SCIENCE

LIFE

Prof Peter O'Donoghue

1

Blackboard exercise (define life)

Cellular basis

Hydrocarbons (H, O. C)
Water (polar, solvent, pH)
Macromolecules (metabolism)
- protein (esp enzymes)
- sugar (E)
- nucleotides (genes) → replication
- fat (membranes) →

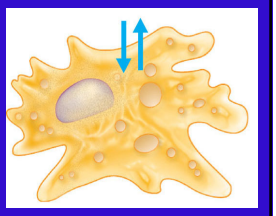
Energy/vitality (electron/proton flow)

All over small distances (um) → microscopic

2

What is LIFE?

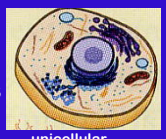
Living organisms are:
- self-replicating,
- membrane-bound,
- microscopic
- bags of
- sugary,
- proteinaceous
- water



3

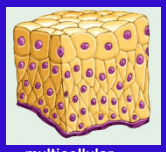
Why bags?

Cells are basic units of life
- preserve structural integrity
- maintain boundary between internal & external environments



unicellular

Cells possess:
- internal cytoskeletal elements
- internal organelle systems
- centralized genetic material

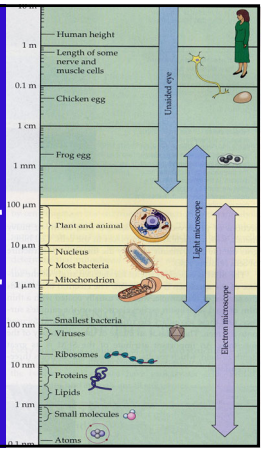


multicellular

4

Why microscopic?

- cells 1-100 μm (note log scale)
- need to preserve high surface-to-volume ratio (for efficient molecular transport)
- imagine cell as cube [double length involves 4-fold change in area and 8-fold change in volume]



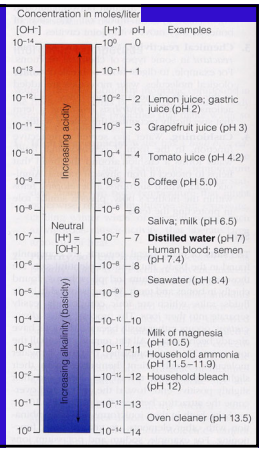
5

Why water?

fantastic molecule
- polar charge (adhesion/cohesion)
- universal solvent (dissolve electrolytes, sugars, proteins, etc)
- biochemical reactant (hydrolysis)

H_2O dissociation into ions
acid-base balance
$[H^+]\,[OH^-] = 10^{-14}$

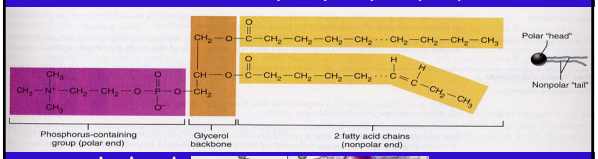
cumbersome, so developed
pH scale = -log $[H^+]$
physiological saline pH 7.4



6

Why membrane-bound?

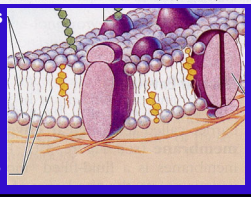
- membranes hold cells together
- made of insoluble phospholipids (fats)



polar heads

phospholipid bilayer

nonpolar tails



semipermeable membrane

plus embedded proteins, sugars, cholesterol, filaments

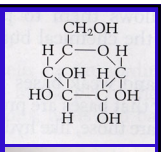
7

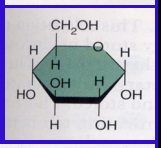
Why sugar?

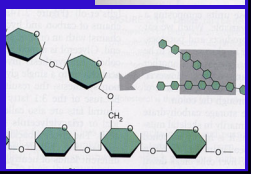
carbo-hydrates (sugars)
rich source of energy
(stored in molecular bonds)

glucose $C_6H_{12}O_6$

- produced by plants (photosynthesis)
- used by animals (glycolysis)
- stored as glycogen



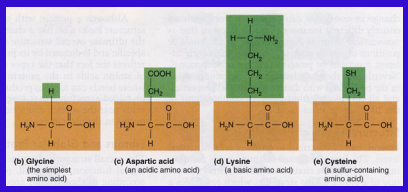




8

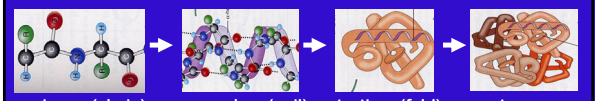
Why proteinaceous?

