Astronomy 330

This class (Lecture 16):
Origin of Life

Next Class:

Biological Evolution

HW 6 due Wednesday

Music: *Chiron Beta Prime* – Jonathan Coulton

HW 2

- **Mitchell Farag**
  http://www.alien-ufo-pictures.com/absolute_proof_aliens_exist.html
- **Cori Johnson**
  http://www.alienandufopictures.com/

Presentations

- **Christopher Moss:**
  Methods of Space Colonization

Outline

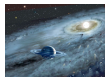
- Origin of Life on Earth?
  - RNA World
- Life Alternative Styles
- So what is f_l?

Drake Equation

Frank Drake

That's 1.24 Life-liking systems/year





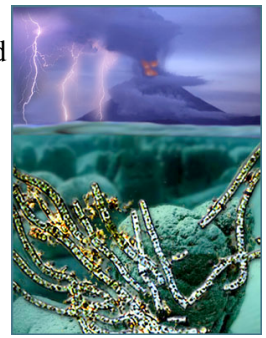



$$N = R_* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$

N	R_*	f_p	n_e	f_l	f_i	f_c	L
# of advanced civilizations we can contact in our Galaxy today	Star formation rate	Fraction of stars with planets	# of Earthlike planets per system	Fraction on which life arises	Fraction that evolve intelligence	Fraction that commun-icate	Lifetime of advanced civilizations
	10 stars/ yr	0.75 systems/ star	1.5 x 0.11 = 0.165 planets/ system	life/ planet	intel./ life	comm./ intel.	yrs/ comm.

Transition to Life

- **Two possibilities**
  - Primitive versions of proteins, nucleic acids, and protocells arose independently and combined to form a life form, called **primitive life**.
  - One of the components was dominant and the first "life" was based on only one polymer, then developed into life as we know it. We can call it **protolife**.
- The statistical argument would argue **against** primitive life and **for** protolife.



http://www.lbl.gov/Science-Articles/Archive/sb/July-2004/2_spinach.html

Protolife

If we assume that early life must have been protolife, then

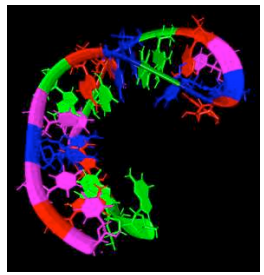
- Two protolife concepts based on nucleic acids or proteins.

1. Protein life
2. RNA life

http://www.perantivirus.com/sosvirus/graficos/bilgates.jpg

2. The RNA World: Protolife

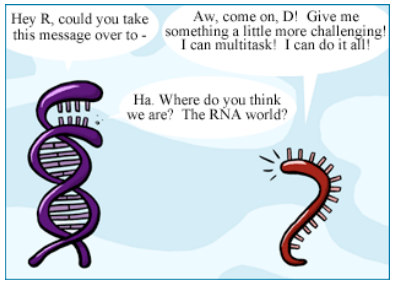
- The other camp believes that the transition to life was dominated by nucleic acids; the opposite problems of the Sydney Fox scenario.
- These genes are naked!
- A ecosystem of self-replicating RNA is nice, but without capability for protein synthesis, they could do little else.
- However, it's the most widely accepted concept due to numerous experiments.



http://www.bizspacebiotechnology.com/rna1.htm

2. The RNA World: Protolife

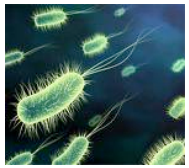
- The basic idea is that RNA did all the tasks.
- Both info storage and enzyme actions.
- Then, the DNA world evolved out of that.
- The rRNA encoding of proteins in today's world may be evolutionary left-overs.



http://evolution.berkeley.edu/evolibrary/images/interviews/rnaworld2.gif

2. RNA World

- RNA is mutating away– eventually one RNA develops an enzyme function.
- This evolves to fill many of the niches that today's enzymes perform.
- At some point, the RNA encode and produce proteins through amino acid encoding, using one of the RNA enzyme functions.
- This would make better enzymes, which would replace the RNA versions.
- Is this possible?



2. RNA World: Experiments

- Virus RNA is added to a test tube with replicase (an enzyme that catalyzes the synthesis of a complementary RNA molecule from an RNA template) and some activated nucleosides.
  - Although proteins were used in this experiment it is thought that RNA enzymes are what played the role on the early Earth.
- The RNA was replicated without cell mechanisms.
- In one experiment, no RNA was added, and still RNA was produced.
- In fact, a number of variants were produced.
- The variant that replicated the fastest might win out.

2. RNA World: Variations

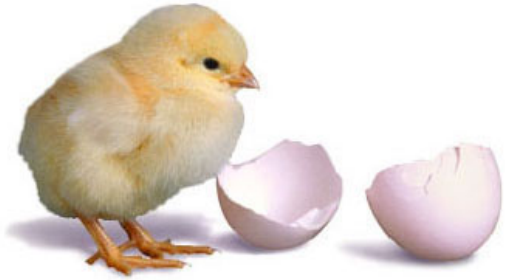
- Some think that RNA might not have been the first nucleic acid.
- On pre-biotic Earth maybe other nucleic acids were more easily formed at first.
- Some other nucleic acids include Peptide nucleic acid (PNA), Threose nucleic acid (TNA) or Glycerol nucleic acid (GNA).
- These would have been replaced with RNA later.

