4. Life on Earth

- Basic biochemical structure
- Origin and Evolution of Life

Basic biochemical structure built on C-chain molecules:

Simplicity:

Limited number of monomer building blocks

Complexity:

Large number of polymer molecules

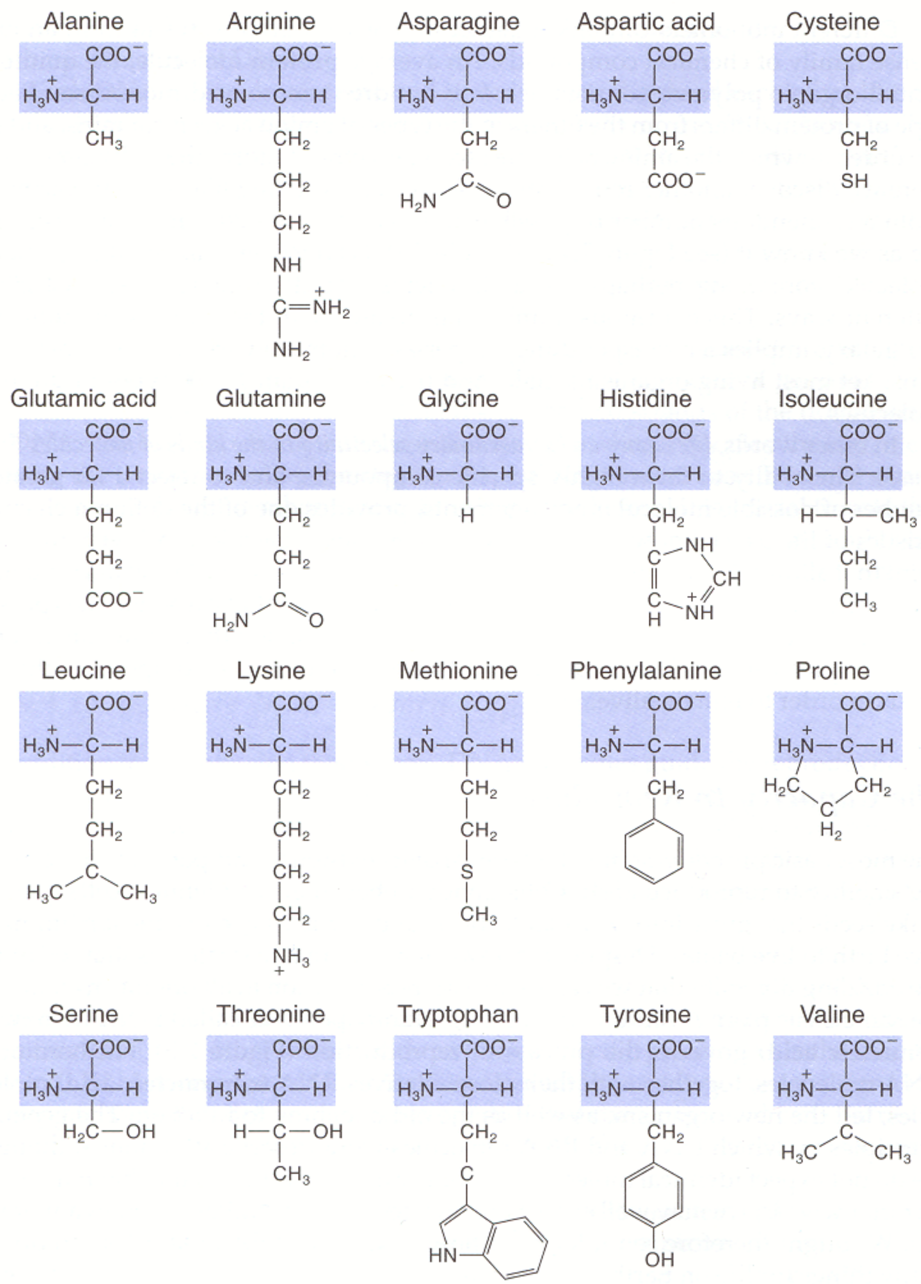
20 Amino acids → proteins
4 Nucleotides → genetic code (DNA cross-links)
Sugars → structural and energy storing molecules

Distinguish between

- Polymers repeating without ordering (e.g. cellulose, glycogen)
- Polymers with specific ordering of monomers → complex shapes and highly specific functionality (e.g. proteins)

20 amino acids → 10,000 proteins << "theoretical number" (see Lecture 1)

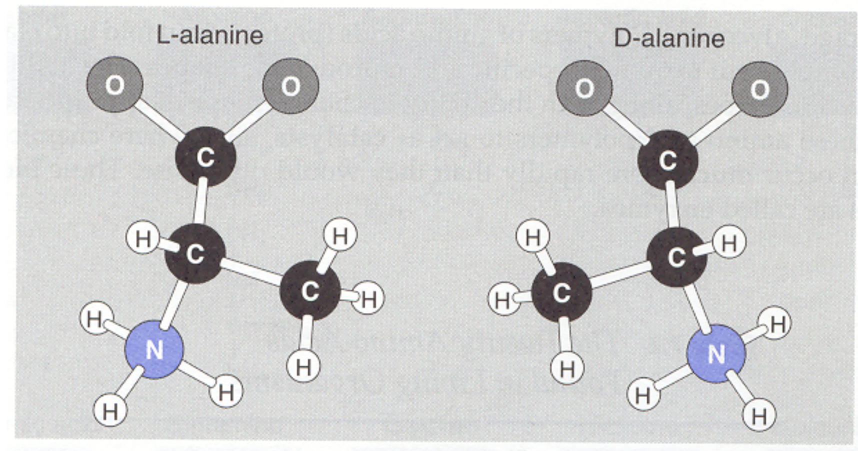
20 amino acids in terrestrial life



The "handed-ness" of terrestrial Life

All amino-acid monomers found in terrestrial life are "left handed" (in sense of arrangement of the bonds to CO_2, NH_3, H and the 4th branches)

Note: glycine is actually ambidextrous because of having an H atom as the 4th branch



- System of right-handed monomers would "work" equally well
- Having only one handedness allows greater structural definition of molecules
- Evidence that amino-acids in Murchison meteorite are 2-9% enhanced in Left vs. Right (not terrestrial contamination) – see Science Feb 14, 1997

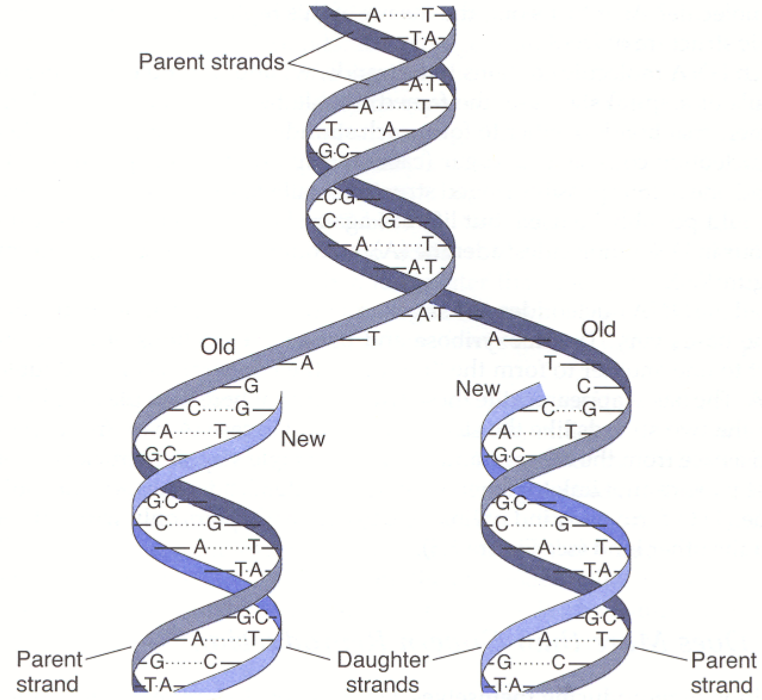
Role of DNA in replication and protein synthesis

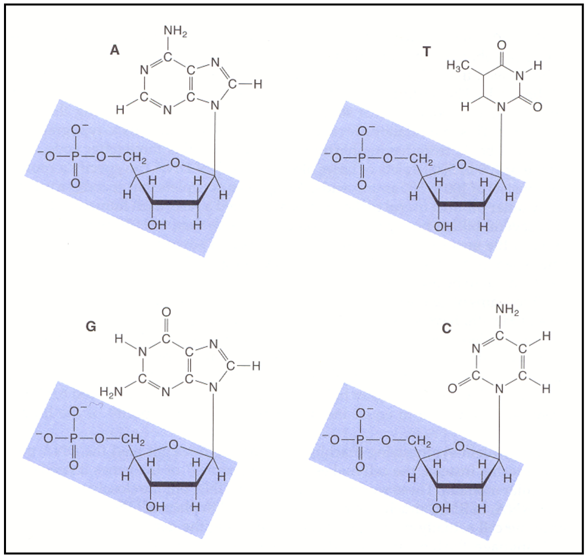
Double helix structure of DNA with ladder of sugar+phosphate and "rungs" composed of nucleotide pairs:

