31 October 2019

POSSIBILITIES FOR EXTRATERRESTRIAL LIFE IN THE OUTER SOLAR SYSTEM, EVOLUTION OF LIFE ON EARTH, & SENSES AND NEURONS

Homework #6 on WeBWorK due Wednesday at 7pm
Review session Wednesday at 7:45pm

1

Exam #2

1 hr 15 min in-class exam, open book and open notes

- Things you should DEFINITELY bring with you:
  - Writing utensil (pencil or pen – blue or black ink)
  - Calculator
- Things you should PROBABLY bring with you:
  - Lecture notes
  - Laptop or tablet (so that you can access the WeBWorK homework problems)

REVIEW SESSION – Wednesday, 11/6, at 7:45pm in B&L 203H

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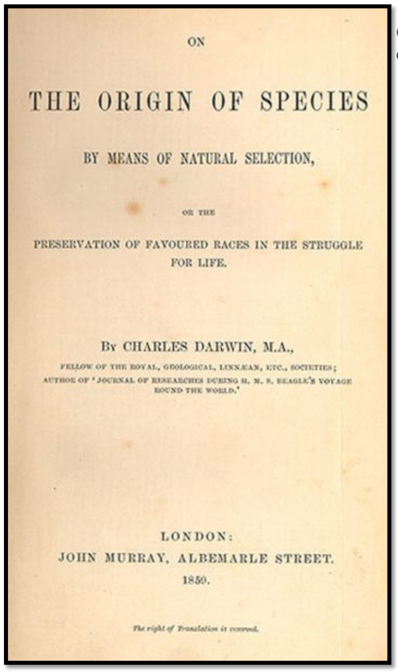

Cover of the first edition of Darwin's Origin

Possibilities for extraterrestrial life in the outer Solar System, Evolution of life on Earth, & Senses and neurons

- Enceladus, Ganymede, and Dione: their global subsurface liquid-water oceans
- Titan, its surface liquid-hydrocarbon lakes *and* possible global subsurface liquid-water ocean
- The accurate measurement of ages through Earth's history
- Phylogeny
- The fossil record and the increasing diversity of life: biological evolution
- Information, DNA, and phylogeny
- On the way to the Cambrian explosion: evolution of senses and neurons
- Information, neurons, and phylogeny: setting the table for intelligence
- Pre-intelligence summary of facts and theories of biological evolution: Darwin wins

3

Question!

Which life-promoting feature(s) of Earth's oceans is (are) likely to be absent from Europa's oceans?

A. Hydrothermal vents (smokers) providing local heating and material from deeper within Europa
B. Dissolved organic prebiotic molecules such as those made in the Miller-Urey experiment's "atmosphere"
C. Dissolved inorganic substances
D. Circulation of the ocean water
E. Sunlight

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Enceladus' global subsurface ocean

Enceladus has the highest albedo in the Solar System, very close to 1. So, it must be covered in clean (water) ice with a smooth surface.

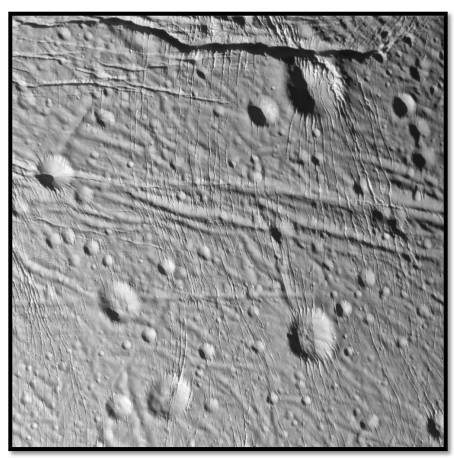
Indeed, the surface is smooth: not many impact craters, just lots of thin cracks and fissures. At close range, it displays a Europa-like or pack-like appearance.

Enceladus' global subsurface ocean

So the surface also gets frequently recoated. This requires heat sufficient to melt water ice, and a means to distribute it over the surface.

Because of its position within one of Saturn's outer, icy rings – the one called the E-ring – it has long been thought that Enceladus was responsible for the formation of this ring.

Precisely how this happens was obscure until the flybys by *Cassini*, which revealed water geysers at Enceladus's south pole.

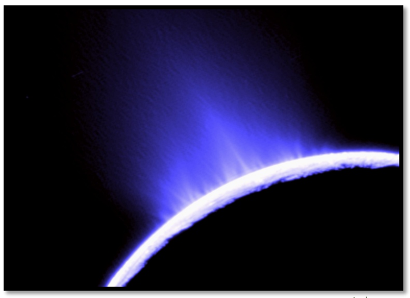


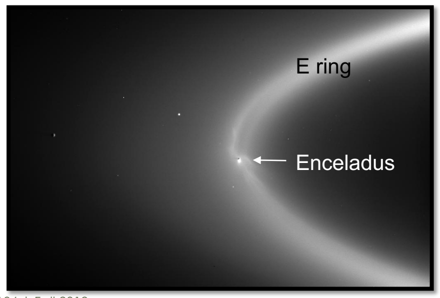
Enceladus' global subsurface ocean

Thus Enceladus, too, has bodies of liquid water underneath the ice in at least some places.

Along with water, minerals and organic molecules are detected in the geyser plumes.

The plumes produce enough ice particles to explain the E-ring and to refresh the moon's ice coating.





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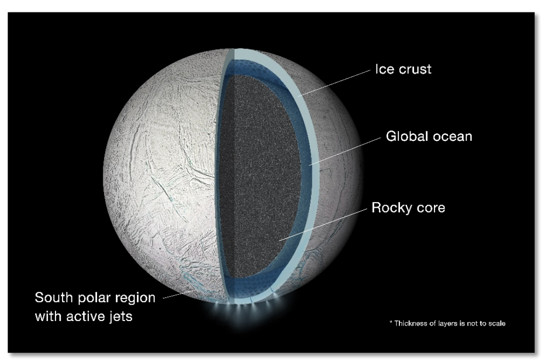
Enceladus' global subsurface ocean

It has not yet been possible to determine the extent of the ocean magnetically, but there is another clever way:

- Elliptically-orbiting bodies undergo oscillations in their orientation, an effect known as **libration**. Theory and observations of libration agree for essentially all Solar System bodies.
- For Enceladus, the observed libration is ten times as large as expected, if one assumes that the moon is solid (Thomas et al. 2016).
- So far, the only way to account theoretically for the observations is to disconnect the surface and core with a **global ocean**. The ocean might be **preferentially tidally heated** from this stirring.
- The ocean probably sits on top of the rock/ice core.



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Ganymede & Dione

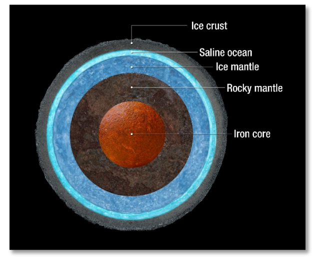
Ganymede and Dione mostly create the eccentricities that provide Europa and Enceladus with tidal heating. In turn, their orbits are also eccentric, but they are far enough from their planets that the tidal heating is much less.

For Ganymede, we observe magnetic "repulsion," though it is not as perfect as on Europa. In part, this is due to the moon having its own magnetic field in addition to Jupiter's.