Genetic Code and Origin of Translation

- One of the essential aspects of life is the synergistic interaction between proteins and nucleic acids– still the Chicken and egg problem.
- If protein-like polymers of amino acids formed, they would have to polymerize (create) the nucleotides.
  - The resulting nucleic acid would have to direct the synthesis of more protein, leading to more of the nucleic acid. Etc.
- Or in some RNA world ribozymes (RNA enzymes) began to construct the proteins– the favored view.

Neither Chicken nor Egg?

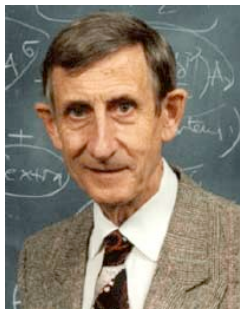
- While RNA world is favored, the difficulty is still in producing the nucleic acids on the early Earth.
- Freeman Dyson had argued that nucleic acid can not have been the first information carrying molecule.



http://www.antivegan.de/kochkurs/chicken-wings/chicken_egg2.jpg

Neither Chicken nor Egg?

- Transition between living and non-living requires a balance between order-preserving replication and error in replication.
- If too precise, nothing evolves.
- If too many errors, nothing consistent forms.
- He argues that RNA is not the easiest to start with, perhaps there were other polymers that preceded nucleic acids.



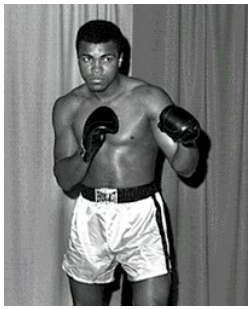
http://www.dartmouth.edu/~lhc/archive/sponsored/dyson.html

Alternatives: Clay

- Spontaneous life from non-living matter — abiogenesis
- Clay based genetic systems.
  - Layers of impurities in clay can produce patterns.
  - The layers can separate, settle elsewhere, and grow.
  - The patterns are not perfectly copied.
  - In 2007, researchers concluded that the crystals were not faithful enough to transmit info from one generation to the next.

Alternatives: Clay

- Would not have been a big deal, BUT clays can capture and help polymerize amino acids.
- Maybe there was clay based life?
- Eventually the proteins make nucleic acids, which then provides a parallel genetic system that disregards the clay.
- Bottom line is that the step from molecules to life is so great that we are far from understanding it.

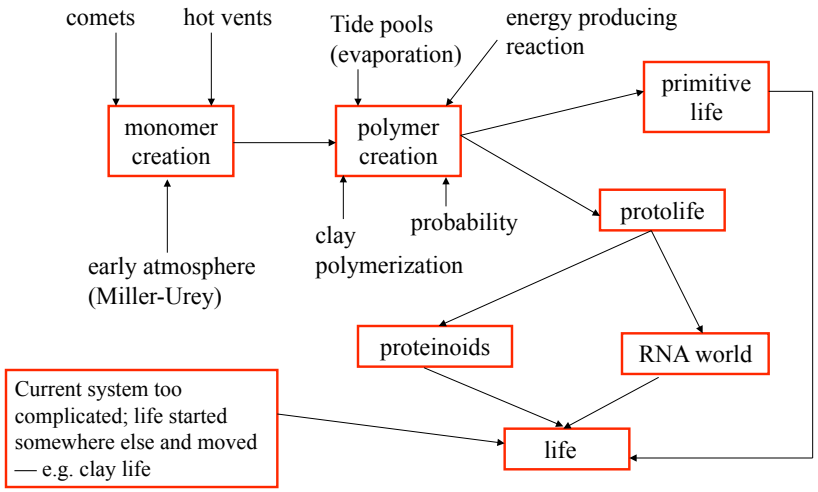


Question

We think the most likely path for life was

a) Life just arose with nucleic acid and proteins working together.
b) Life first started as a nucleic acid (RNA world).
c) Life first started as a nucleic acid (DNA world).
d) Life first started as a protein world.
e) Life first started as an amino acid world.

Pathways to Life on Earth



Question

Which of the following is not a way that life's monomers might have formed on Earth?

a) Hot vents at the bottom of the ocean.
b) In a clay substrate.
c) In the oceans, using energy sources and the early atmosphere of Earth (assuming reducing atmosphere).
d) From comets landing on Earth.
e) Debris from the early circumstellar disk (which had a reducing atmosphere).

Exotic Life

- We have spent a long time with Earth Chauvinism, but ET life would be very different?
  Probably very alien!
- If other options are possible, then that gives a more optimistic value of f_l.
- As we just discussed, there are options for life based on other molecules than amino acids, some have been shown to sort of work in the lab.

http://www.itg.uiuc.edu/people/mcdowell/puppet-gallery/

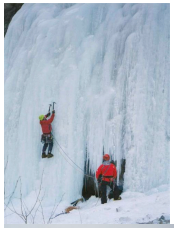
Silicon Based Life?