Adenine (A) + Thymine (T)
Cytosine (C) + Guanine (G)

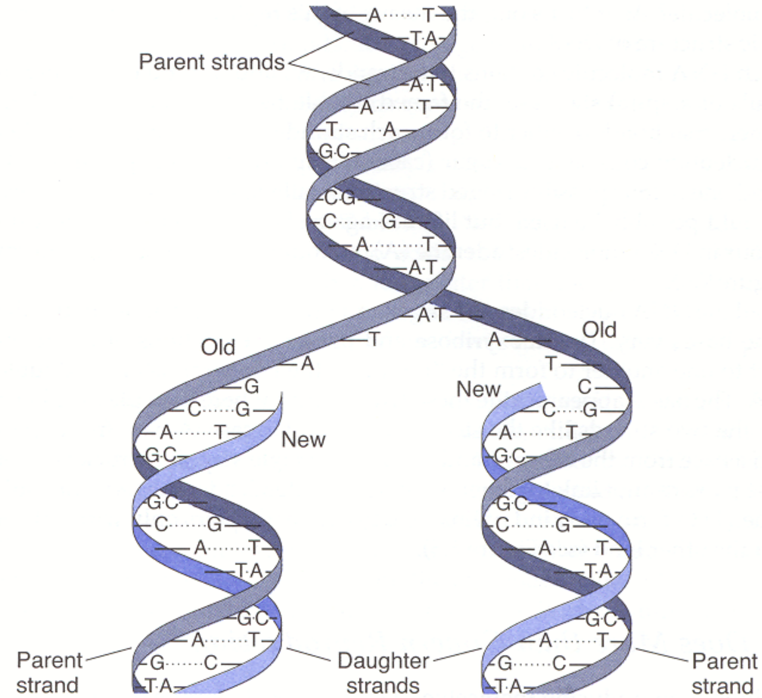
When DNA splits in half:

- each half contains all the required information to replicate the missing half
- each single strand can code for amino-acid chains (RNA)

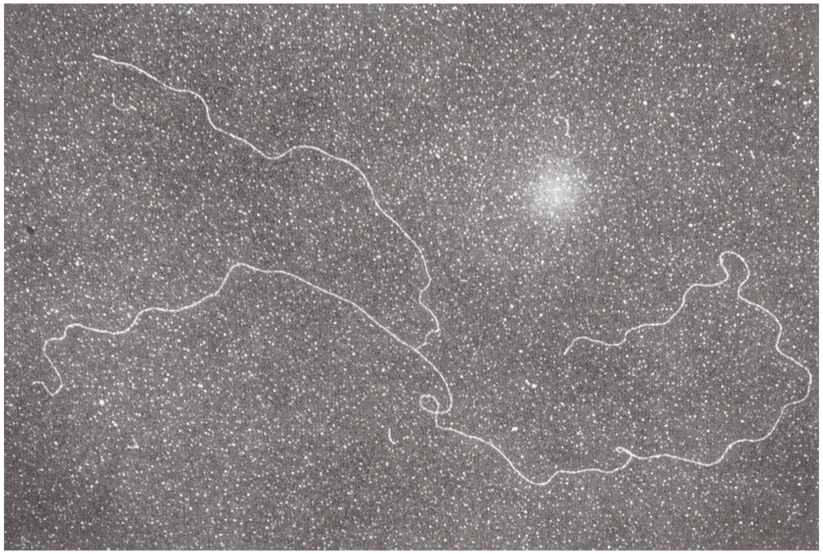




Role of DNA in replication and protein synthesis:



Replication through splitting now seen directly in electron microscopy



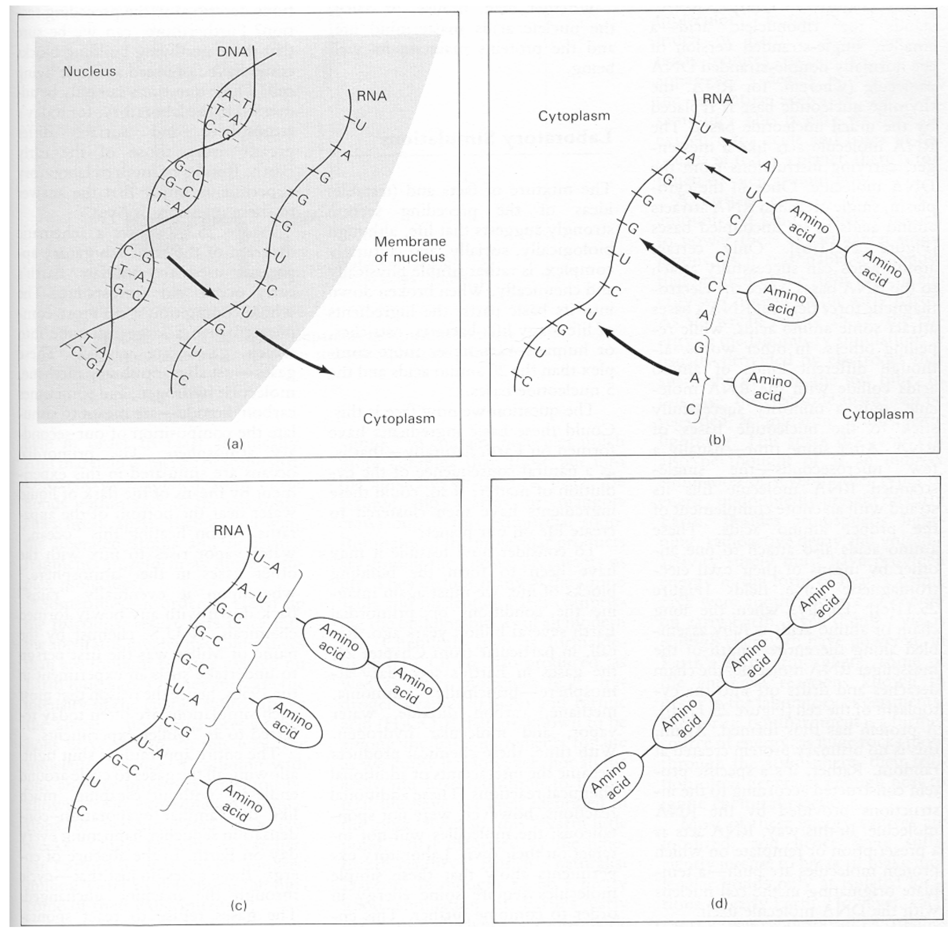
Electron micrograph of DNA in process of replication

Triplets of bases on RNA code for individual aminoacids in protein chain (with some redundancy)

First Letter	Second Letter: U		C		A		G		Third Letter
U	UUU	phe	UCU	ser	UAU	tyr	UGU	cys	U
U	UUC	phe	UCC	ser	UAC	tyr	UGC	cys	C
U	UUA	leu	UCA	ser	UAA	stop	UGA	stop	A
U	UUG	leu	UCG	ser	UAG	stop	UGG	trp	G
C	CUA	leu	CCU	pro	CAU	his	CGU	arg	U
C	CUC	leu	CCC	pro	CAC	his	CGC	arg	C
C	CUA	leu	CCA	pro	CAA	gln	CGA	arg	A
C	CUG	leu	CCG	pro	CAG	gln	CGG	arg	G
A	AUU	ile	ACU	thr	AAU	asn	AGU	ser	U
A	ACU	ile	ACC	thr	AAC	asn	AGC	ser	C
A	AUA	ile	ACA	thr	AAA	lys	AGA	arg	A
A	AUG	met	ACG	thr	AAG	lys	AGG	arg	G
G	GUU	val	GCU	ala	GAU	asp	GGU	gly	U
G	GUC	val	GCC	ala	GAC	asp	GGC	gly	C
G	GUA	val	GCA	ala	GAA	glu	GGA	gly	A
G	GUG	val	GCG	ala	GAG	glu	GGG	gly	G

Abbreviations:

ala = alanine	gln = glutamine	leu = leucine	ser = serine
arg = arginine	glu = glutamic acid	lys = lysine	thr = threonine
asn = asparagine	gly = glycine	met = methionine	trp = tryptophan
asp = aspartic acid	his = histidine	phe = phenylalanine	tyr = tyrosine
cys = cysteine	ile = isoleucine	pro = proline	val = valine



Note: 4 bases give $4^3 = 64$ triplets (> 20 amino acids + 1 "stop") but only $4^2 = 16$ pairs.
2 bases would give only 8 triplets.