Ganymede also has its own auroras. The positions of the auroras are in agreement with theory only if Ganymede has a saltwater-like shell like Europa's, 150-330 km beneath the surface (Saur et al. 2015).

So Ganymede, too, is likely to have a global ocean, though it probably sits on top of an ice mantle rather than directly on the rocky mantle.

Unfortunately, Dione has not yet been frisked for oceanic contents.



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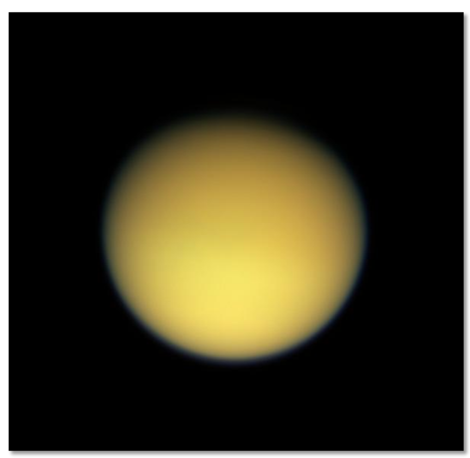
Titan's hydrocarbon lakes

Titan is the second-largest satellite in the Solar System (slightly smaller than Ganymede) and was the first one discovered after the Galilean satellites (by Huygens in 1665).

It is not locked in an orbital resonance, but it has a relatively large orbital eccentricity: four times the tidal stretch of Ganymede.

It is the only moon in the Solar System with a dense atmosphere: pressure of about 1.6 Earth atmospheres at the surface, 95% nitrogen (most of the rest is methane and ammonia), and is so heavily laden with photochemical smog that the surface cannot be seen at visible wavelengths.



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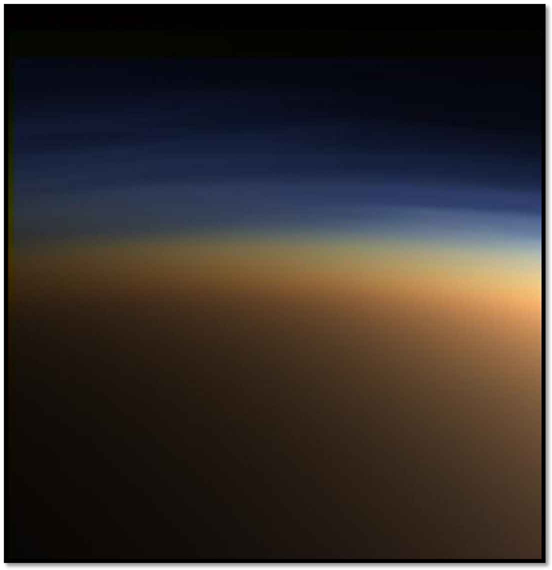

Titan's hydrocarbon lakes

Haze in Titan's upper atmosphere

Photochemical smog below

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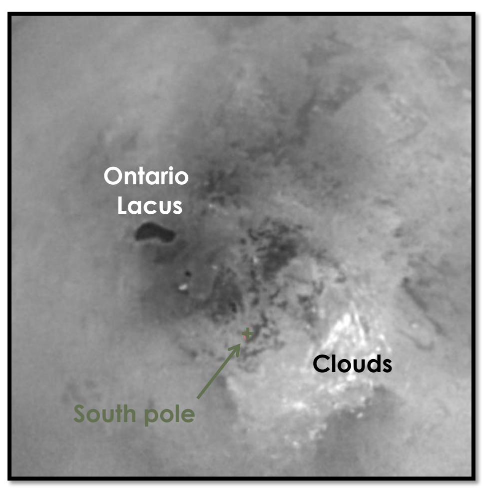
Titan's hydrocarbon lakes

Besides Earth, Titan is the only Solar System body to have liquids permanently resident on its surface.

Hundreds of lakes are seen, especially near the poles: they change in depth over time and are fed by rivers with deltas.

In Ontario Lacus, liquid ethane (70%) and methane (10%) dominate the contents.

Ligeia Mare is nearly pure liquid methane and ethane and is 170 m deep.



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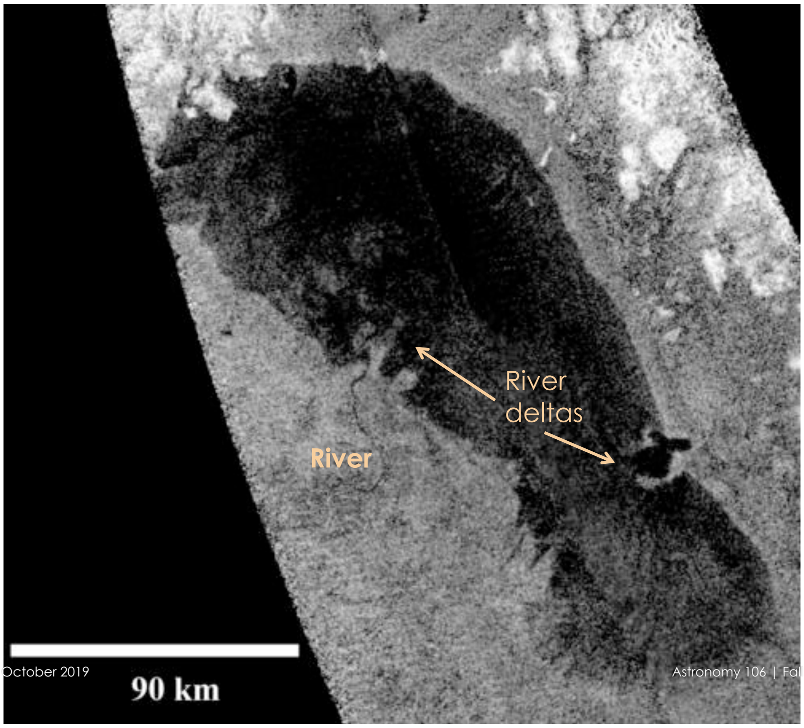

Titan's hydrocarbon lakes

Radar image of Ontario Lacus, taken in 2010 by *Cassini*.

Note the rivers – rivers imply rain!

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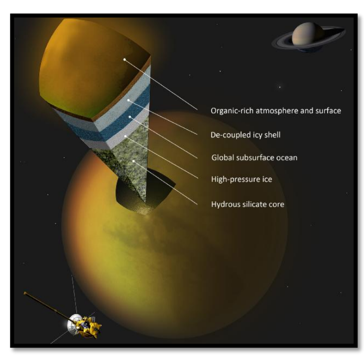
Titan's global subsurface (water) ocean

Titan has several non-LAWKI habitability features in its favor. But for good measure, and despite the lack of significant orbital resonances, it also seems to have a subsurface ocean.

Titan rotates synchronously: the direction of its stretch is constant, but its magnitude varies through its relatively eccentric orbit.

The variation of the tidal stretch through the orbit has been measured by *Cassini* and is a factor of 10 too large for the surface to be solidly connected with the rest (Iess et al. 2012). A subsurface ocean would work fine; **the ocean may be preferentially tidally heated.**

As on Ganymede, the low density of Titan makes it likely that the ocean sits on a water-ice mantle rather than atop the rocky core.



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Summary: AST 106 habitability ratings

Rating these worlds according to supply of water and organics; supply of minerals and inorganics; supply of heat; and consistency of the heat source, on a 100-point scale.