Building blocks of life (structural, functional)
polymers composed of chains of amino acids



20 amino acids produced

chains with 3D structure



primary (chain) secondary (coil) tertiary (fold) quaternary

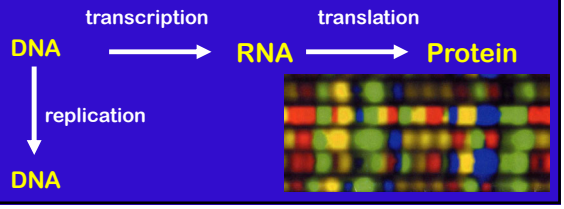
9

Why self-replicating?

Cells not immortal (need to grow and divide)

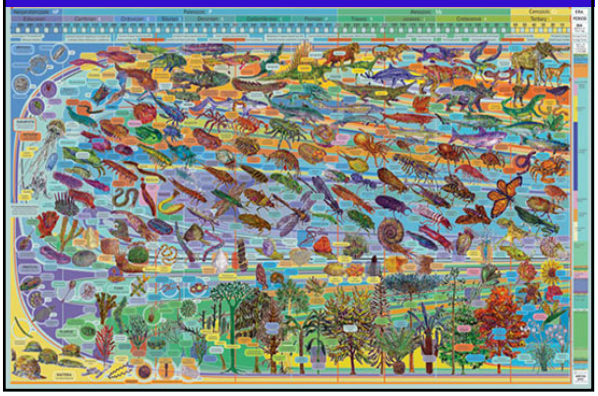
Type of division

- asexual (mitosis, fission, budding, endogeny)
- sexual (meiosis)



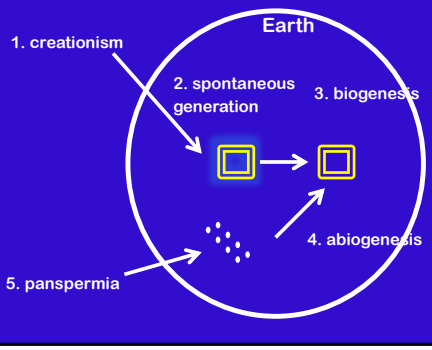
10

Biodiversity (N = 1,749,577)



11

Blackboard exercise (origins)



12

ORIGIN OF LIFE?

Historically a mixture of pseudo-science and science

- creationism (life from God)
- spontaneous generation (life from non-life)
- biogenesis (life from life)
- abiogenesis/biopoiesis (life from inorganic matter)
  - extra-terrestrial (panspermia theories)
  - terrestrial (multiple theories)

13

Scientific extrapolation

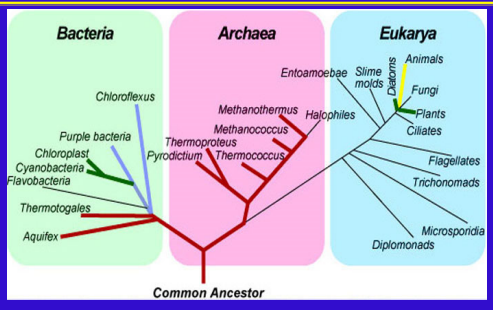
Work with extant/extinct physical forms
- comparative biology (greatest divide – 'Prokaryotes'/Eukaryotes)
  - chemical basis (hydrocarbon macromolecules)
  - cellular basis (hereditary, metabolism)
- paleontology (microfossils – oldest 3.5 BYA)
- phylogenetic reconstruction (differential 'molecular clocks')
- environmental prerequisites (vary with time, 'Goldilocks' zone)

Speculation
- common ancestry (Last Universal Common Ancestor - LUCA)

Why study 'origins'?
- Understand past - esp. evolution (competition/collaboration)
- Understand present - esp. interactions (eco-systems)
- Predict /manipulate future!