A key feature of replication is that it is not perfect

Inaccuracies in replication of DNA (mutations) due to:

- Radiation (cosmic rays or radioactivity)
- Chemical agents
- Rare errors of DNA copying machinery

Differential propagation of the resulting "trials"

- "natural selection" in one form or another

Charles Darwin

Thomas Malthus

Gregor Mendeleev

Energy for Life:

- Chemical energy from surroundings (very small amounts)
- Geothermal energy
- Sunlight
- Other life products (sugars)

Origin of Life on Earth:

0. Earth's evolving atmosphere:

- Initially highly reducing (NH_3, H_20, CH_4)
- Early: photo-dissociation by solar ultraviolet and H loss → less reducing atmosphere (CO, CO_2, N_2 and H_20)
- Later: Production of O_2 by Life (photosynthesis) → oxidizing atmosphere (N_2, O_2)

0.1 Panspermia (life brought from elesewhere)?

- Long duration interstellar travel hazardous (radiation, CR)
- "Martian" meteorites suggest interplanetary travel certainly not impossible
- Just defers the question of the "origin"
- Complex organic molecules do exist in space

Aside: "complex" molecules detected in interstellar space (in giant molecular gas clouds)

- Detected with characteristic spectral lines (generally in mm)

# atoms	Molecule	Name	Mass
10	$(CH_3)_2CO$	Acetone	58
	$(CH_2OH)_2$	Ethylene glycol	62
	CH_3CH_2CHO	Propanol	58
	CH_3OCH_2OH	Methoxymethanol	62
	CH_3C_5N	Methyl-cyano-diacetylene	89
	CH_3CHCH_2O	Propylene oxide	58
11	HC_8CN	Cyanotetra-acetylene	123
	C_2H_5OCHO	Ethyl formate	74
	CH_3COOCH_3	Methyl acetate	74
	CH_3C_6H	Methyltriacetylene	88
12	C_6H_6	Benzene	78
	C_3H_7CN	N-Propyl cyanide	69
	$(CH_3)2CHCN$	Iso-Propyl cyanide	69
13	C_6H_5CN	Benzonitrile	104
	$HC_{10}CN$	Cyanopenta-acetylene	147
60	C_{60}	Buckminsterfullerene	720
70	C_{70}	C_{70} fullerene	840

1. **Chemical synthesis of organic chemicals:**

- Requires reducing atmosphere and absence of free oxygen
- Miller-Urey experiments (highly reducing atmosphere) do make amino-acids, sugars, nucleotide bases etc: e.g. glycine

$$NH_3 + 2\,CH_4 + 2\,H_2O + \text{energy} \rightarrow C_2H_5O_2N + 5\,H_2$$

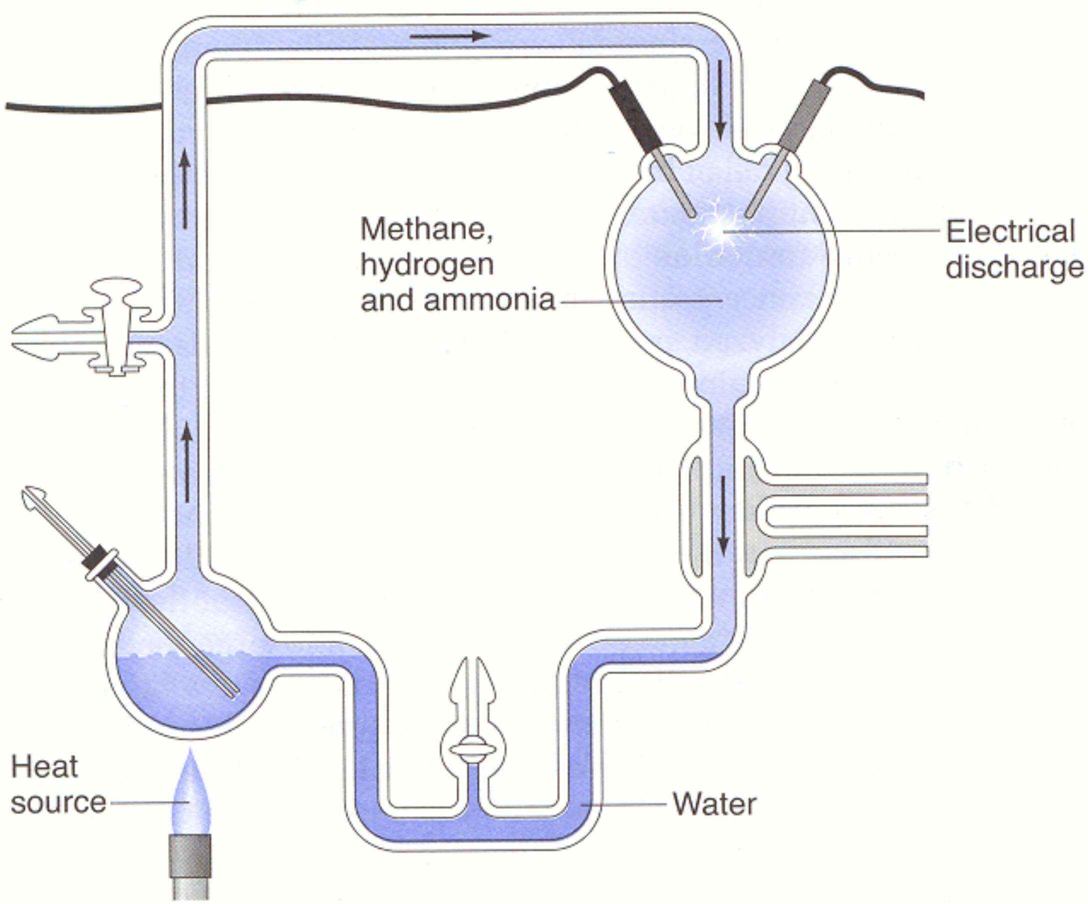
- Experiments with less reducing atmospheres also work:

$$3\,HCN + 2\,H_2O + \text{energy} \rightarrow C_2H_5O_2N + CN_2H_2$$

- Chemical reactions in small surface pools are attractive: preserve reagents, utilize solar energy etc., compared to undersea vents which have short duration, severe dilution, extreme conditions.
- Role of impacts on young Earth? External origin of complex organic molecules? – e.g. amino-acids found in meteorites. Can renew source of reducing atmosphere by replenishing volatile materials (CH_4, NH_3, H_20 etc).

e.g. Murchison meteorite contains 14,000 organic compounds including 70 amino acids, with a small excess of Left- over Right- chirality.

Miller-Urey-type experiments



Miller-Urey experiment (1953)
One of several similar conducted at the time.

Debate over precise composition of atmosphere (e.g. effect of volcanoes, CO_2 vs CH_4, H-content etc) but basic conclusions remain.

Analysis of sealed vials indicate results better than earlier analysis indicated: >25 amino acids produced. Most of the natural amino acids, hydroxyacids, purines, pyrimidines, and sugars have been made in variants of the experiment.

Bottom line: it is relatively easy to make basic organic building blocks of complex molecules in the kind of reducing atmosphere(s) that are expected on early Earth.

Amino acids in Miller-Urey, Murchison and used in proteins

Amino acid	Miller-Urey	Murchison meteorite	Used in proteins
glycine	****	****	✔
alanine	****	****	✔
α-amino-N-butyric acid	***	****	✗
α-aminoisobutyric acid	****	**	✗
valine	***	**	✔
norvaline	***	***	✗
isovaline	**	**	✗
proline	***	*	✔
pipecolic acid	*	*	✗
aspartic acid	***	***	✔
glutamic acid	***	***	✔
β-alanine	**	**	✗
β-amino-N-butyric acid	**	**	✗
β-aminoisobutyric acid	*	*	✗
γ-amino-butyric acid	*	**	✗
sarcosine	**	***	✗
N-ethylglycine	**	**	✗
N-methylalanine	**	**	✗