Europa (100)

After cancelling the ambitious Europa Jupiter System Mission, NASA is now planning a Europa orbiter – the "Europa clipper" – carrying nine experiments to characterize Europa's surface and contents noninvasively. Set to launch around 2025. Meanwhile, the European Space Agency (ESA) is planning to get its JUpiter Icy-moons Explorer (JUICE), carrying *ten* experiments to Europa, Ganymede, and Callisto by 2029. Still no landers.

Ganymede (57)

EJSM would have gone here, too, but now it falls to JUICE, and some possible interest by Russia to build an orbiter-lander mission they call Laplas-P (Laplas Posadka = Laplace's Lander). The latter might be coordinated with JUICE for a 2030 arrival, but mission development is at a standstill.

Summary: AST 106 habitability ratings

Titan (56)

The score includes a 5-point bonus for the hydrocarbon lakes and possible nonpolar-solvent biochemistry. With *Cassini* recently ended and the cancellation of the ambitious Titan Saturn System Mission (TSSM), NASA has done little besides conceptual exercises, such as a mission to place a submarine in the Kraken Mare. Since contributing the *Huygens* lander to the *Cassini* mission and helping their partner NASA cancel TSSM, ESA has expressed little interest; Russia has expressed none.

Enceladus (41)

Worries about the consistency and longevity of its tidal heating source, and a small deduction for being so tiny, have reduced Enceladus' score.

Summary: AST 106 habitability ratings

Mars (40)

Along with Earth-based astronomical detections of methane and water on Mars, NASA has 14 robotic Mars life-search missions in its past, five currently operating, and two in the near-term development stages. ESA currently has one, and two big ones coming up soon. ISRO (India) has an orbiter operating. Including failures and counting the MERs as one: a total of 42 missions.

The Jupiter (Saturn) systems have received six (four) dedicated missions, sharing three of them – Pioneer 11, Voyagers 1 and 2 – and including only one short-lived lander (*Cassini*/*Huygens*, Titan). *Juno* is currently in orbit around Jupiter, but it is studying just the planet and not its moons.

And we hear of doubling down: preparations are underway to send humans to Mars, despite the huge expense and near-certainty of deaths in transit, in the hope that geologists and biologists will find life where robots could not.

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Review of life prospects in the Solar System

Temperature

Sun's radiation (within habitable zone)
- Only Venus

Additional heating due to atmosphere (greenhouse effect)
- Only present on planets with atmospheres
- Venus is too hot because of the greenhouse effect

Additional heating due to tidal forces (tidal heating)
- Saturnalian and Jovian moons (no planets!)

Too hot for life on at least half of the surface
- Mercury, Venus, Moon

Water

Water only found in permanently-shaded craters
- Mercury, Moon

Evidence of water on or below surface
- Earth, Mars, most of the moons discussed

Evidence of sub-surface water oceans
- Most moons *except* Io and Mimas

Liquid methane and ethane on surface
- Titan

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Back to Life on Earth: more on age measurement

Now that we know how life evolves from prebiotic organic molecules and water, what happens next?

This can be determined experimentally by examining the **fossil record**: the state of living things on Earth as a function of time since the formation of the Solar System.

- As usual, the chronology is the most important thing to establish.

Then, the steps can be illuminated in finer detail by **phylogeny**: the structural classification of different forms of life, and comparison of genetic material among the forms that still exist.

- Measurement of "genetic distance" can be hooked through the fossil record to chronology.

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Age of Earthly objects

We already know how to measure the ages of old igneous rocks and meteorites using Rb-Sr radioisotope dating of their minerals. Several similar methods give redundancy to check each other, or better precision over different age ranges.

Radionuclide	Daughter	Stable reference	Half life [Gyr]
^{147}Sm	^{143}Nd	^{144}Nd	106
^{87}Rb	^{87}Sr	^{86}Sr	50
^{187}Re	^{187}Os	^{186}Os	43
^{176}Lu	^{176}Hf	^{177}Hf	35
^{232}Th	…^{208}Pb	^{204}Pb	13.9
^{238}U	…^{206}Pb	^{204}Pb	4.5
^{40}K	^{40}Ca	^{44}Ca	1.5
^{235}U	…^{207}Pb	^{204}Pb	0.71

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Age of Earthly objects – K-Ar dating

There are also a couple of interesting methods that do not involve mineral chemistry *per se*.

Potassium-argon. Normal potassium is ^{39}K. About 0.01% of potassium exists as ^{40}K, which can decay radioactively by two means: ordinary beta decay and electron capture.

$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^- + \upsilon_e \quad 88.8\%\ \text{of decays}$$
$$^{40}\mathrm{K} + e^- \rightarrow {}^{40}\mathrm{Ar} + \upsilon_e \quad 11.2\%\ \text{of decays}$$

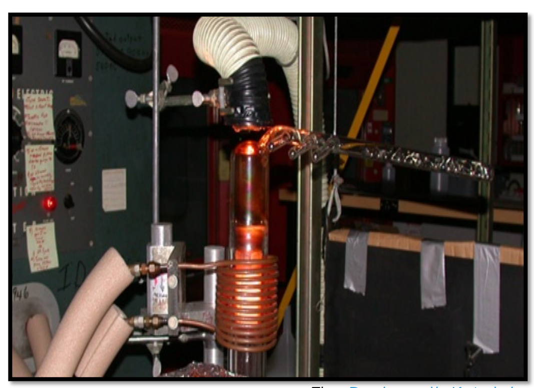
The half-lives are 1.5 Gyr (see previous chart) and 11.9 Gyr.

- Argon, though not a gas and not chemically bound to the mineral, does not escape from the site it occupied as a K atom unless the rock is sufficiently heated.
- The rock would otherwise contain no argon.

Age of Earthly objects – K-Ar dating

- Therefore, counting the trapped argons gives an accurate number of decays since the rock was formed, and this can be done by baking the rock to release the gas.
- The potassium must still be counted, though. The slickest way to do this is to subject the sample to a neutron beam from a nuclear reactor. This quickly converts all the ^{39}K to ^{39}Ar, which can be baked out and counted either separately or along with the ^{40}Ar.
- The analysis works the same as Rb-Sr.

This gives accurate ages in the 50,000 year – 1 Gyr range, nicely extending the range of Rb-Sr to younger ages.



The Dartmouth K-Ar lab

Age of Earthly objects – ^{14}C dating

In the atmosphere, cosmic rays transmute a tiny fraction of the normal isotope of nitrogen, ^{14}N, into the radioactive form of carbon, ^{14}C.

- The half-life of ^{14}C is shorter than any of the other radioactive clocks considered so far: **5730 years**. Consequently, it is only good for measuring young ages, $\sim 100 - 60{,}000$ years.
- The atmospheric concentration of ^{14}C is roughly constant throughout time: **^{14}C/total C $= 1.18\times 10^{-12}$.**

Age of Earthly objects – ^{14}C dating

- The carbon in plants comes from atmospheric CO_2, so live plants have this same fraction of their carbon in ^{14}C.
- The carbon in animals comes from plants, so live animals also have their ^{14}C in the atmospheric abundance.
- As soon as the plant or animal stops either photosynthesizing or eating, the ^{14}C stops being replenished: dead things have less ^{14}C than the atmosphere by amounts directly related to how long they have been dead.
- Caveats: the atmospheric concentration of ^{14}C does vary with such things as the Solar sunspot cycle. For high accuracy, ^{14}C dates must be corrected by comparison to other methods (e.g. ^{14}C dates of tree rings, which go back about 9000 years).