14

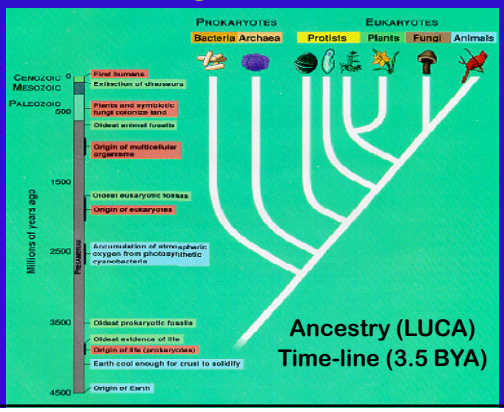
Three domains of life*



Remarkable uniformity:
biochemistry, metabolism, reproduction, cellularity…

15

Six kingdoms of life*



Ancestry (LUCA)
Time-line (3.5 BYA)

16

History of planet Earth

- 4.5 BYA Earth forms
- 4.3 BYA water
- 4.1 BYA massive bombardment
- 4.0 BYA carbon

prebiotic

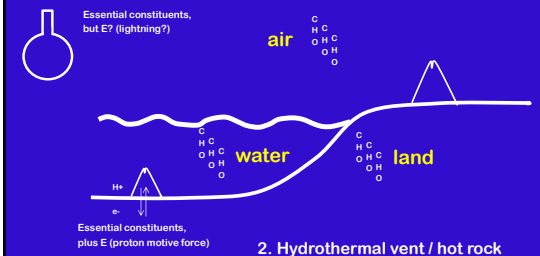
- 3.5 BYA first archaea
- 3.2 BYA first eubacteria
- 2.4 BYA photosynthesis
- 1.9 BYA first eukaryotes
- 0.5 BYA first animals
- 66 MYA dinosaurs
- 5 MYA hominids

biotic

17

Blackboard exercise (where?)

1. Warm pond



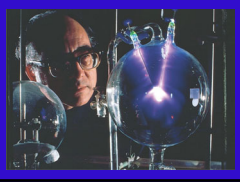
2. Hydrothermal vent / hot rock

Life driven by thermodynamics
[reactions create energy under certain conditions]

18

Prebiotic conditions

- 50 years ago, Miller & Urey simulated primordial environmental conditions in glass flasks
- ocean of water (polar molecule, universal solvent) + atmosphere of hydrogen, carbon dioxide, methane, ammonia + volcanic heat + lightning sparks
- observed spontaneous synthesis of organic compounds, including simple amino acids and sugars



19

Origin of organic molecules

Primordial soup (components)
- warm pond (oceanic/atmospheric)
- hydrothermal vents (upwellings)
- hot rock (nanobes)

Structured models (templates)
- pyrites (iron-sulfur world) (built-in E)
- sphalerite (zinc world) (retain radiant E)
- radioactive beach (actinides)
- community clay (mineral crystals)

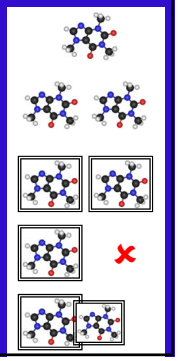
Stochastic models (unpredictable)
- hypercycles (ribozymes)
- autocatalysis (chemical networks)

20

Blackboard exercise (series of small steps)

Abiogenesis

1. formation of organic molecules
2. self-replication
3. enclosure by membrane
4. natural selection
5. serial endosymbiosis



21

1. Organic molecules

$CO_2 + H_2 \rightarrow$ organic molecules + E

need proton-motive force (electrical driving force)

cells powered by electricity (difference in concentration of protons across membrane)

produces electrical potential difference of ~150 mV but operates only over 5 nm

(equivalent to 30 million volts per metre)

(similar to lightning)

used to make E-rich fuel ATP, power flagella, etc

but how to establish proton gradient?

22

Proton gradients

Natural proton gradients

= alkaline hydrothermal vents

(not volcanic smokers, but seepers)

- seawater percolates down electron-dense rocks (iron-magnesium mineral olivine) which react to form serpentinite that expands and cracks rocks allowing in more water (self-perpetuating)
- serpentinization produces alkaline proton poor fluids rich in hydrogen gas, and the heat it releases drives these fluids back up to ocean floor where they precipitate and form towers

23

Hot rock hypothesis

Early oceans with little oxygen, rich in dissolved iron, mildly acidic, excess of protons

Proton-motive force (differential between alkaline fluids from vents and acidic ocean)

Vents were labyrinths of micropores rich in mineral catalysts which:
- facilitated reaction of CO_2 and H_2
- to form aa, lipids, sugars, nucleobases + E

conforms to second law of thermodynamics (concerning E flow) (Life driven by it!)