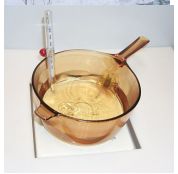
- Silicon makes 4 bonds like Carbon
- It is 135 times more abundant than carbon on Earth.
- But there are 4 arguments against it:
  - C-C bonds are twice as strong as Si-Si
  - Si-O or Si-H is stronger than Si-Si, so harder to make long stands
  - Si does not usually make multiple Si bonds
  - C with O makes CO_2, but Si with O makes silicates (SiO_2), which are large solid crystals.
- Still it is a possibility that can not be ruled out.

http://www.decipher.com/startrek/cardlists/mirrormirror/images/horta.gif
http://soundwavs.trekkieguy.com/25.html

Other Solvents

Molecule	*Freezes (K)*	*Boils (K)*
Water (H_2O)	273	373
Ammonia (NH_3)	195	240
Methyl alcohol (CH_3OH)	179	338
Methane (CH_4)	91	109
Ethane (C_2H_6)	90	184





Water is about twice as good as ammonia or methyl alcohol. Water also has a high energy of vaporization, so it is very good at evaporative cooling (sweat).

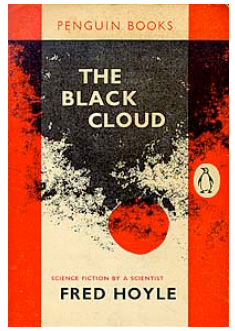
http://www.talisman-activities.co.uk/winter/images/ice%20climbing.jpg
http://web.media.mit.edu/~fletcher/tags/boiling.jpg

Non-Chemical Life

Life is based on chemical energy. Thinking is an electrochemical activity. What about a life form that uses electromagnetic energy instead, perhaps without a body.

The Black Cloud (1957) by Fred Hoyle

The story describes a small interstellar molecule cloud that is alive. The organism is half a billion years old, as big as the orbit of Venus, and as massive as Jupiter. The brain is a complex network of molecules. Once it discovers the Earth it communicates with us:



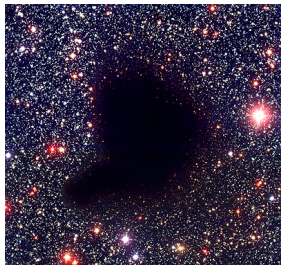
The Black Cloud Speaks

Paraphrased "badly"

- It is most unusual to find animals with technical skills inhabiting planets
- Living on a planet, greatly limits your size, thus the scope of your neurological activity.
- Living on a planet, forces you to possess muscular structures to promote movements.
- Your very largest animals have been mostly bone and muscle with very little brain.
- One only expects intelligent life to exist in a diffuse gaseous medium. At the moment, I myself am building basic chemicals at about 10,000,000,000 times the rate as your whole planet.

Cloud Problems

- How would such a cloud evolve?
- The most dense clouds are 10^{13} times less dense than our atmosphere, which makes molecule interactions very rare.
- In space, interstellar clouds are torn apart in about 10^{7} years. It took 10^{9} years for intelligent life to form on Earth.
- Still it is a cute idea.



Other Voices, Other Energies

- Life based on nuclear energy (put forward by Drake)
  - Life on the surface of a neutron star?
  - Gravity and temperature too high for normal life.
  - Life made of closely packed nuclear matter instead of molecules
  - They interact quickly 10^{-21} seconds, much faster than chemical reactions.
- It has been fictionalized by Robert Forward in *Dragon's Egg*
  - Talking to these beings would be difficult.
  - Their Biology uses the strong nuclear force.
  - A time difference of a million to one.
  - In the time it takes to say "Hello" - would be the equivalent of a week to a star creature. It would hear "He . . . " on Sunday and ". . . lo" on the following Saturday.

Or Too Big

- Life based on gravitational energy?
- In this creature, the gravity force would dominate– very large!
- The monomer of life would have to be a star.
- Perhaps individual stars play the role of individual atoms or molecules in Earth life.

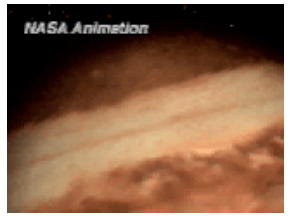
Or Too Big

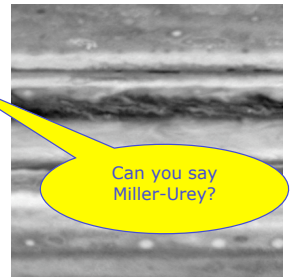
- Could galaxies be alive?
- Stars interact with one another on a time scale of many millions of years, so if life is to originate from such interactions it would take longer than the age of the Universe.
- If life is occurring, it is only at the stage where life was when the Earth was a few years old.

http://www.astro.cz/cz/wallpapers/index.php?id=15

Back to Jupiter's Atmosphere

- Although mostly gas, by 20,000 km in, the pressure is 3 million atmospheres!
- Due to an internal heat source, the temperature rises as one penetrates the atmosphere.
- The outer atmosphere is made of freezing clouds of ammonia, methane, and ice.
- The swirling patterns are evidence of great storms.