Calculating ^{14}C ages

Ignoring corrections, the concentrations of ^{14}C are given by the master equations for radioactive decay:

$$\text{Concentration: } n(t) = n_0 e^{-t \ln 2 / t_{1/2}}$$

$$\text{Decay rate: } \quad r(t) = \frac{\ln 2}{t_{1/2}} n(t)$$

which can be rearranged to yield

$$\boxed{t = \frac{t_{1/2}}{\ln 2} \ln\left(\frac{n_0}{n(t)}\right) = \frac{t_{1/2}}{\ln 2} \ln\left(\frac{r_0}{r(t)}\right)}$$

You need to understand how to use this formula.

where

- $n_0 = 1.18 \times 10^{-12}$
- $r_0 = 13.56$ decays per minute per gram of C
- $t_{1/2} = 5730$ years

Nobel prize in chemistry (1960) to Willard Libby for the invention of radiocarbon dating

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The ^{14}C concentration in a prehistoric corpse is ¼ that of the atmosphere. How long ago did it die?

Question!

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The ^{14}C concentration in a prehistoric corpse is measured to be 3.39 decays per minute per gram of C from the corpse. How long ago did it die?

Question!

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The dating of sedimentary-rock strata

Currently, we have a good way of measuring the ages of

- Igneous rock of just about any age
- Corpses of plants and animals that died within the last 60,000 years.

Unfortunately, fossils are

- not organic: their material has been replaced by inorganic material. So, ^{14}C dating would not work, even if it could reach very old.
- only found in sedimentary rocks. Sedimentary rocks are made of granules of other sorts of rock whose solidification ages bear no natural resemblance to one another.

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The dating of sedimentary-rock strata

Fortunately, the Earth is volcanic, and there are sheets of sedimentary rock hundreds of miles across that have been horizontal since formation on ancient ocean floors.

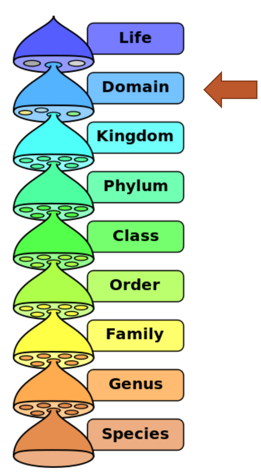
- Sedimentary strata are overlain and underlain with igneous rocks whose ages can be measured by radioisotope means (most frequently K-Ar or K-Ca).
- Sediments build from the bottom up, so older sediments were buried by newer ones and now lie at a lower elevation or greater depth. Paleontologists call this the **principle of superposition**.
- Fossil ages can therefore be measured with a few-percent accuracy, and we can construct the **fossil record**: the census of living things through the last few Gyr.

The structure of fossils and life forms: phylogeny

To go with our accurate measures of time, we characterize the structure and, nowadays, the **genetic content**, of organisms.

This study is called **phylogeny** and was invented by Carl Linnaeus in the early 1700s.

The broadest classification is the **domain**. It is based on the distinction between cells that have organelles like nuclei, mitochondria, etc. (**eukaryotes**) and those that do not (**prokaryotes**, divided into **eubacteria** and **archaea**).

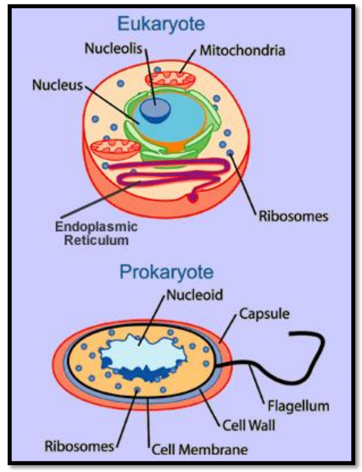


The structure of fossils and life forms: phylogeny

Archaea were first identified among the extremophiles; later, they were found genetically to be much different from eubacteria in their ribosomal RNA. (They still have essentially the same genetic code as other Earthly organisms, though.)

Evolutionary sequence of archaea → eubacteria → eukaryotes seems clear:

- Complexity and diversity increase in this direction
- Some organelles, particularly mitochondria and plastids, look like prokaryotes that assimilated into the structure of eukaryotes



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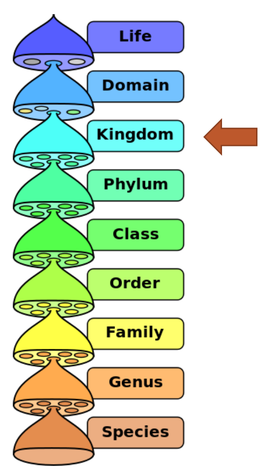
The structure of fossils and life forms: phylogeny

So far, all types can either manufacture their own nutrients out of monomers in the environment (**autotrophs**, the forerunners of plants) or need to eat processed nutrients or other life forms (**heterotrophs**).

The eukaryotes are the most diverse and are thus further sorted into **kingdoms**:

- **Animalia**: multicellular heterotrophs
- **Plantae**: multicellular autotrophs
- **Fungi**: multicellular symbionts
- **Protista**: unicellular eukaryotes



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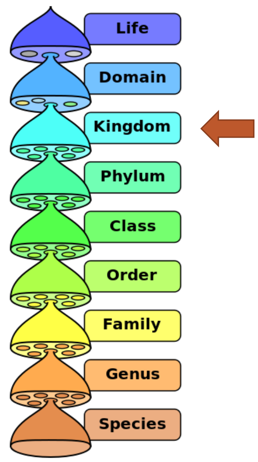
The structure of fossils and life forms: phylogeny

Within kingdoms comes an internal, genetic differentiation: **ploidy**, the number of copies of the nucleic-acid structures each cell contains.

- **Genes**: nucleic acid sequences that code proteins
- **Chromosomes**: structures containing genes
- **Haploids**: Life forms (permanently) containing only one copy of each chromosome
- **Diploids**: Life forms containing two copies of each chromosome. We are diploids.

Importance: this leads to a non-mutation means of having reproduction lead to greater diversity of each multi-ploid life form. We call this, of course, **sexual reproduction**.



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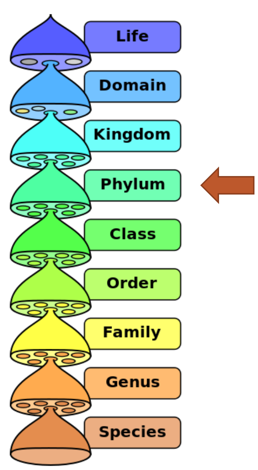
The structure of fossils and life forms: phylogeny

Each kingdom is further sorted into **phyla**.

- For example, the kingdom animalia is divided into 35 different phyla.
- We belong to the phylum chordata, those animals with spinal chords (though not necessarily spines).
- Plants are usually divided into 11 phyla, fungi into 6.
- Phyla first appeared 550 Myr ago: in the Cambrian Explosion, of which the Burgess Shale provides the most examples.