24

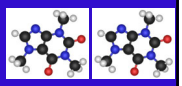
Organic molecules

fundamental biochemicals (monomers)	complex macromolecules (polymers)
• amino acids	• proteins
• saccharides	• polysaccharides
• nucleotides	• nucleic acids

25

2. Self-replicating molecules

Replication / metabolism
(chicken and egg conundrum)



- nucleotides (good replicators, poor catalysts)
- proteins (poor replicators, good catalysts)

need good replicator, good catalyst
(= RNA)

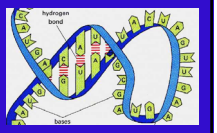
- ribozymes
- RNA world hypothesis

26

Replicating organic molecules

Gene-first

- RNA world hypothesis (good replicator, good catalyst)



Metabolism-first

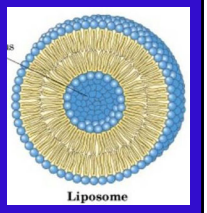
- iron-sulfur world hypothesis (membrane-like surfaces)
- thermosynthesis (chemiosmosis)
- bubbles (amphiphilic foam)
- pumice rafts (percolation pores)

27

3. Cell membranes

Replicating molecules enclosed by lipid membranes
formation of double-walled liposomes ("bubbles")

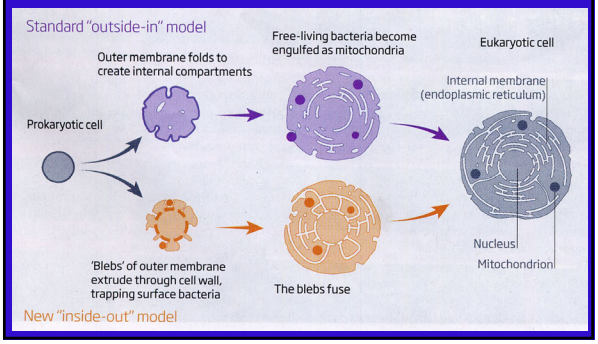
- clay theory
  (some clays catalyse formation of RNA)
- vents
  (proto-cells in pores)



Cellular basis of all life (except viruses)

28

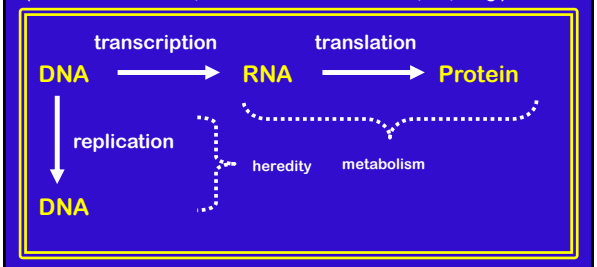
Endomembranes



29

Proto-cells

Cellular basis of life
(external membrane for containment, metabolism, replication)
(not endomembranes, such as nuclear membrane, ER, Golgi)



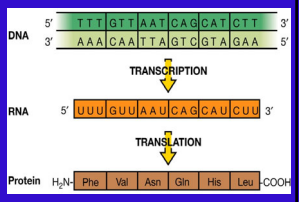
30

4. Natural selection

Better metabolic processes inherited

Evolution through:
- mutation
- recombination
- lateral gene transfer

('selfish' gene)



Phenotype
- survival of fittest
- natural selection

Darwinism "evolution based on competition"