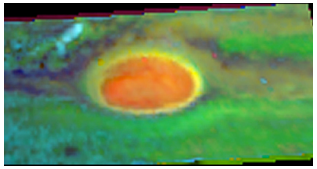




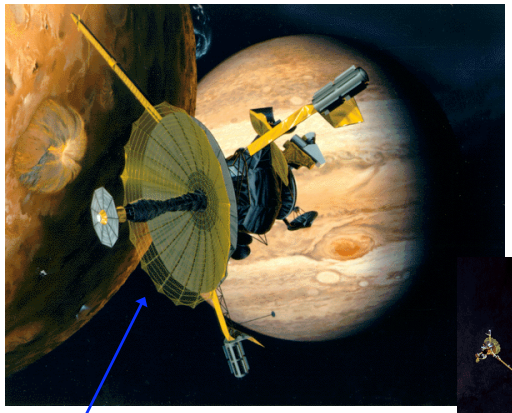
Jupiter's Atmosphere

- The atmosphere resembles the conditions of the Miller-Urey experiment.
- The red bands and spots may be biological molecules.
  - The Miller-Urey experiment produces amino acids and **red polymers**.
  - Carl Sagan suggested that the atmosphere might be an optical photochemistry, like photosynthesis but more effective. Not much evidence for such a statement.
- But, constant churning of the atmosphere probably makes development of complex life nearly impossible.

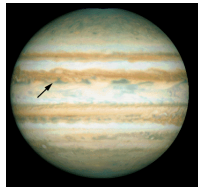
Icy ammonia (light blue) discovered by Galileo



The Galileo Spacecraft (1989 – 2003)



How the main antenna *should* have looked



First atmospheric probe

Probing the Atmosphere

- The probe lasted for 57 minutes before it was destroyed by temperature and pressure.
- Found a lot of turbulence, strong winds (330 mph), very little water ice, and no lightning.

Probing the Atmosphere

- Did not encounter the layers of clouds that was expected.
- The probe entered the least cloudy region of Jupiter.
- Did not rule out life, but did not support it.
- Later, the spacecraft Galileo was crashed into Jupiter.

What Did Galileo Experience?

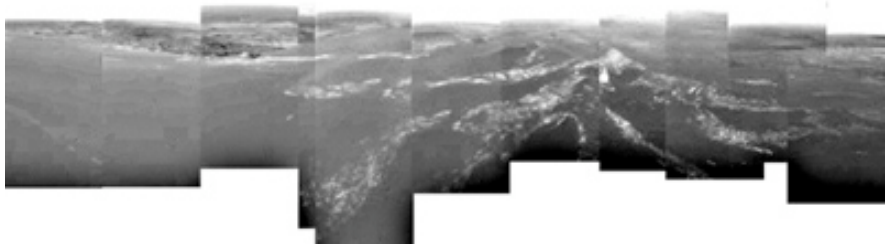
- An atmosphere unlike Earth's
  - 92% Hydrogen, 8% Helium, 0.1% other stuff
    - Very similar to the Sun's composition
    - Not too far from a binary star system
  - Rich chemistry
    - Ammonia, methane, other hydrocarbons, water, phosphine, etc..
- 400 mph winds
- Incredible pressures
- Increasing temperatures with depth

How to search for life?

- How do we search for life in our Solar System and beyond?
- What test will indicate life exclusively?
- Remember the Viking problems on Mars.
  - Need flexibility to test interpretations.
- But, it is difficult to anticipate fully the planet conditions.

How to search for life?

- Is is apparent that future missions need to land as near as possible to sites of subsurface water or other solvents.
- On Titan, what are the important tests for determining biological signatures of non-water life?
- What if the life is still in the protolife stage? Can we detect that?
- The boundary between chemical and biological processes is difficult to distinguish.



Decision Trees– Search for Life

- Wait for it to come to us via meteorites or comets.
- Robotic one-way investigations– Mars rovers.
- Fetch and return with samples.

http://www.ibiblio.org/wm/paint/auth/friedrich/tree.jpg

Problems

- In the last 2 cases, we have the problem of contamination by Earth life.
- Organisms can live in Mars-like conditions on Earth.
- If some Earth life survives the space journey, it could colonize Mars, possibly destroy any Martian life. Think of Kudzu.
- Current missions must be sterilized.

http://www.hope.edu/academic/biology/faculty/evans/images/Angiosperms/CoreEudicots/EurosidsI/Fabaceae/Kudzu.JPG

Biomarkers: How to look for extrasolar life.

- We need to decide how to search for biomarkers or chemical signatures of life.
- On Earth, methane and oxygen are indicators. They normally react. Something is keeping it out of equilibrium. Sort of like Venus disequilibrium.
- The Galileo spacecraft on its way out to Jupiter, turned and looked at the Earth.
- Did it detect life?

Biomarkers: Looking at Earth.

- Strong "red edge" from reflected light. Absorption from photosynthesis.
- Strong O_2. Keeping oxygen rich atmosphere requires some process. It should slowly combine with rocks.
- Strong methane. Should oxidize. Replenished by life.
- Strange radio emissions that could be intelligent life.

http://epod.usra.edu/archive/epodviewer.php3?oid=56256

Biomarkers: Looking at Earth.