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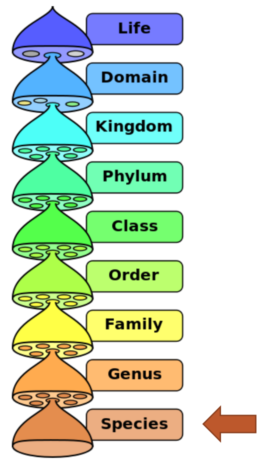
The structure of fossils and life forms: phylogeny

And so on, down to genus and species.
Examples:

Human	Giant sequoia redwood
Eukarya	Eukarya
Animalia	Plantae
Chordata	Pinophyta
Mammalia	Pinopsida
Primatae	Pinales
Hominidae	Cupressaceae
Homo	Sequoiadendron
sapiens	giganteum



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Myr ago	Era	Fossil group	Event
Now	Cenozoic		
	Mesozoic		
		Burgess Shale	
	Paleozoic		Macroscopic life
		Ediacara	
			Snowball Earth
	Precambrian		
1000		Bitter Springs	Worm tracks (?)
			Multicellular algae
		Beck Spring Dolomite	
			Eukaryotes certain
		McArthur Group	Sexual reproduction (?)
2000		Gunflint chert	Eukaryotes possible
	Proterozoic		Oxygen-rich atmosphere
			Snowball Earth
			Formation of continents
3000		Bulawayan	
		Fig Tree	
		Onverwacht	
		Warrawoona	Autotrophs-Stromatolites
	Archean		Life begins (?)
			(Prokaryote heterotrophs)
4000			Formation of oceans
			Bombardment decreases
			Frequent impacts
	Hadean		Formation of Earth
5000			

The fossil record

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Myr ago	Era	Fossil group	Event
Now	Cenozoic		
	Mesozoic		
		Burgess Shale	
	Paleozoic		Macroscopic life
		Ediacara	
			Snowball Earth
	Precambrian		
1000		Bitter Springs	Worm tracks (?)
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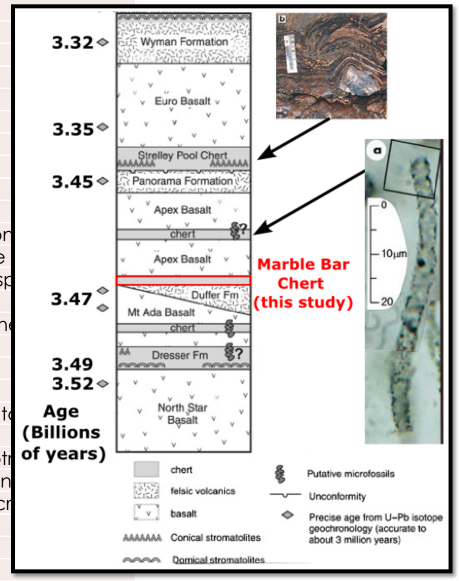

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Myr ago	Era	Fossil group	Event
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	Paleozoic		Macroscopic life
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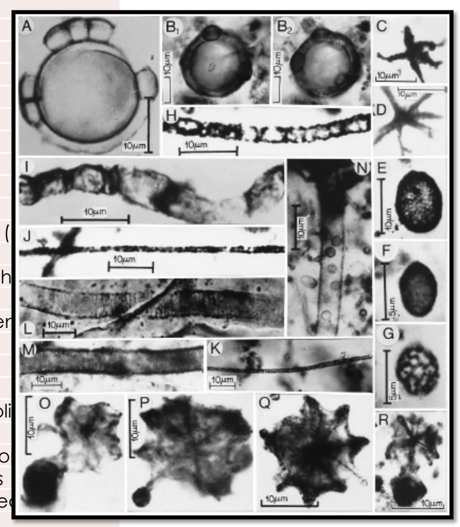

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Myr ago	Era	Fossil group	Event
Now	Cenozoic		
	Mesozoic		
		Burgess Shale	
	Paleozoic		Macroscopic life
		Ediacara	
			Snowball Earth
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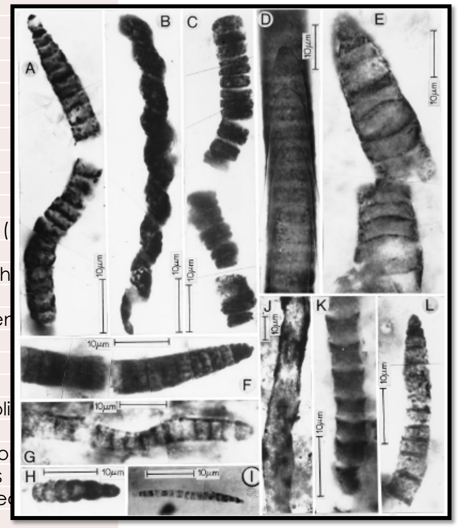
		Onverwacht	
		Warrawoona	Autotrophs-Stromatoli
	Archean		Life begins (?)
			(Prokaryote heterotro
4000			Formation of oceans
			Bombardment decre
			Frequent impacts
	Hadean		Formation of Earth
5000			



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Myr ago	Era	Fossil group	Event
Now	Cenozoic		
	Mesozoic		
		Burgess Shale	
	Paleozoic		Macroscopic life
		Ediacara	
			Snowball Earth
	Precambrian		
1000		Bitter Springs	Worm tracks (?)
			Multicellular algae
		Beck Spring Dolomite	
			Eukaryotes certain
		McArthur Group	Sexual reproduction (?)
2000		Gunflint chert	Eukaryotes possible
	Proterozoic		Oxygen-rich atmosphere
			Snowball Earth
			Formation of continents
3000		Bulawayan	
		Fig Tree	
		Onverwacht	
		Warrawoona	Autotrophs-Stromatolites
	Archean		Life begins (?)
			(Prokaryote heterotrophs)
4000			Formation of oceans
			Bombardment decreases
			Frequent impacts
	Hadean		Formation of Earth
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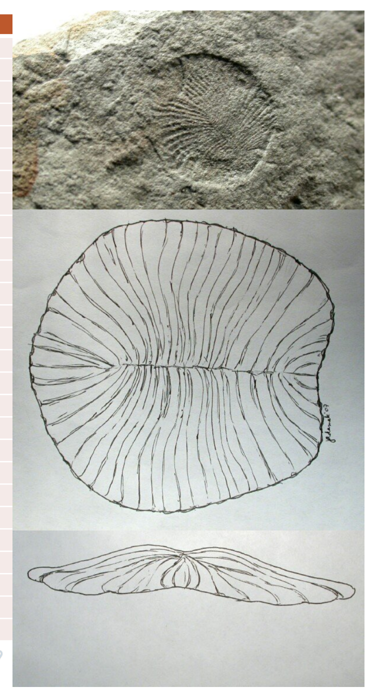

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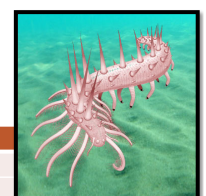
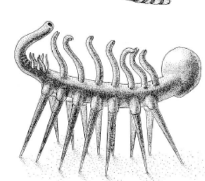
The fossil record 0-800 Myr ago: the Cambrian Explosion and its descendants



Era	Period	Myr ago	Life forms	Events
Cenozoic	Quaternary	2	H. sapiens	Ice ages
	Tertiary	65	Primates	Extinction of dinosaurs
Mesozoic	Cretaceous	136	Birds	South Atlantic open to 1900 miles
	Jurassic	190		North Atlantic open to 600 miles
	Triassic	225	Mammals	Continental drift
Paleozoic	Permian	280	Reptiles	Pangaea breaks up
	Carboniferous	345	Amphibians	Formation of coal
	Devonian	395	Insects	
	Silurian	430	Land plants	
	Ordovician	500	Fish (Chordata)	Burgess Shale forms
	Cambrian	543	Trilobites	
Precambrian		545	Small shelly fossils	*Appearance of phyla*
		580	Ediacarans	
		600-680		Snowball Earth episodes
		0		
			Multicellular life	



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The fossil record 0-800 Myr ago: the Cambrian Explosion and its descendants

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	Cambrian	543	$\boxed{\text{Trilobites}}$	*First good example of classes*
Precambrian		545	Small shelly fossils	
		580	Ediacarans	
		600-80		Snowball Earth episodes
		0		
			Multicellular life	

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The fossil record 0-800 Myr ago: the Cambrian Explosion and its descendants

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The fossil record 0-800 Myr ago: the Cambrian Explosion and its descendants

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Summary of fossil record

Cellular life has been around for at least 3 Gyr.