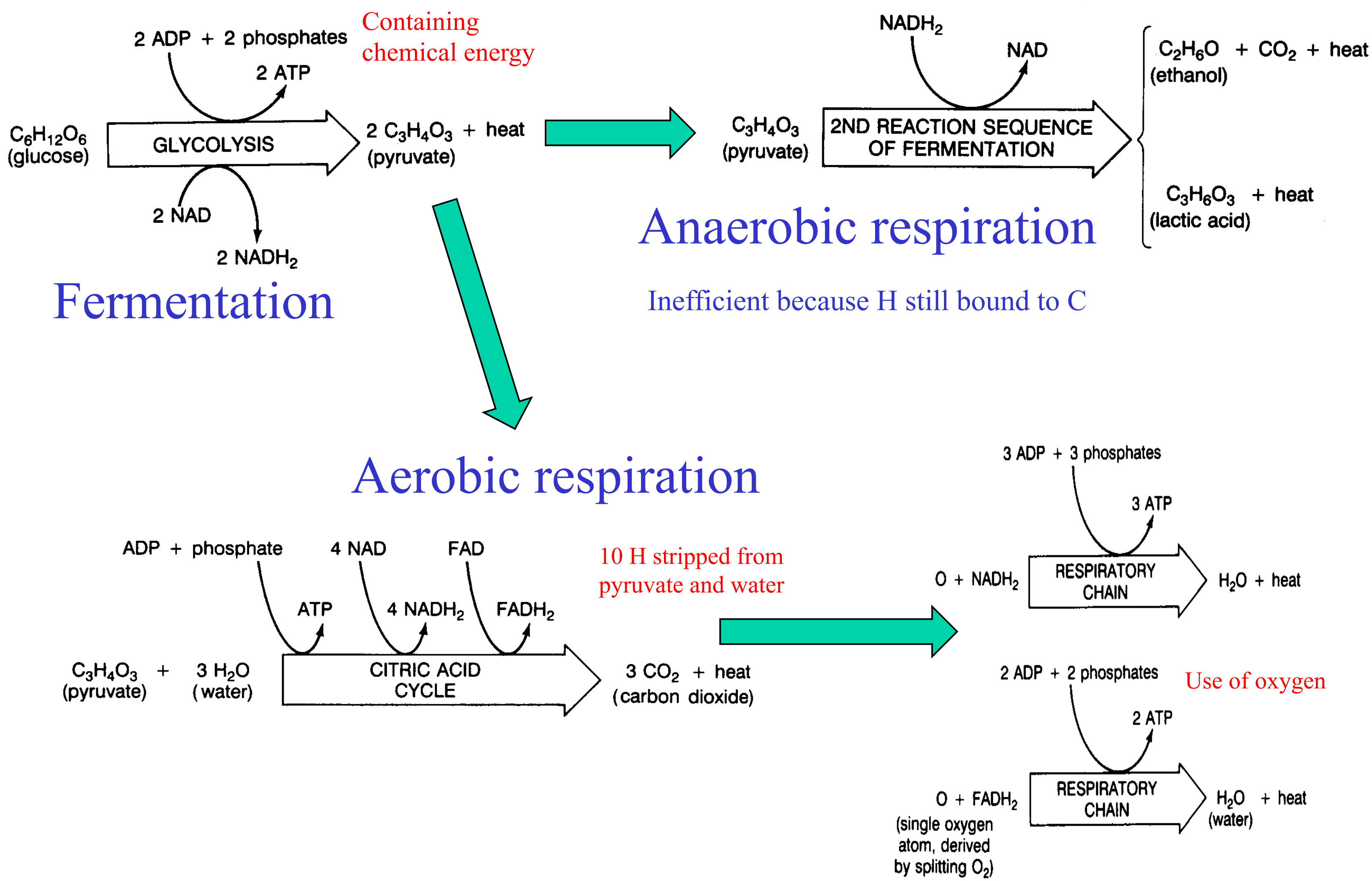
2. Polymerization (how to make the initial strand of DNA)

- Today, the production of polymers (e.g. proteins) from DNA (i.e. RNA) itself depends on catalysis by other proteins made from RNA. Chicken and egg?
- Some sequences of RNA can perform catalysis function → "RNA-World": how to make the RNA?
- Interest in clays as structures to promote polymerization
    - Regular structures with high surface area
    - Organic compounds attracted to surface
    - Water is absorbed
    - Located near standing water
- Idea of possible earlier, simpler, but now <u>disappeared</u>, non-DNA "Life" as a kind of "scaffolding"?

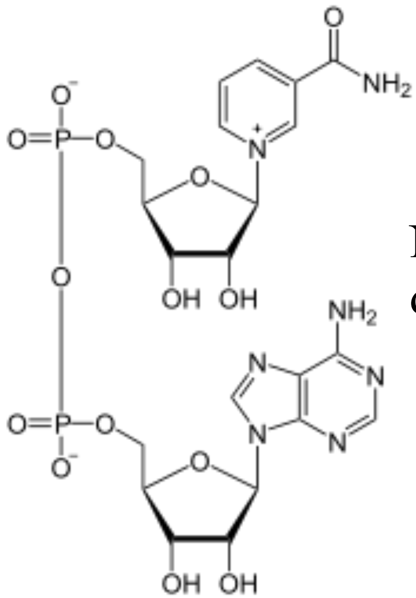
3. Emergence of prokaryotic cells (~3.5 Gyr ago)

- Proto-cells as droplets in solution?
- Simplest cells: Prokaryotes (without nucleus): Archaea and Bacteria (differ on basis of RNA). Single long strand of DNA (several 1000 genes).
- Archaea likely developed first – still found as extremophiles (extreme conditions) and anaerobic systems. Depend on (small amounts of) local chemical energy.
- Source of free organic compounds gradually reduced as atmosphere became less reducing
- 2-3 billion years ago, some prokaryotes develop photosynthesis (earliest form may have used H_2S) – producing O_2 and sugars (e.g. glucose) out of sunlight emergy. This enabled more complex Life using more efficient aerobic respiration. First solid fossil evidence of Life.

Energy for cells: fermentation and respiration

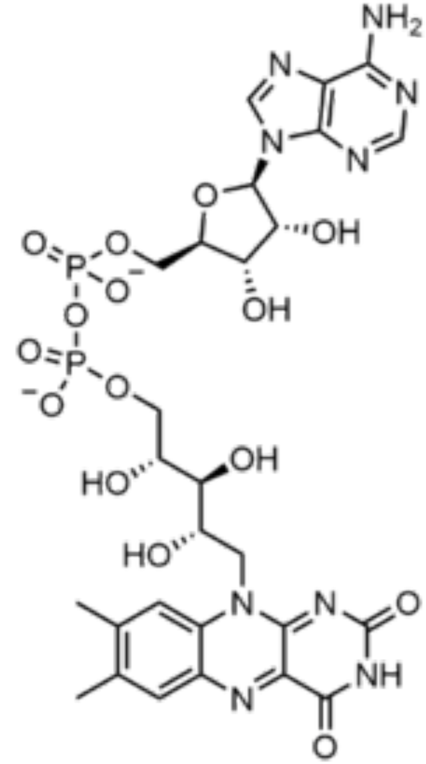


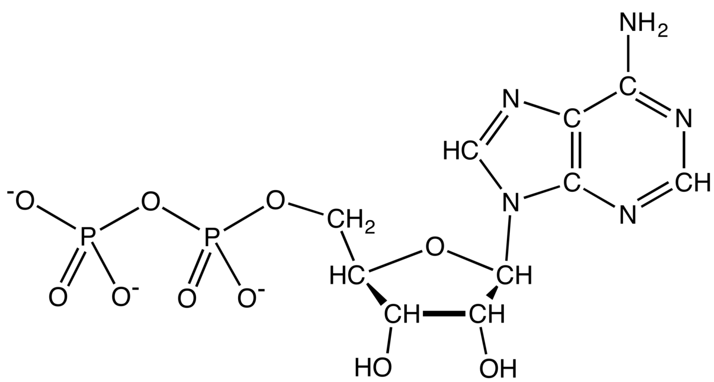
All very complicated...



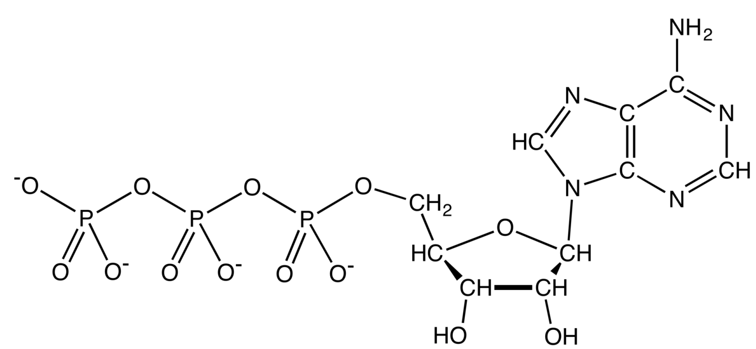
Nicotinamide adenine dinucleotide (NAD)

Flavin adenine dinucleotide (FAD)



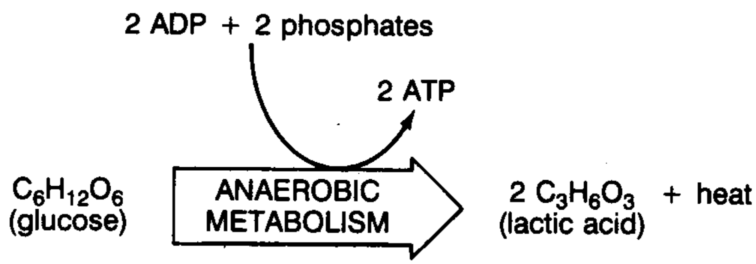


Adenosine diphosphate (ADP)