- Recently, researchers have looked at the Earthshine from the moon.
- They agree with Galileo result. There is life on Earth.
  - Water
  - Oxygen
  - Tentative detection of "red edge"

http://epod.usra.edu/archive/epodviewer.php3?oid=56256

Summing Up

- Existence of organic molecules in space implies that amino acid complexity is common.
- Fact: On Earth polymers arose and evolved to life.
- Life it seems evolves naturally through a number of intermediate steps if conditions are right and $\mathbf{f_l = 1}$
- But how often are the conditions right?
- Nonetheless, even with only a vague notion of how life on Earth evolved, it seems that there are possible pathways that take the mysterious polymerization to transition to life steps.
- Still a number of questions:

Summing for f_l

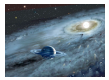
- Is life a natural occurring consequence of the laws of nature?
- Will each planet from n_e outgas and produce water?
- Will it have a reducing atmosphere?
- Will it have the right energy sources to produce life's monomers?
- Monomers from space?
- Will polymerization occur?
- Are tides necessary to wash polymers back into liquid water?
- Will basic life occur? Protolife or life?
- Alternative life?
- Maybe the conditions that produced life on Earth are unusual or maybe common.
- That means f_l can range from small numbers 0.0001 to 1.

Drake Equation

Frank Drake

That's 1.24 x ? life systems/decade








$$N = R_* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$

# of advanced civilizations we can contact in our Galaxy today	Star formation rate	Fraction of stars with planets	# of Earthlike planets per system	Fraction on which life arises	Fraction that evolve intelligence	Fraction that commun-icate	Lifetime of advanced civilizations
	10 stars/ yr	0.75 systems/ star	1.5 x 0.11 = 0.165 planets/ system	? life/ planet	intel./ life	comm./ intel.	yrs/ comm.

Evolution of Intelligence

- What is intelligence?
- "The ability to model the world, including the organism's own self" is a workable definition.
  - A spectrum of ability
- Crucial development for the full spectrum of intelligence is the diversity of life on Earth.
- Intelligence is not a requirement of life.

http://www.amonline.net.au/insects/images/site/insect1.jpg

Evolution of Intelligence

- First, we will examine the diversity of life; the fossil record shows a huge diversity with time.
- Organisms range from bacteria to humans.
- 1.8 x 10^6 known species
  - Insects account for most (1.0 x 10^6)
  - Estimated that only 10% are known.
  - Bacteria are hard to classify– only 7700 species so far.

http://www.amonline.net.au/insects/images/site/insect1.jpg

Evolution of Intelligence

- Remember that all of these organisms use nearly identical genetic codes, so life descended from a common ancestor.
- Primary challenge of biology is to explain how life from a single type of organism, diversified so much.
- Evolution is the primary concept.

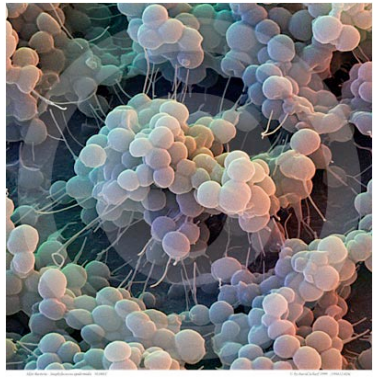
Life

If we took all the biomass of all the animals, and all the biomass of all the viruses, bacteria, protozoa, and fungi– who weighs more?

Around 90% of all biomass on the Earth is in the smallest and simplest lifeforms.

Bacteria

- 40 million bacterial cells in a gram of soil
- 1 million bacterial cells in a milliliter of fresh water
- Something like five nonillion (5×10^{30}) bacteria in the world.



Staph bacteria
http://www.scharfphoto.com/fine_art_prints/archives/000608.php

You or not you?

- This is more non-you cells in your body than you-cells in your body!
  - You are outnumbered 10 to 1!
  - Mostly on your skin and in your digestive track

Bacteria under a toe-nail

http://news.nationalgeographic.com/news/2007/02/070206-skin-microbes.html

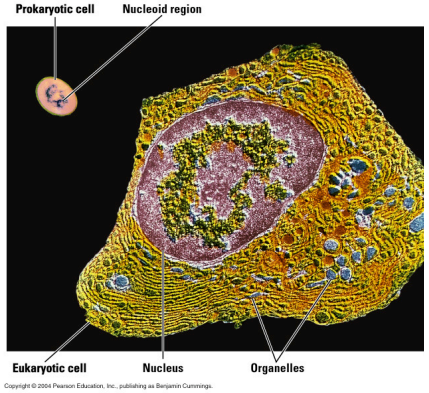
Question

What is a fair definition of intelligence?

a) Able to get an A on the midterm.
b) Able to develop a new iphone application
c) Leslie
d) The ability to model the world, including the organism's own self
e) The ability to model the world into food or threat

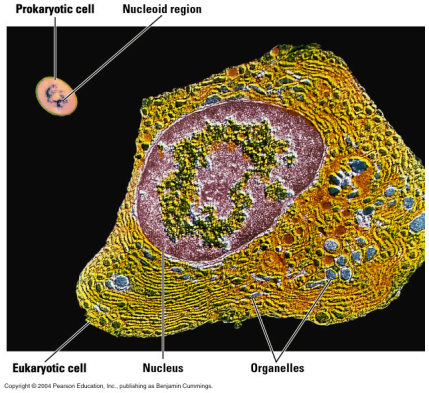
Classification of Life

1. Prokaryotes
   - No cell nucleus– DNA floating around
   - Always single-cell creatures like bacterium
   - Came first
   - Outnumber and outweigh the second class (eukaryotes)



Classification of Life

2. Eukaryotes
   - Have a cell nucleus, a membrane to protect the DNA
   - Basis of all multi-cell creatures
   - Also some single-cell creatures like amoebas.
   - DNA arranged into chromosomes in nucleus– 23 pairs for humans.