Simple organisms developed first, more complex ones later: prokaryotes, then eukaryotes, then multi-cells.

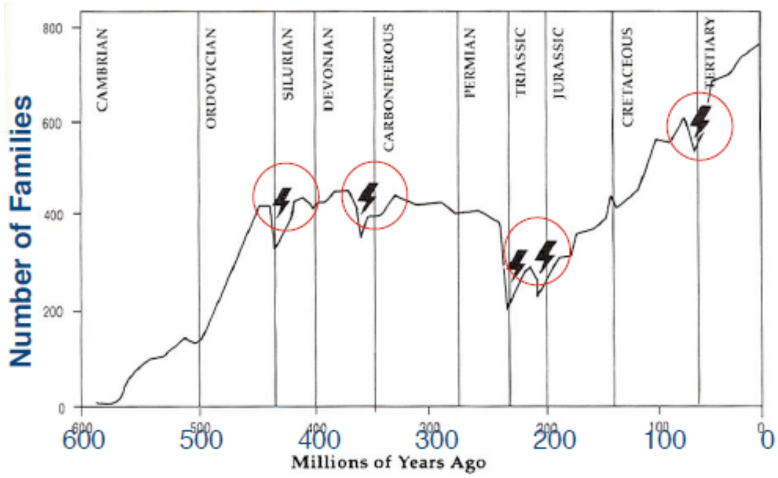
Deterministic "progress" of families is not observed:

- Many organisms develop and become extinct with no links to successors.
- Some families develop greater diversity, but many stay about the same complexity (e.g. bacteria).

General increase in complexity and diversity of life forms, though:

- Huge animal boom in the Cambrian Explosion.
- Plant boom in the last 150 Myr, driven by flowering plants and insect hosts.

Major extinctions



Diversity rising

"Biological diversity has increased slowly over geological time, with occasional setbacks through mass global extinctions. There have been five such extinctions so far, indicated here by lightning flashes. The data given are for families (groups of related species) of marine organisms. A sixth major decline is now underway as a result of human activity." - E.O. Wilson, *The Diversity of Life*

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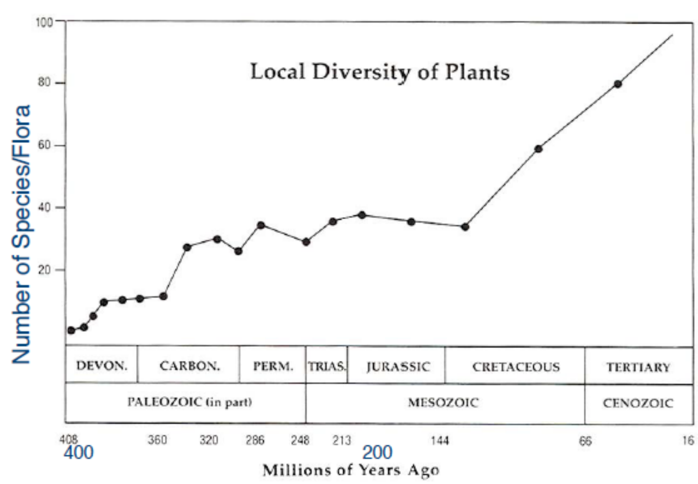

Local diversity of plants

"The average number of plant species found in local floras has risen steadily since the invasion by plants 400 million years ago. The increase reflects a growing complexity in terrestrial ecosystems around the world." - E.O. Wilson, *The Diversity of Life*

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Biological evolution

Features of the fossil record:

- Change of Earth's population with time over billions of years
- Development of greater structural complexity and diversity of fossils as time goes on
- Clear developmental patterns among species within many families as time goes on

These features are all experimental facts. Thus, **biological evolution is also an experimental fact** to go with all the other cosmic evolutions we have found so far.

The Burgess Shale formation in British Columbia is the richest source of Cambrian-era fossils.

Information, DNA, and phylogeny

The modern ability to determine the sequence of nucleotides in complete **genomes** has added a lot to the classification.

Genetic complexity grows with structural complexity: eubacteria have $\sim 10^3$ genes, single-cell eukaryotes $10^4 - 10^5$.

All organisms possess a lot of non-coding, or **junk**, DNA: stretches of nucleic acid that do not lead to proteins.

Useful to evolutionary biologists:

- Mutations in junk DNA do not affect the organism, allowing us to study the mutation rate separately from the fate of the species.
- In turn, this has allowed estimates of the time scale of DNA evolution.

Three fossils of the same species are found. Two have accurate geological ages of 2.0 and 3.0 Myr and differ in junk DNA along a certain stretch by 20 base pairs. The third was found in a 100 Myr-old geological context and differs by 5 base pairs from the older of the first two. How old is the third fossil?

Question!

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Why do you suppose that there is such a big difference in the ages of the geological context among these fossils?

Question!

A. The third one was found in a cave.
B. The third one was found in an ancient lake bed among nothing but sedimentary rock.
C. The third one was found in the ice in Antarctica.
D. The third one was found in a carbonaceous chondrite meteorite.
E. K-Ar dating accuracy is not any better than 100 Myr.

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Question!

Why would this age-dating scheme not work if the base-pair difference were found in non-junk DNA?

A. The fossils would probably be of different species if non-junk DNA differ by this many base pairs.
B. Non-junk DNA never changes.
C. It would still be in disagreement with the geological ages.

Information, DNA, and phylogeny

The total information content – the length of DNA – does not connote complexity.

Junk usually dominates the genome!

Unit	Bits	Pages	Books
Base pair	2		
Codon	6		
Virus	10^3	1	
(Eu-) bacterium	10^6	1000	1
Single-cell eukaryote	5×10^8		500
Human	6.4×10^9		6400
Newt	10^{11}		100,000

Only 128 non-junk (2%)

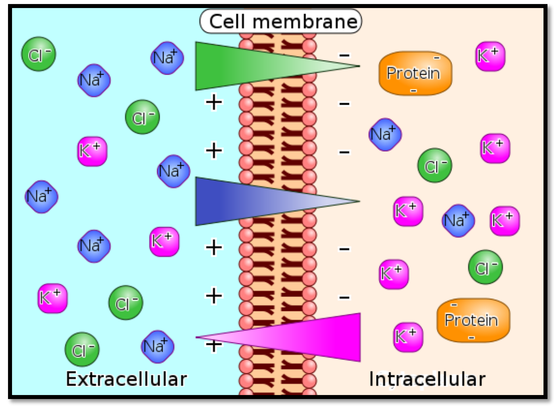
On the way to the Cambrian explosion: evolution of senses and neurons

The fifth part of our provisional definition of life is

- [Living things] exhibit **sensitivity**: they respond to changes in their environment.