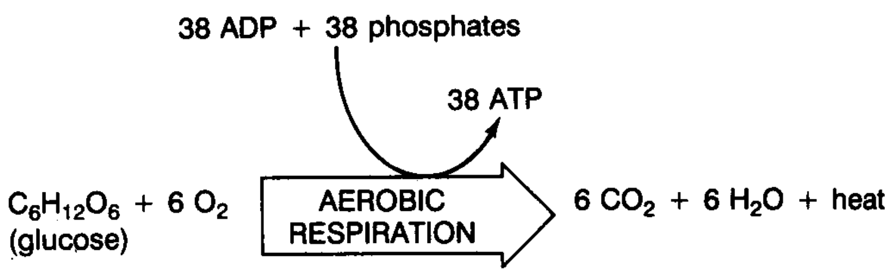


Adenosine triphosphate (ATP)

Net effect of "burning" glucose in controlled way



2% energy "efficiency"
(energy in *useful* form)



40% energy "efficiency"

(c.f. 0% in a wood fire – burning uncontrollably – and 30% in modern combustion engine)

Supply of oxygen allows vastly more efficient extraction of energy

Photosynthesis: extraction of energy from sunlight to make glucose

Easy to write basic reaction, but the details are extremely complex:

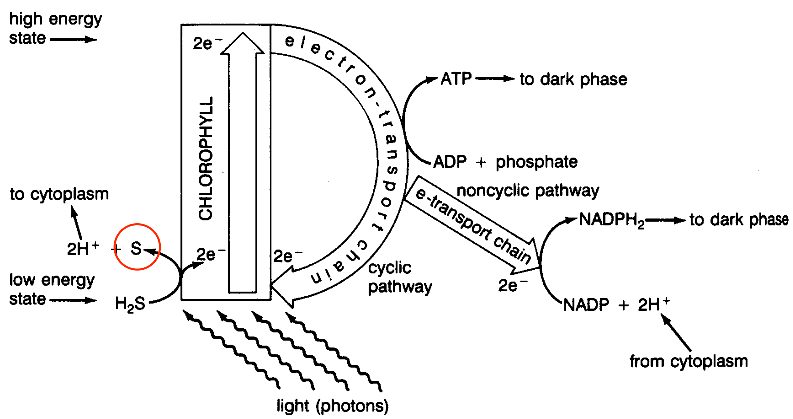
Photosynthesis:

(some bacteria use S not O)

$$6\ CO_2 + 6\ H_2 0 + \text{light} \rightarrow C_6H_{12}O_6 + 6\ O_2$$

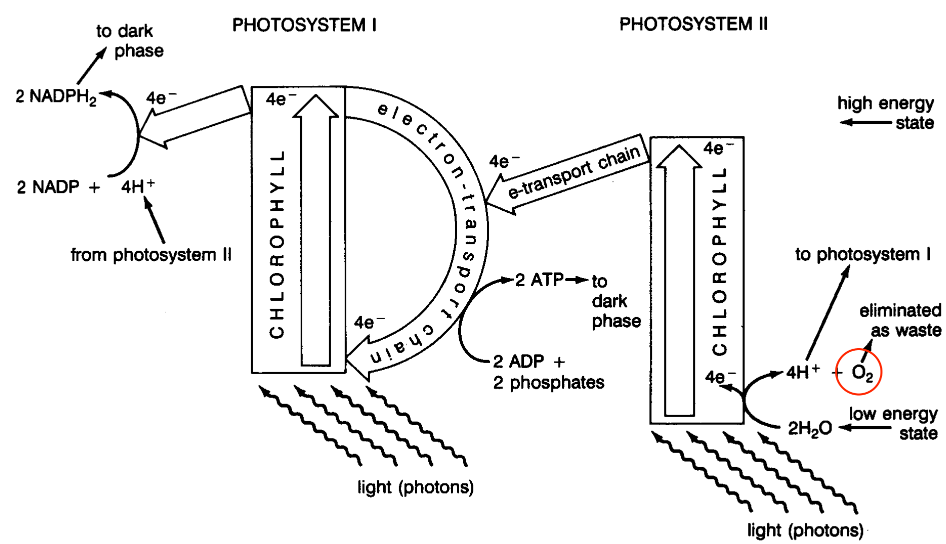
Photosynthesis: extraction of energy from sunlight to make glucose

Two forms: both produce glucose to be used in fermentation and/or respiration. The most efficient form also liberates O_2 as waste.



Anaerobic photosynthesis (light phase) liberating e.g. sulphur from H_2S

Aerobic photosynthesis (light phase) liberating oxygen from H_20.



Added new Photosystem II producing oxygen to Photosystem I from anaerobic.

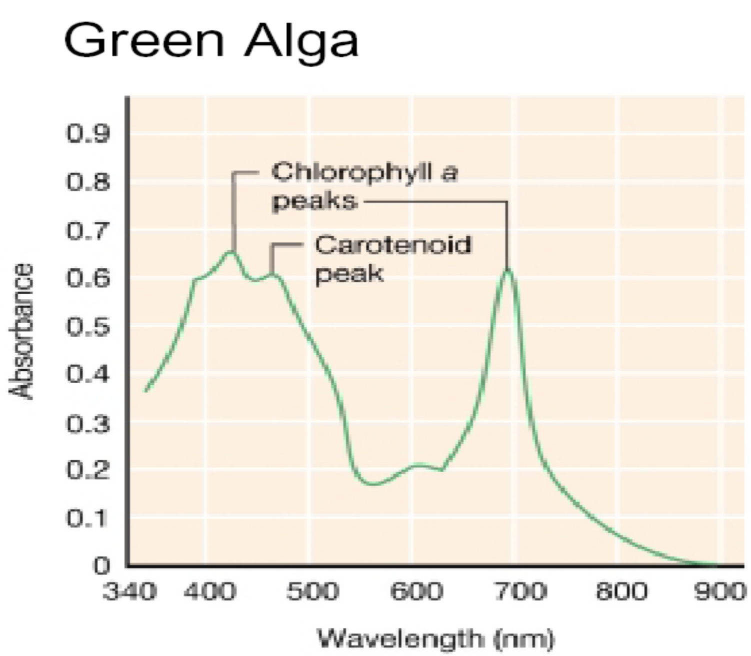
High energy photons needed to split (abundant) water

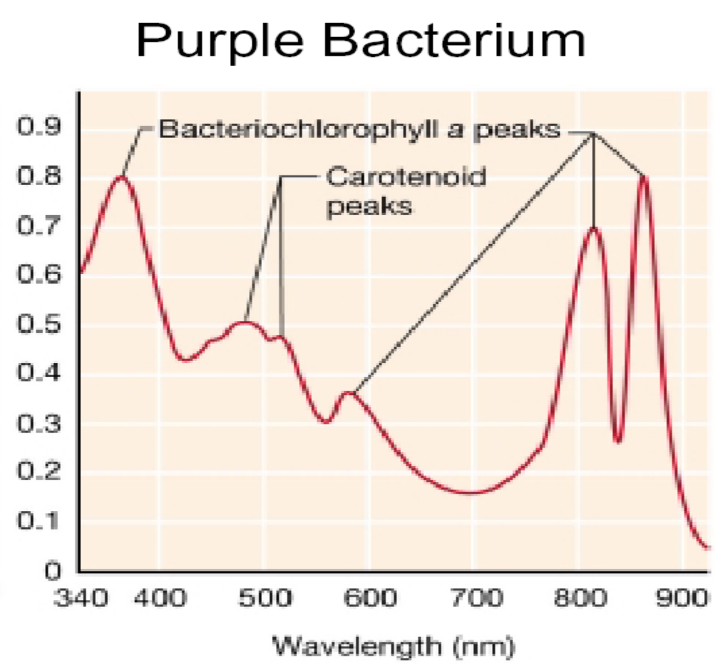
Common dark phase: ATP, $NADPH_2$ synthesize glucose out of CO_2

Complex absorption spectrum of light due to multiple electronic transitions in chlorophyl