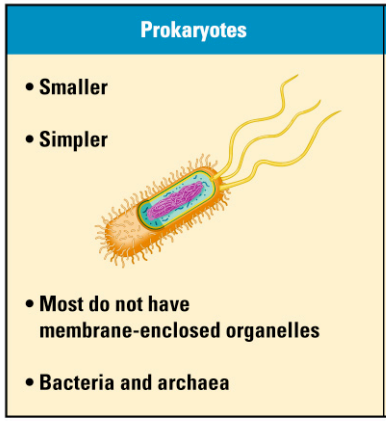


Prokaryotes

Divided into 2 domains:

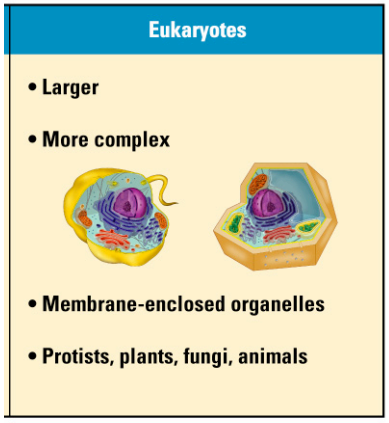
1. Eubacteria or "true" bacteria
2. Archaea
   - 20% of the world's biomass.
   - Thought to be the oldest surviving organisms.
   - Often found in harsh environments: hot springs, undersea vents, salty seashores, etc, which were probably more common on the early Earth.
   - Some evidence that ancient organisms were heat-lovers (maybe)

Carl Woese here at UIUC, discovered Archaea scheme.



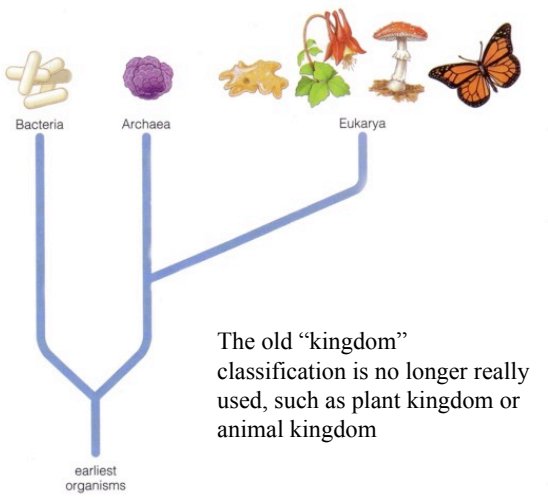
Eukaryotes

- All animals, plants, and fungi.



3 Domains of Life

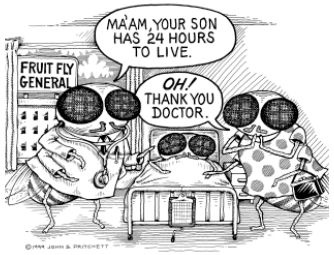
- Genetically speaking, Archaea and Eukarya are more similar to one another than are Bacteria and Archaea
- Implies that Archaea and Bacteria split and then all Eukarya split from Archaea
- A major implication for the evolution of life on Earth



The old "kingdom" classification is no longer really used, such as plant kingdom or animal kingdom

Genetic Relations

- This is a major change from the old methods of assigning groups based on outward form and anatomy.
- Instead based on studies of the genetic code.
- Surprise: Human and chimpanzees share about 99% of the same DNA, and about 97% with mice.
- Surprise: 2 species of fruit fly look very much alike, but only share about 25%. Some of this differences is due to "*junk*" DNA.



http://www.uglybug.org/index00.shtml

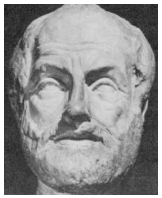
http://www.pritchettcartoons.com/fruitfly.htm

Question

What type of life is more closely related to us?