31

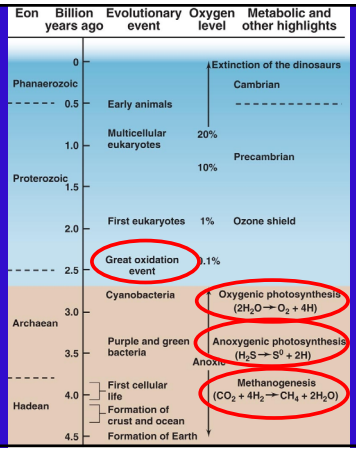
CELLS

first cells (LUCA) – anaerobic autotrophs
$2H_2 + CO_2 \rightarrow H_20 + [CH_20]$

metabolic diversification
- methanogenesis
  $4H_2 + CO_2 \rightarrow CH_4 + 2H_20$ (archaea) 3.9 BYA
  [microfossils, stromatolites, protobionts, nanobes]
- phototrophy (solar E)
  $H_2S \rightarrow S + 2H$ an-oxygenic (eubacteria) 3.2 BYA
  $2H_2O \rightarrow O_2 + 4H$ oxygenic (cyanobacteria) 2.7BYA

⇒ Great Oxidation Event 2.6 BYA
(ozone shield, surface colonization)

32



33

5. Endosymbioses

Bacterial world (half life of planet)
then complex cells evolved (apparently only once as no variety or intermediates extant or extinct)

1.9 BYA eukaryotes
chimeras of eubacteria and archeabacteria
serial endosymbiosis theory (SET)
(morphotypic + genotypic evidence)

"Life did not take over the globe by combat, but by networking!"

34

PROKARYOTES

Archaea
(extremophiles)
methanogens
requiring H

Eubacteria
(true bacteria)
anaerobes
producing H

LUCA [4 BYA]
(last universal common ancestor)

35

SYMBIOGENESIS

Eukaryotes [2 BYA]

Archaea
(extremophiles)
methanogens
requiring H

Eubacteria
(true bacteria)
anaerobes
producing H

36

EUKARYOTES

Protists 1.8 BYA | Plants 1.0 BYA | Fungi 0.7 BYA | Animals 0.5 BYA

Eukaryotes [2 BYA]

37

Serial Endosymbiosis Theory (eukaryotes = chimeras)

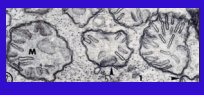
ur-karyote

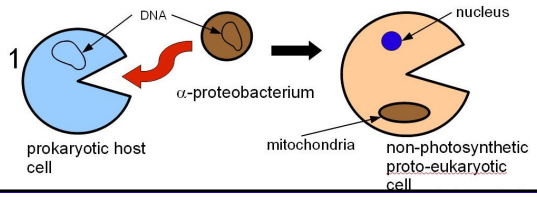
endomembranes (nuc env, ER, Golgi)	phagotrophic? syntrophic?
flagella (2+9)	direct filiation? exogenous? (spirochaetes)
mitochondria	α-proteobacteria
chloroplasts	cyanobacteria
other plastids	miscellaneous?

38

MITOCHONDRIA

Symbiogenesis
- attachment of alpha proteobacterium
- endocytic uptake into cytoplasm
- mutualistic symbiosis

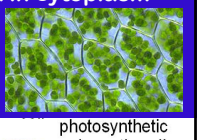


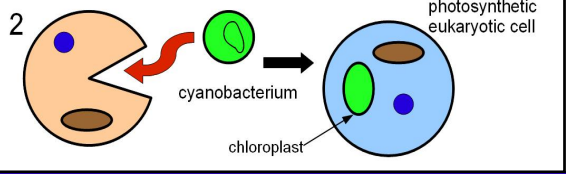


39

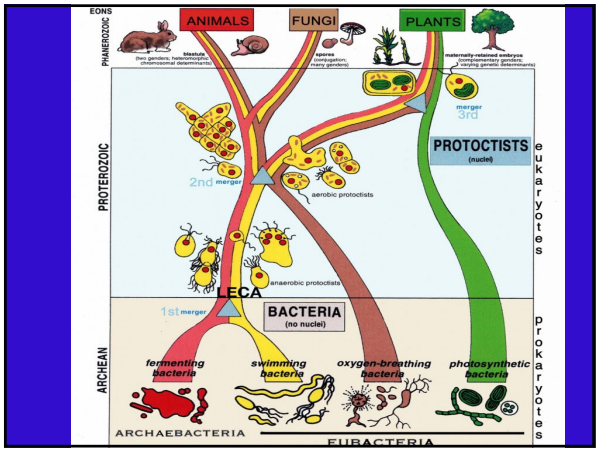
CHLOROPLASTS

Symbiogenesis
- endocytic uptake of cyanobacterium
- biochemical modification in cytoplasm
- mutualistic symbiosis





40



41