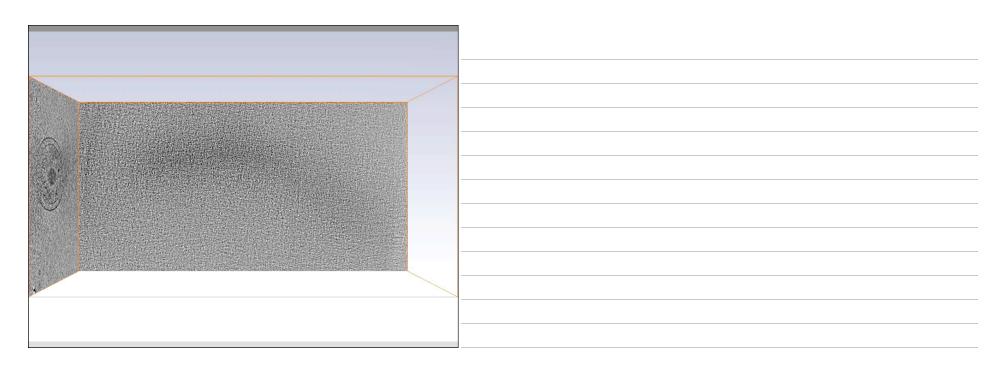
C. Woese, N. Pace

Ancient
Numerous
Ubiquitous
Diverse

Morphological diversity,
Sophisticated cell biology

Thiomargarita namibiensis
Diameter 0.75 mm

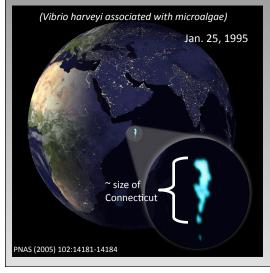*M. Dworkin*

Fruit fly

H. Schulz

Myxobacteria

100 nm

Ancient
Numerous
Ubiquitous
Diverse

Behavioral Diversity
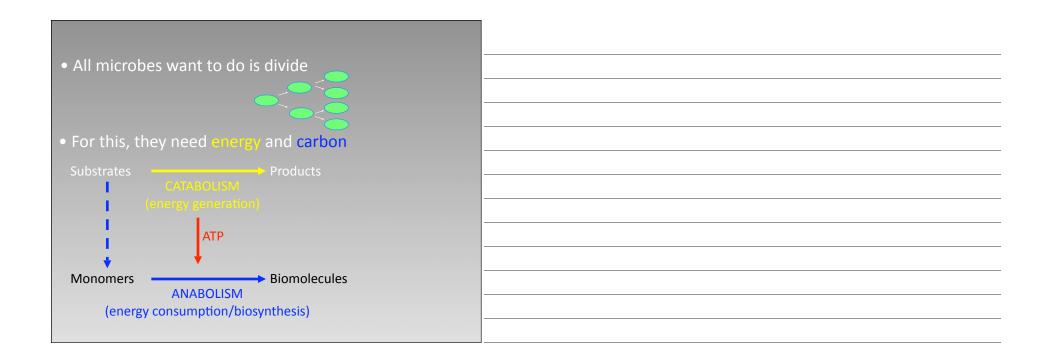
Some bacteria glow in the dark…

Hawaiian bobtail squid
Euprymna scolopes

Vibrio fisherii

M. Mcfall-Ngai and N. Ruby, UW-Madison   Egland and Leadbetter, U. Iowa

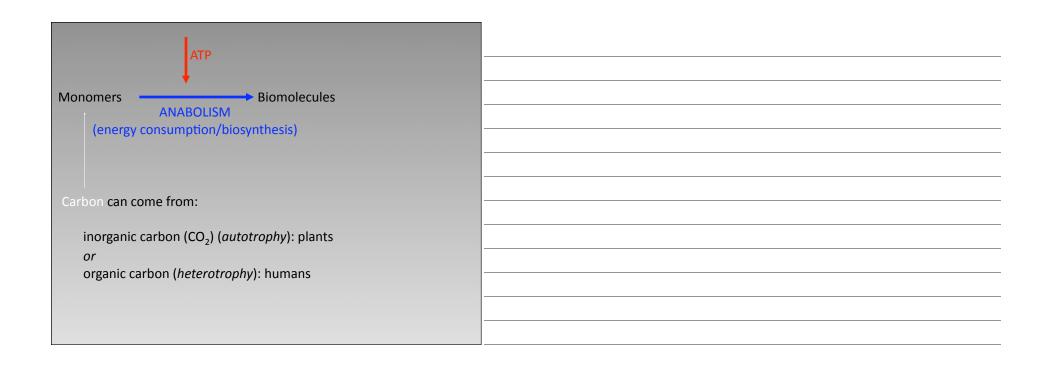## ...and are responsible for the "milky seas" described by ancient mariners