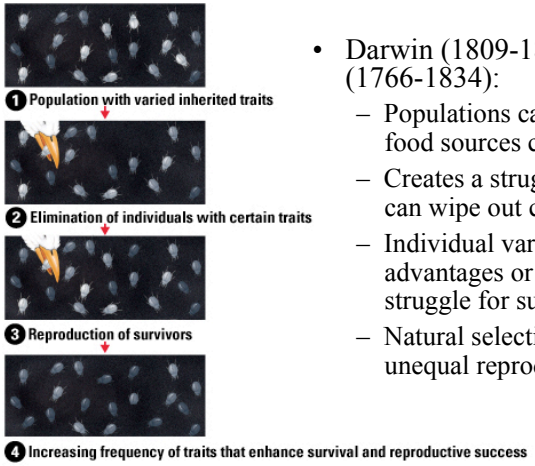
a) Archaea
b) Eubacteria
c) True Bacteria

Changes in Bio-Systems



- Today's view: evolution is the most important and unifying property of life.
- Anaximander (c. 610-547 BC): life arose in water and gradually became more complex
- Empedocles (c. 492-432 BC): survival of the fittest (but, "*a good idea stated within an insufficient theoretical frame loses its explanatory power and is forgotten"* by Hans Reichenbach)
- Aristotle (384-322 BC): species are fixed and independent of each other → evolution discarded for 2000 years
- Fossil record: slowly broke down the Aristotelian theory

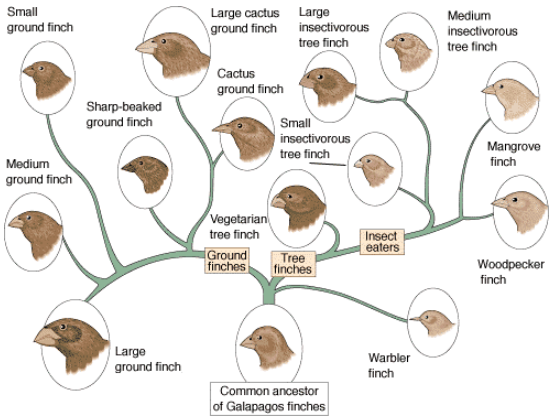
For the Species Survival



- Darwin (1809-1882) & Malthus (1766-1834):
  - Populations can grow faster than food sources can support them.
  - Creates a struggle for survival that can wipe out competitors.
  - Individual variations has advantages or disadvantages in the struggle for survival
  - Natural selection can create unequal reproductive success

Filling the Niche with Finch

- Other Evidence:
  - Adapted species in the Galápagos Islands, in particular finches
  - Artificial breeding of house/farm animals and vegetables
- DNA is really the mechanism of natural selection, but evolution requires both heredity and environment



Mutant Sex

- Mutations from changes in the bases of DNA.
- Usually copying errors, but also radiation– radioactivity, cosmic rays, chemical agents, or UV light.
- About 3 mutations per person per generation.
- Most mutations are neutral, changes in the *junk* DNA.
- Why is sex important to this class?

http://www.mutantx.net/features/press_vw_sexy.html

Mutant Sex

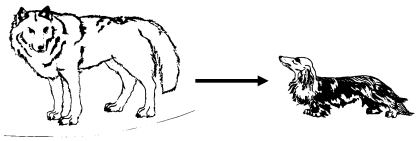
- Sexual reproduction leads to greater genetic diversity– a difference between prokaryotes and eukaryotes?
- Asexual reproduction does not allow 2 new and beneficial mutations to combine.
- Blackberries have not changed much in 10 millions years, but sexual plants have produced: raspberries, thimbleberries, cloudberries, dewberries, etc.
- Sex is useful in the process, but the mutations are still key.

http://www.alcasoft.com/arkansas/blackberry.html

Does it take a long time?

Cabbage, kale, kohlrabi, brussels sprouts, cauliflower and broccoli have same common ancestor– wild mustard. All bred by humans on a very short time scale.

This is selective breeding, but still the potential is in the DNA.



Or domestic lap dogs from wolves in about 5000 years.

Question

Sex in space, or on Earth, is important because

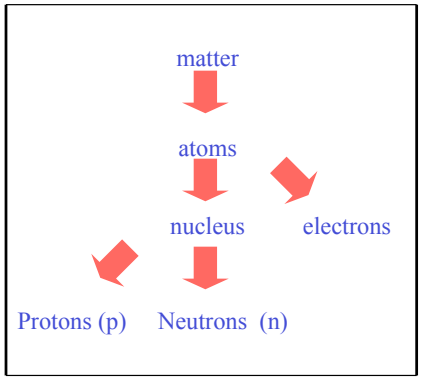
a) sex, although fun, also stimulates gene mutations.
b) it allows the genetic material of the better organisms to survive.
c) mutations can only occur in sexual reproduction.
d) it leads to greater genetic diversity and an increase of positive mutations in the offspring.

Comparing Ages

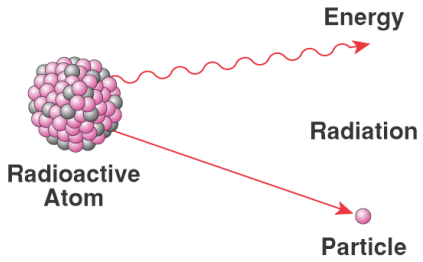
- Important to understand history of Earth life is the ability to age different components
- Can be difficult
- Radioactive dating….
  - ^{14}C for the last 60,000 years
  - ^{40}K and ^{235}U for 100's of millions of years

Radioactive Dating

Recall:



- Most atomic nuclei stable
- But some nuclei are *unstable*,
  ⇒ *decay* to new nucleus
  "radioactive"



The Law of Radioactive Decay

As radioactive “parent" decays, the number of decay product or “daughters" increases

Decay is a good “clock"