Oxygenic photosynthesis under aerobic conditions

Anoxygenic photosynthesis under anerobic conditions



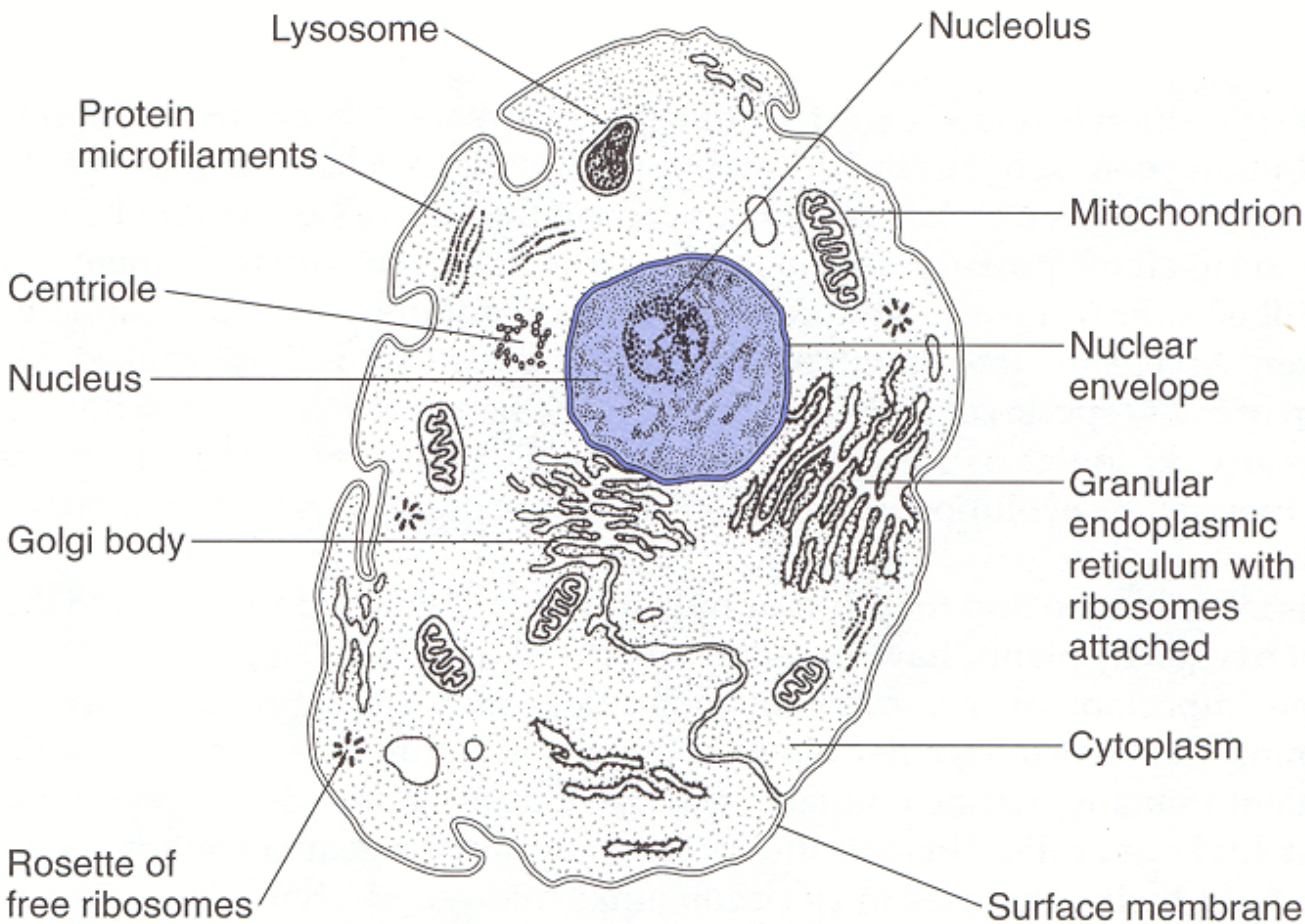


Origin of Life on Earth (continued)

4. Emergence of Eukaryotic cells (~2.7 Gyr ago)

   - Single cells with distinct cell nucleus, plus specialized organelles (mitochondria, chloroplasts etc.)
   - 10-1000 times more DNA than in bacteria
   - Incorporation of prokaryotes into proto-Eukaryote (similar gene systems to bacteria)?
   - Development of sexual reproduction (meiosis), producing vastly increased genetic sampling (about 1 Gyr ago?)
   - Development of multi-cellular organisms (multiple development)
     - → e.g. Jellyfish (700 Myr ago)***

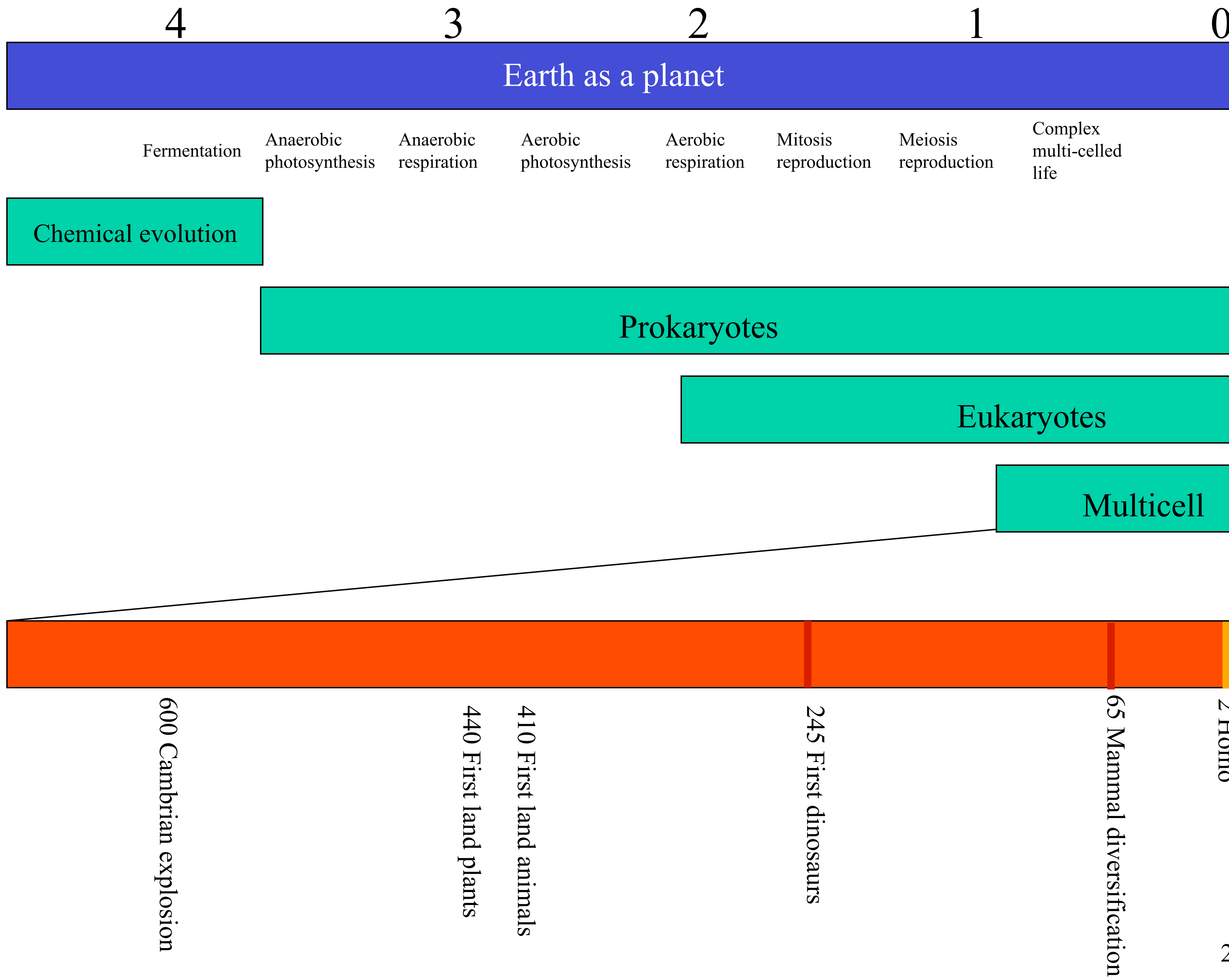
*** note only 15% of age of the Earth ago


Lysosome
Nucleolus
Protein microfilaments
Mitochondrion
Centriole
Nuclear envelope
Nucleus
Granular endoplasmic reticulum with ribosomes attached
Golgi body
Cytoplasm
Rosette of free ribosomes
Surface membrane

Origin of Life on Earth (continued)

5. Emergence of advanced animals

- Cambrian explosion (600 Myr ago) → anatomically modern animals (two eyes, legs, shells/carapaces/skeletons, etc.)
- Invasion of land by plants and arthropods (440 Myr ago)
- Appearance on land of vertebrates, amphibians, insects, seed plants (410 Myr ago)
- Diversification of reptiles (285 Myr ago)
- Emergence of dinosaurs and reptiles (245 Myr) after a mass extinction
- Diversification of mammals (65 Myr) after another mass extinction
- Appearance of Homo (2 Myr)….


4
3
2
1
0
Earth as a planet
Fermentation
Anaerobic photosynthesis
Anaerobic respiration
Aerobic photosynthesis
Aerobic respiration
Mitosis reproduction
Meiosis reproduction
Complex multi-celled life
Chemical evolution
Prokaryotes
Eukaryotes
Multicell
600 Cambrian explosion
440 First land plants
410 First land animals
245 First dinosaurs
65 Mammal diversification
2 Homo

Short lesson on statistics:

What if anything can be inferred from the apparently rapid emergence of the most basic life on Earth?