Sensation indicates the beginning of neural activity.

- As discussed a couple of weeks ago, cell membranes are made of **polarized** lipid bilayers: the negatively-charged ends of these zwitterions always lie toward the cell's interior, and the positive charges toward the cell's exterior.



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On the way to the Cambrian explosion: evolution of senses and neurons

As a result, there is an **electric voltage** across the membrane, albeit a small one.

This is a result of natural selection: other arrangements of "containers" do not retain the proteins and nucleic acids or allow the transmission of ions and monomers from the outside.

But it has other uses, too, as the **polarization allows the membrane to be distorted or modified by other electrical impulses**. For example,

- Impulses specific to certain large molecules, like nutrients that would save the cell from having to make such molecules
- Impulses passed on from cell to cell in a multicell organism: transmission of **signals** in a rather familiar modern fashion.

This would be very different in life that developed in non-polar solvents!

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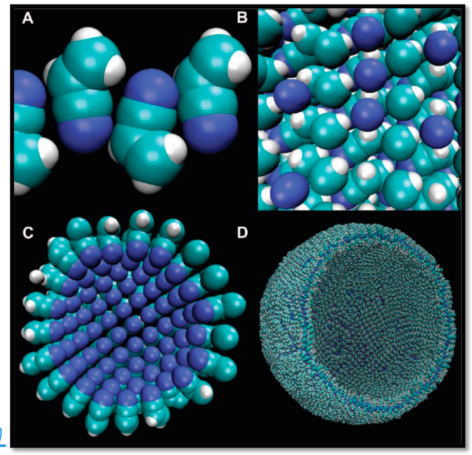
Evolution of senses and neurons with non-polar solvents

In the liquid-methane azotosome models of membranes which we previously discussed, the polar molecules in the membrane line up + to −.

This promotes the passage through the membrane of nonpolar molecules…

…but leaves essentially **zero voltage** across the membrane. So multicellular life in Titan's hydrocarbon lakes would have to have a completely different means of transmitting and receiving sensory signals.



Stevenson, Lunine, & Clancy (2015)

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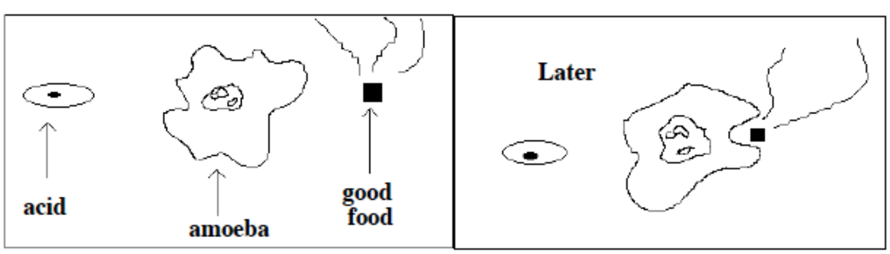
Evolution of senses and neurons

If a certain cell-membrane configuration…

- Which, of course, is coded in the DNA

…is electrically conducive to beneficial electrical distortion that makes it easier for organisms to survive or reproduce, the population of these organisms will dramatically increase. Another example of natural selection.



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Evolution of senses and neurons

Simple example: jellyfish, in which membrane-mediated electrical transmission among the cells around the edges synchronize the movement of these cells, help propel the organism through the water and thereby make more food accessible.

Jellyfish have no brain or memory: this simple nervous system is **autonomic**. Cut a jellyfish in half and the halves will still "swim" in the same fashion.

60

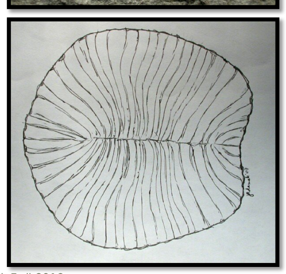
Evolution of senses and neurons

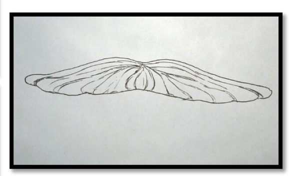
Before the Cambrian Explosion, no organism in the fossil record was any more complex than a jellyfish.

- Like the "Ediacara" organisms of 900–600 Myr ago.

The Cambrian Explosion gave rise to organisms with structures that, in modern organisms, do not correspond to autonomous functions.

The difference is the presence of cells that **store** electrical impulses and can therefore transmit that **memory** among the cells.





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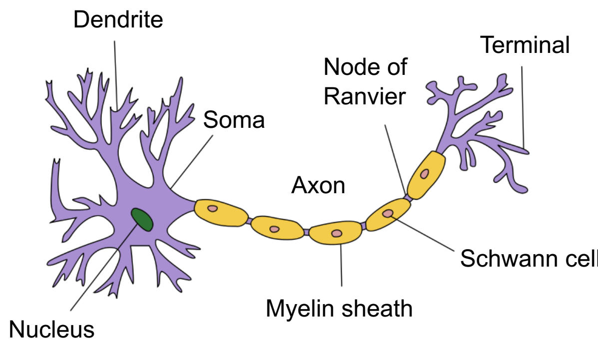
Evolution of senses and neurons

These new, specialized cells remember previous sensations and can compare them (by adding or subtracting voltages) to current sensations. Nowadays, we call them **neurons**. Their advent **apparently coincides with the Cambrian Explosion**.



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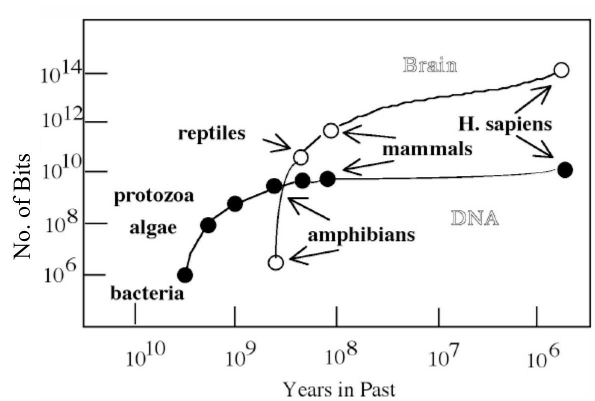
Information, neurons, and phylogeny

Once neurons exist, memory and commanding is possible and would clearly give a species a high propensity to reproduce, survive, and, if necessary, compete for scarce resources.

As it is beneficial, the trait of having increasingly larger memory and commanding capacity will continue to be selected naturally until the memory capacity of neurons far outstrips the storage capacity inherent in the nucleic acids.

The structure of neurons is (still) encoded in the nucleic acids. The nucleic acids serve the same purpose as the boot ROM and BIOS in your computer; the neurons the same purpose as the RAM and hard disk.



Plot of information capacity of DNA in filled circles – including junk – and of nervous system in open circles.

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Information, neurons, and phylogeny

Information stored in DNA, though it contains the instructions for building a new copy of the organism and may even account for instinctive reactions to stimuli, cannot tell the entire story.