(Vibrio harveyi associated with microalgae)

Jan. 25, 1995

~ size of Connecticut

PNAS (2005) 102:14181-14184
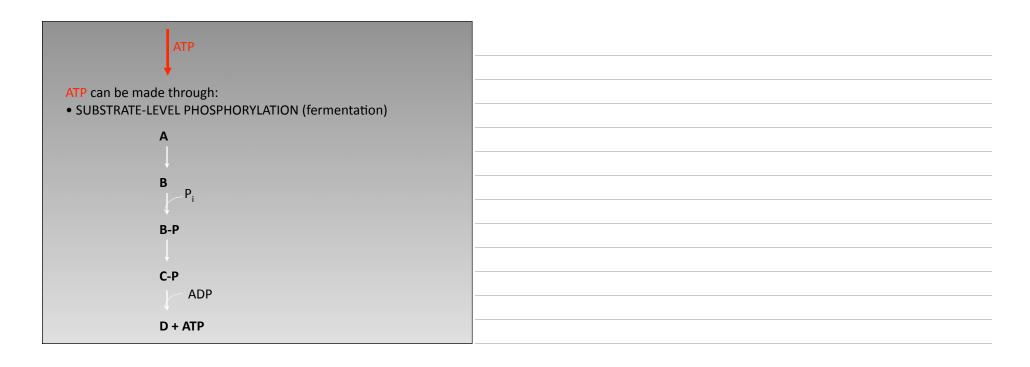
Ancient
Numerous
Ubiquitous
Diverse

Metabolic diversity rules!

Slide 1

- All microbes want to do is divide

- For this, they need **energy** and **carbon**

Substrates ⟶ Products
CATABOLISM
(energy generation)

ATP

Monomers ⟶ Biomolecules
ANABOLISM
(energy consumption/biosynthesis)

Slide 2

Substrates ⟶ Products
CATABOLISM
(energy generation)

ATP

Energy can come from:

chemicals (chemotrophy)
- inorganic (chemo*litho*trophy): H_2, H_2S, $FeS_{2(s)}$…
- organic (chemo*organo*trophy): glucose…
and/or
sunlight (phototrophy)

ATP

Monomers ———————→ Biomolecules
         ANABOLISM
    (energy consumption/biosynthesis)

Carbon can come from:

   inorganic carbon (CO_2) (*autotrophy*): plants
   or
   organic carbon (*heterotrophy*): humans

ATP

ATP can be made through:
• SUBSTRATE-LEVEL PHOSPHORYLATION (fermentation)

   A
   ↓
   B
   ↓ P_i
   B-P
   ↓
   C-P
   ↓ ADP
   D + ATP

• OXIDATIVE PHOSPHORYLATION
(electron transport chains in membranes)

energized membrane

ADP + P_i

ATP

less energized membrane

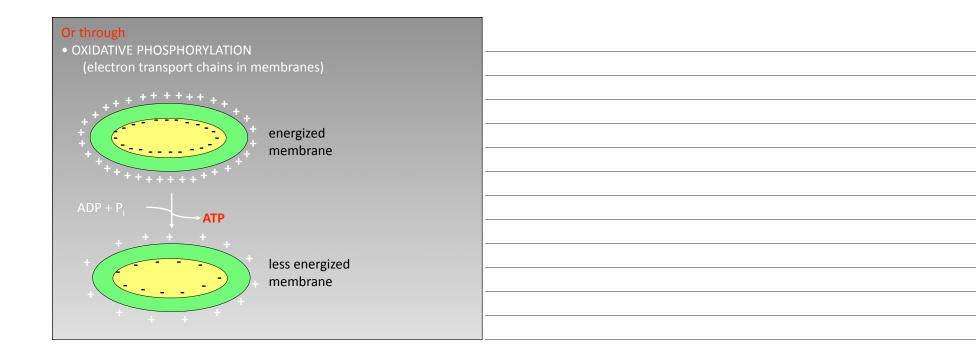## Metabolic diversity is vast & modular, yet subject to certain limits:

1. It must provide the minimal amount of energy necessary to sustain the cell (thermodynamics)

$\Delta G = -nF\Delta E$ (kJ/mol)

n = number of e^- transferred
F = Faraday constant
ΔE = difference in redox potential

$\Delta G = -4$ (kJ/mol)

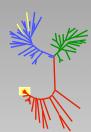"Anaerobic metabolism can proceed close to thermodynamic limits", *Nature (2002)* 415:454-456

Metabolic diversity is vast & modular,
yet subject to certain limits:

2. The substrates must be bioavailable
   (kinetics, transport issues
   across the membrane)

3. The substrates or products must
   not be toxic

"Anaerobic metabolism can proceed close to thermodynamic limits", *Nature (2002)* 415:454-456

SUMMARY

Ancient
Numerous
Ubiquitous
Diverse