Life is common in the Universe? Not necessarily!

Interesting aside on conditional probabilities….

Suppose we have a sequence of "steps" in a process, each of which has a certain chance p_i of happening per unit time. Generally, we would expect to have to wait a time $t_i \sim p_i^{-1}$ for a given step to occur. Easy steps have $p_i > t_{avail}^{-1}$ and are likely to happen, difficult steps have $p_i < t_{avail}^{-1}$ and are unlikely to happen.

Clearly, if we have one or more difficult steps in the process, the chance that all the steps take place is small.

But, if we look only at those systems that were, by great good luck, able to complete all the steps, what is the distribution of the time spent waiting for each step?

Perhaps counter-intuitive answer:

- For easy steps, $<t_i> \sim p_i^{-1}$ (as expected)
- For difficult steps, $<t_i>$ is independent of the difficulty p_i, and is instead given just by the number N of difficult steps $<t_i> \sim (N+1)^{-1}$.

Example: Run a simulation with a time interval of 10^6 units, and eight "steps" with individual probabilities of occurring per unit time of 10^{-1}, 10^{-2}, 10^{-3} …. 10^{-8}.

The chance of them all happening in 10^6 time steps is very small, of order $10^{-2} \times 10^{-1} \times 1 \sim 10^{-3}$ (actually $\sim 3.3 \times 10^{-4}$). The distribution of $<t_i>$ in the successful ones is

"easy" steps, $<t_i> \sim p_i^{-1}$ | "difficult" steps, $<t_i> \sim N^{-1}$

Step p_i^{-1}	10	100	1000	10^4	10^5	10^6	10^7	10^8	left
$<t_i>$	9.8	95.8	989	9,810	68,385	207,920	257,860	254,910	220,015
$\sigma(t_i)$	9.3	99.5	837	11,236	60,212	164,590	179,680	189,212	161,118

Note that the dispersion in the individual step lengths $\sigma(t_i)$ is large, $\sigma(t_i) \sim <t_i>$

The explanation of this perhaps counter-intuitive result is actually straightforward:

If we know that all the hard steps completed, then the probability that we have a particular configuration of t_i is given by the product of the probabilities that each step completed, which is $p_i t_i$ (for $p_i t_i << 1$)

$$P = \prod_i t_i p_i = \prod_i p_i \prod_i t_i$$

The Πp_i is constant, so P is maximized when Πt_i is maximized, subject to the constraint that $\Sigma t_i + t_{end} = t_{tot}$, where t_{end} is the time after the last step completed before the end of the experiment.

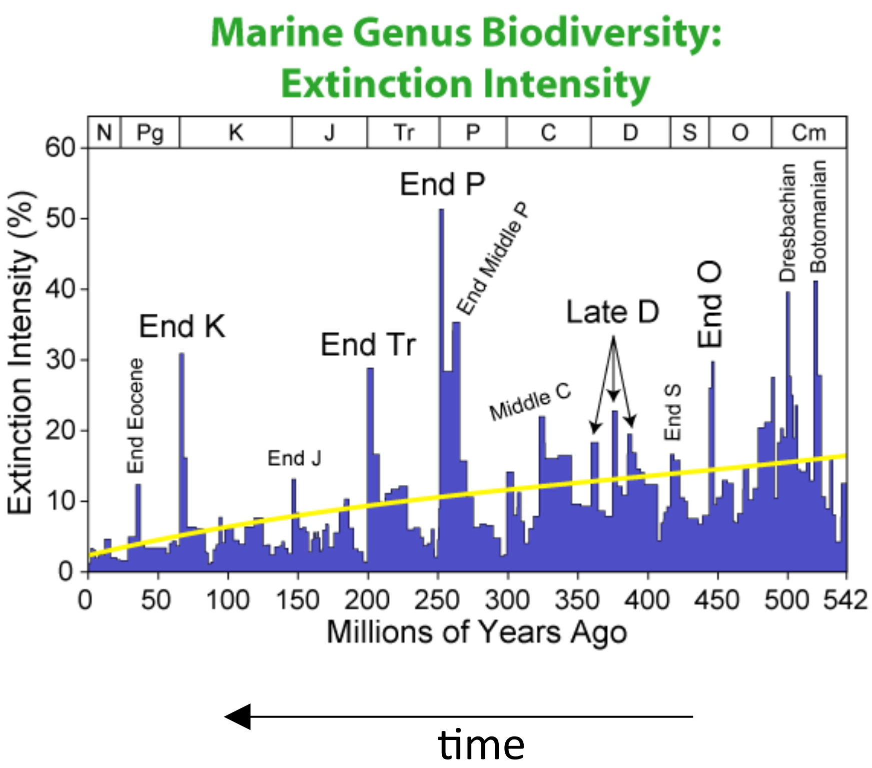
It is easy enough to show that P is maximized when all the t_i and t_{end} are all equal, i.e.

$$t_i = \frac{t_{tot}}{(N+1)}$$

We think on Earth that $t_1/t_{tot} \sim 0.1$. This may tell us nothing at all about p_1. It is just as consistent with all the steps being very unlikely (all p_i being very small) and $N \sim 10$.

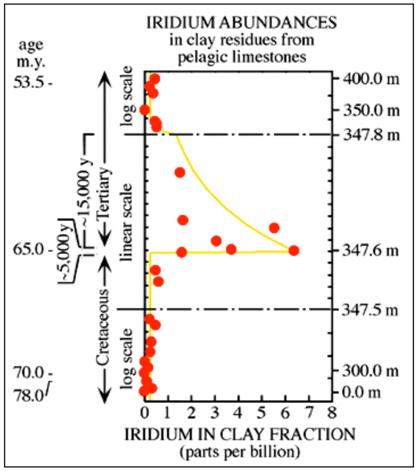
Mass extinctions

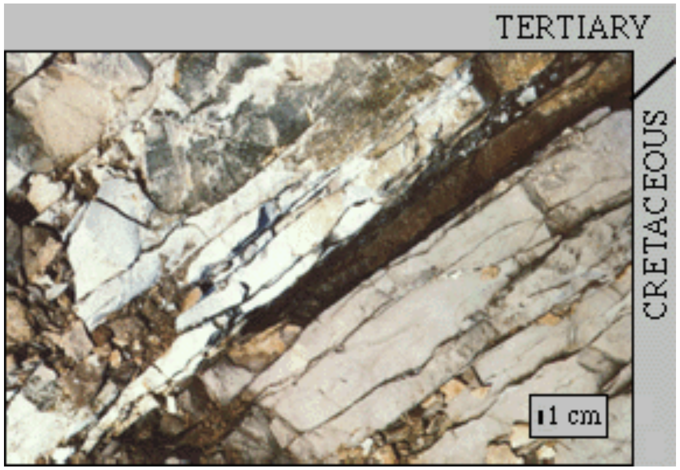
- The rate at which species (families etc) become extinct shows wide variations, leading to "sudden" loss of large numbers (e.g. Permian/Triassic 50% of marine families = 95% of marine species, 70% of land species)
- Easiest to see in marine fossil record, but the effect is distributed across environments and across the planet (synchronous?)
- Almost impossible to estimate the duration if less than 10^4-10^5 years due to resolution of fossil record.



Causes are debated but there is good evidence that the K/T extinction 65 million years ago (dinosaur extinction) was associated with major impact (10-20 km asteroid). The KT boundary has:

- Iridium anomaly (Alvarez et al 1980) --> leading to estimate of 10 km asteroid.
- Shocked quartz beads, especially near Caribbean region.
- Isotope anomalies in Iridium and Chromium that are similar to those found meteoritic material.
- The major impact crater Chicxulub (Yucatan) accurately dated to KT event (200 km diameter)





Key Point: Large impacts do happen

There will be a broad spectrum of impacts:
Size of impact (= energy) vs. frequency

$$\frac{\Delta t}{yr} \sim \left(\frac{E}{0.01\,\mathrm{MT}}\right)^{0.8}$$

e.g. 2013 Chelyabinsk meteorite (~20m diameter, 500kT energy) was likely the largest impact since Tunguska in 1908 (~100m, 50 MT energy).