To learn, a life form must have a non-genetic way of storing information, thus to record the unique and random experiences of the individual.

This, of course, is the function of the nervous system in higher animals, exemplified by our brain.

The ultimate product is **intelligence**.

Intelligence can change the rules of evolution when it reaches a certain stage, as there are aspects of intelligence that can be passed to progeny.

Our observations for the first 13.2 Gyr

1. Evolution of the atomic composition of the Universe and the Galaxy, by explosive and stellar-core nucleosynthesis, producing the relative abundances of the elements
2. Evolution of the structure and lifetimes of stars and their planetary systems
3. Evolution of the molecular composition of the interstellar medium, resulting in prebiotic molecules on habitable planets
4. Evolution of primitive life – RNA World – from prebiotics (speculation, but with strong theoretical and experimental support)
5. Evolution of complex cellular life from primitive life
6. Evolution of organisms from complex cellular life

The first five Evolutions are explained by means which we would not hesitate to call **natural selection**. How about the sixth?

Theories of the origin of species

An origin of species in evolution was first suspected in the 1700s, after Linnaean phylogeny had become widespread.

There have been fewer basic scientific theories of the origin of species than you might think. Only two, really:

- **Evolution by adaptation**. Individuals acquire characteristics that help them cope with environment, pass these acquired characteristics on to their progeny.
- **Evolution by natural selection**. A population develops a diversity of traits by a combination of mutation and sexual reproduction. Those traits which are better matched to the environment or its changes will help those with the traits to survive or reproduce, and eventually those traits become the new norm.

Guided evolution **Unguided evolution**

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Guided evolution

Jean-Baptiste Lamarck (France, 1744–1829) is the leading figure in evolution by adaptation.

- Circumstances force individuals to adapt: to lose characteristics they do not need and to develop useful ones.
- Individuals that succeed have adapted well to the conditions – climate, food supply, etc. – with which they are faced.
- Beneficial adaptations are thereafter inherited: "better" species descend from these individuals.

Today, it is easiest to refute this theory by noting that individuals cannot adapt their DNA, and DNA governs inheritance, but other objections are not difficult to find.

67

True or false: Extinction would represent a failure of Larmarck's theory.

Question!

68

True or false: Modern organisms and the fossil record indicate that more complex, intelligent organisms are more likely to survive.

Question!

69

Unguided evolution

According to Charles **Darwin** (1809 – 1882) and Alfred **Wallace** (1823 – 1923), evolution proceeds by natural selection, as follows:

- There are random, inborn variations among individual life forms of a given type or species. Mutation or sexual reproduction can produce such variations.
- Such inborn variations can (obviously) be inherited.

Today, mutation is understood as either DNA transcription errors or external modification of DNA (e.g. by high-energy radiation).

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Unguided evolution

Most of these variations are neutral or harmful, but occasionally a variation is beneficial, suiting the individual better to its circumstances.

If a beneficial variation makes it easier for an individual to survive or reproduce, the variation will appear in large numbers in a short time compared to the geological timescale.

- Thus *populations* evolve; individuals *develop*.
- Small variations could produce gradual evolution and differentiation of species; even “small” and “gradual” can be geologically fast, and a new species can appear suddenly in the fossil record.

71

Unguided evolution

Additional nuances: whether there are chronologies known accurately enough to rule out such **gradualism** is occasionally tested but has not yet succeeded:

- Saltationism (e.g. Thomas Hunt Morgan): substantial mutation leading to a new species in a single generation. Popular in the early 20th century, this is now ruled out by more recent chronology.
- Punctuated equilibrium (e.g. Stephen Jay Gould): environmental pressures on *part* of the population of a species will lead to more rapid selection and development of new species, while the rest of the population is in stasis. This is still under discussion, but it is not that different from gradualism.

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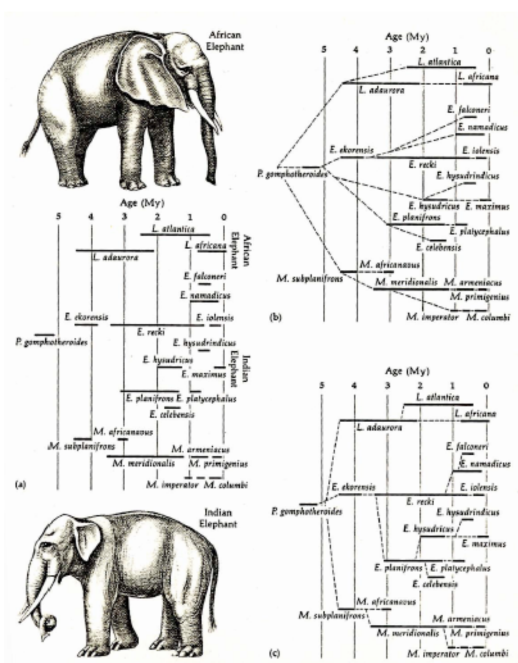


Gradualism v. punctuated equilibrium

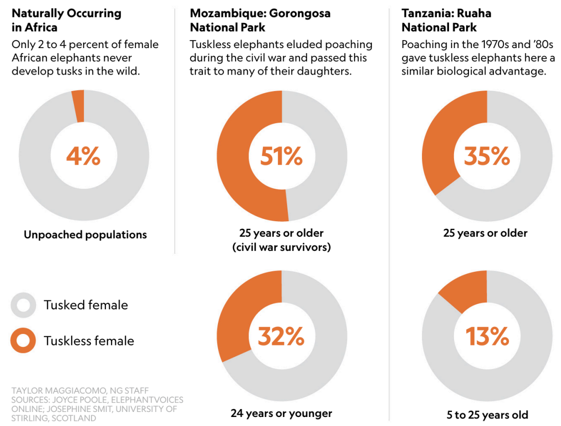
Fossil record of elephants, interpreted as gradualism (upper) or punctuated equilibrium (lower). From Gould, *Wonderful Life*.

73

Forced evolution

The process of natural selection can also be affected by a species' habitat.

- A recent study found there are more tuskless elephants in Mozambique than is typical. It has been surmised that the hunting of these creatures for their ivory has preferentially "selected" those without tusks to have a higher survival rate.
- Biologists are unsure what affect this will have on this and other species, since tusks are used to dig for water, debark trees for food, and compete for mates.



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Evolution by natural selection

The theory of evolution by natural selection has been very successful and has, in particular, stood up remarkably well against the findings of molecular biology and genetics.

Consistent with many experiments based on artificial selection (breeding), as Darwin noted.

Seems a natural successor to RNA World, which is the most consistent explanation of the emergence of biomolecules and in which natural selection functions.

Consistent with genetics, including mutation timescales measured from junk-DNA variation.

Consistent with the existence of junk DNA and gene duplication in different species. Other, more "guided" theories of evolution (and creation) are not.

75

True or false: extinction represents a weak point for Darwin's theory, one that the theory does not well explain.

Question!

Darwin's view of natural selection is often described as "survival of the fittest" – see the cover of *Origin*. Is this an accurate summary of natural selection?

Question!

A. Yes, as there is always competition for resources.
B. Maybe: introduction of species from harsh environments to hospitable environments usually results in predominance of those species.
C. No. Natural selection works the same no matter what the abundance of resources, as better-suited species would still reproduce more copiously than poorer-suited ones.