- Each radioactive species has different “tick"
- Rate= ”half-life"
- Exponential decay from original population of n_0

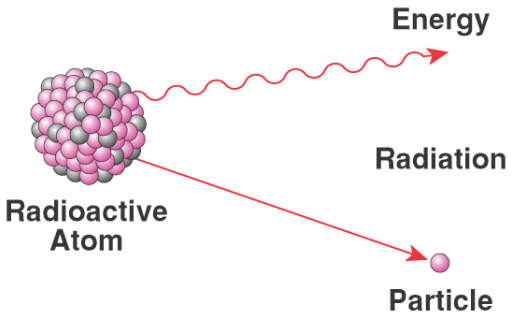
Decay Rule

Start out with N parents, 0 daughters

Time t since start	# parents	# daughters
0	N	0
$t_{1/2}$	½ N = half as much	½ N have appeared
$2t_{1/2}$	¼ N = half again as much	¾ N
$3t_{1/2}$	1/8 N	7/8 N
$30t_{1/2}$	About $N/10^9$	99.9999999% N

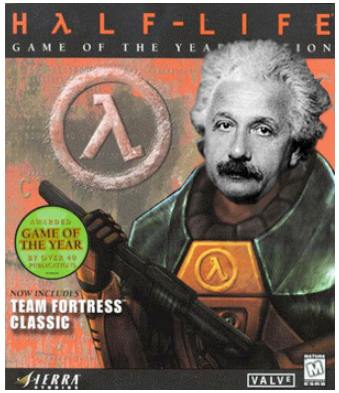
Radioactive Decay Examples

http://www.colorado.edu/physics/2000/isotopes/radioactive_decay3.html



Carbon-14

- Cosmic rays from space are constantly hitting the Earth.
- React with ^{14}N in atmosphere to create ^{14}C.
- Decays back to ^{14}N with half life of 5730 years.
- But, there is an equilibrium in abundance
- In atmosphere, the ^{14}C is mostly in $^{14}CO^2$.



http://bbspot.com/Images/News_Features/2003/12/half-life.jpg

Carbon-14

- Plants take in $^{14}CO^2$ with the $^{12}CO^2$ and other animals eat the plants.
- So, every living creature has a equilibrium ratio of $^{14}CO^2/^{12}CO^2$.
- When the organism dies, the ^{14}C decays to ^{14}N. By measuring how much ^{14}C remains, you can date the fossil.
- This works well to about 60,000 years.
  - Viking remains in Newfoundland– 500 yrs before Columbus.
  - Shroud of Turin to 1330 AD

http://web.mit.edu/smcguire/www/newfoundland/newf16.html

Dating Rocks

- First you ask them out?
- No, you need a radioactive decay that has a longer half-life than ^{14}C.
- Potassium-argon
  - ^{40}K decays to ^{40}Ar with a 1200 Myr half-life.
- Uranium-lead
  - ^{235}U to ^{207}Pb with 700 Myr half-life.
- But these only work with volcanic layers.
- So, the ages of fossils are interpolated from ages of volcanic layers above and below them.

Era	*Period*	*Myr Ago*	*Life Forms*	*Events*
Cenozoic	Quaternary	2	H. Sapiens	Ice ages
	Tertiary	65	Primates	Extinction of Dinosaurs
Mesozoic	Cretaceous	136	Birds	S. Atlantic open to 1900 miles
	Jurassic	190		N. 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	
	Cambrian	543	Trilobites	
Precambrian		545	Small Shelly Fossils	
		580	Ediacarans	
		600-800	Multicellular life	Snowball Earth episodes

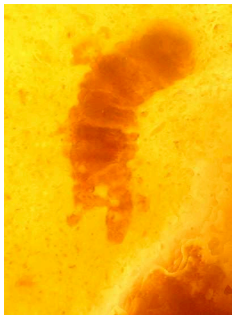
Increase of Complexity

- Last table showed only the last 800 Myrs.
- The more complex and intelligent organisms appeared towards the end.
- For many years it was thought that life originated in the Cambrian era, then Precambrian fossils were found.
- Then, it was realized that there were single-celled fossils that required microscopes.

Myr Ago	*Era*	*Event*
Now	Cenozoic	
	Mesozoic	
	Paleozoic	Macroscopic life/Snowball Earth
	Precambrian	
1000		Worm tracks
		Multicellular algae
		Eukaryotes certain
		Sexual reproduction
2000		Eukaryotes possible
	Protozoic	Oxygen-rich atmosphere
		Snowball Earth
		Formation of continents
3000	Archean	Life begins?
4000		Formation of Oceans
		Bombardment decreases
		Frequent impacts
	Hadean	Earth formed

Concepts

- As prokaryotes are simpler than eukaryotes, we expect them to exist first.
- Identifying fossil prokaryotes is difficult: they're tiny!
- But there is enough evidence that before 1500-2000 Myrs ago there are only prokaryotes fossils.
- Note: the oldest fossils (3800 Myrs ago) are under some dispute, but the 2800 Myr old fossils are universally accepted.
- All of the macroscopic life only arose in the last 600 Myrs– 1/6th of the history of life on Earth.



http://www.earth.ox.ac.uk/research/geobiology/geobiology.htm