Interesting question: what is the worst impact witnessed by "historical humans" in 10,000 years (1000 MT)** and by Homo in 1 Myr (300,000 MT)
** c.f. Tsar Bomba RDS-220 hydrogen bomb= 50 MT

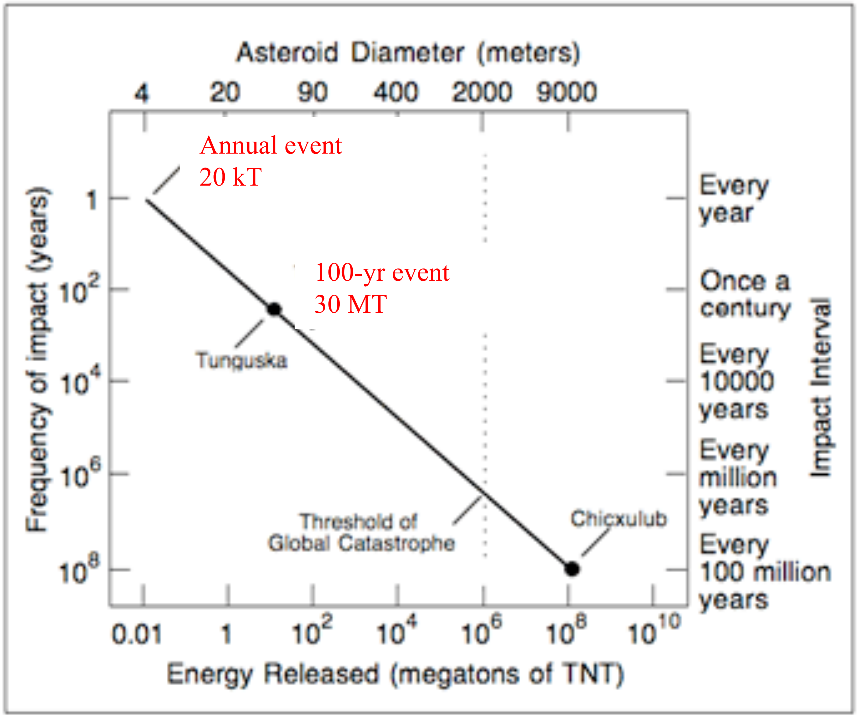
Resulting impact craters are produced by release of gas (vapourized rock) that is produced by the impactor tunneling through rock

Effects are expected to be global for impacts of objects with diameters above about 1 km. These occur of order once every million years.

Expected effects:

- Dust in atmosphere blocks out sunlight
- Tsunamis swamp coastal regions
- Blasts of hot gas
- Fall-out of hot rock

Note: A 10km object contains equivalent material to 2mm deposited over entire surface of Earth



5. Other chemical systems than C-N-H-O based Life

How strange could life be?

Terrestrial Life is based on organic molecules (C-chains) and water as a solvent.

- Carbon's ability to form long hydrogenated chains: carbon with H up to $C_{90}H_{84}$, compared with oxygen (H_2O, H_2O_2) or nitrogen (NH_3, N_2H_2) c.f.)

Could well imagine different details (e.g. other handedness, use of other amino acids, etc.).

But what about other elements and/or solvents?

- e.g. Silicon-based instead of Carbon-based?
- e.g. NH_3 or CH_3OH instead of water as solvent?

What about Silicon-based Life?

Si is the next valence-4 element below C in Periodic Table). BUT:

- Si-Si bond has half the strength of C-C bond
- Chain-ending Si-H and Si-O are stronger than Si-Si (c.f. C-O ~ C-H ~ C-C)
- Si_mH_n is unstable for $m > 3$
- SiO polymers exist (silicones) but are essentially completely inert
- Si has extreme affinity for O: SiH_4 only exists for T > 1000 K
  - e.g. Jupiter has NH_3, PH_3, AsH_3, CH_4, GeH_4, H_2S, H_20 in atmosphere but no detectable SiH_4 (all Si is in the form of SiO_2)
- Si found with other elements as Silicates (e.g. many rocks on Earth!)

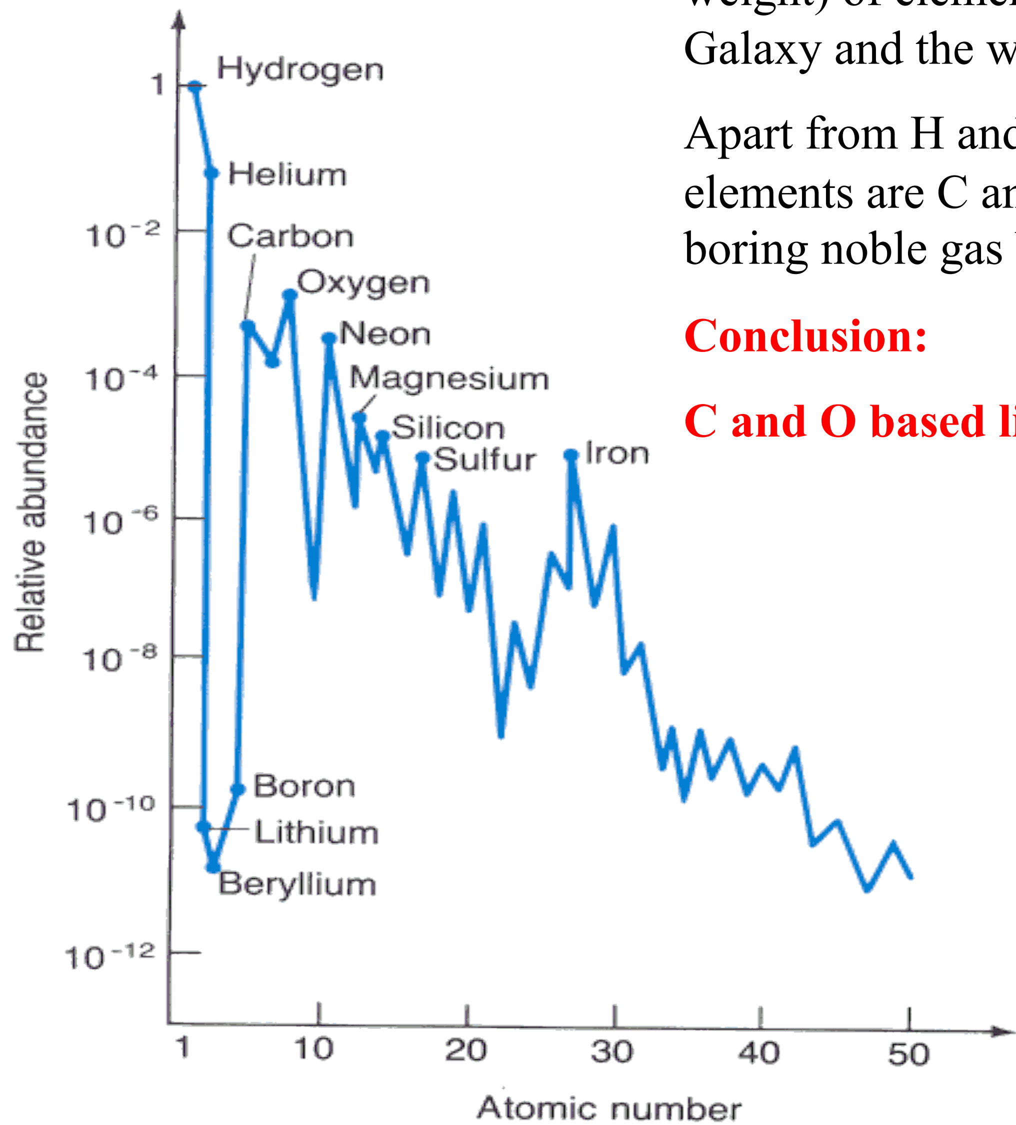
CO_2	SiO_2	CH_4	SiH_4
Gas at > 200K	Gas at > 2300K	Exists in oxidising atmosphere (e.g. 10 yr on Earth)	Bursts spontaneously into flame
Soluble in H_2O	Insoluble (except HFl)		
→ C + O in uv	Stable (quartz)		

What would be an ideal solvent?

- Solvent should be liquid over a range of temperature (better than a gas for concentration reasons) which
  - is high enough for chemical reactions to occur
  - is low enough for survival of complex molecules
  - is wide enough to give tolerance of environmental variations (e.g. on planets)
- Should have high heat capacity and latent heats to facilitate active temperature control

	H_2O	NH_3	CH_3OH
Liquid	0-100 C	-78 – -33 C	-94 – +65 C
SHC	1	1.2	0.6
LHV	600	300	290
Surface tension	1	0.5	0.33
"Solvent"	1	0.5	0.5

H_20 is the best solvent, but NH_3 and CH_3OH are not bad



Look again at the relative abundances (by weight) of elements in the Sun (typical of the Galaxy and the wider Universe):

Apart from H and He, the most abundant elements are C and O with N next (excluding boring noble gas Ne).

Conclusion:

C and O based life is natural and easy!

Key points

- Hierarchy of structure and function in terrestrial Life
- Complexity gives extreme efficiencies for energy conversion
- Organic molecules were naturally produced on and around young Earth
- There were multiple steps in the emergence of advanced Life on Earth
- Little can be said from the early emergence of Life on Earth
- There is interaction of Life with the extraterrestrial environment via impacts etc.
- C-life is extraordinarily much easier than Si-life!
- Other solvents may be possible, but why not H_2O?