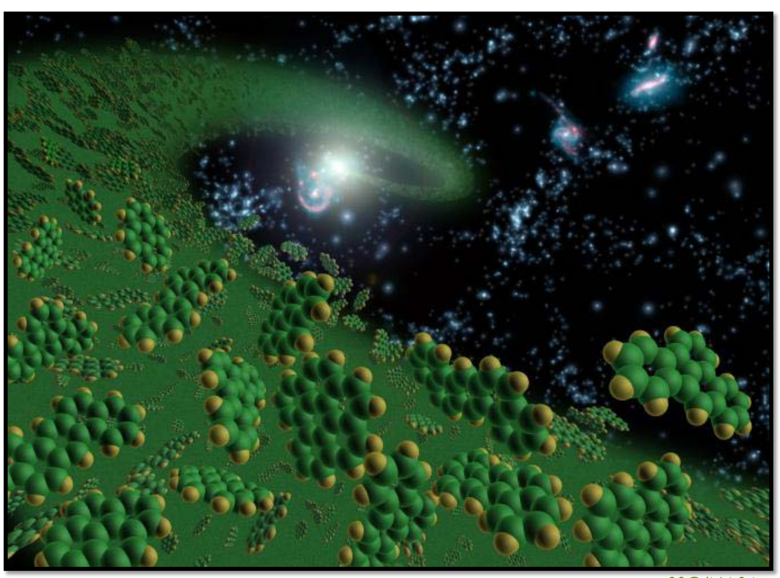
5 September
2019

LIFE AND ITS COMPONENTS

Homework #1 on WeBWorK – due Monday by 7pm



SSC/NASA

Life and its components

Age of the Solar System

The Drake equation: an accounting measure that suggests a path of inquiry into the emergence of life

Life as we know it

Definition of Life: how might we know life when we see it or seek it

A simple case: two minerals

A little bit of algebra is useful at this point. You will not have to do any algebra on the problem sets or exams, but in the interest of offering a simple proof of an important formula, I will risk showing you some here. If you prefer a faith-based approach, you may doze off until the final result.

Suppose a rock solidifies at $t = 0$. A mineral in this rock has radionuclide and daughter number ratios N_0 and D_0, respectively, at that instant.

- Different minerals will have different values of N_0, but all will have the same value of D_0.

At later times, each mineral will obey

$$D = D_0 + (N_0 - N) = D_0 + N\left(2^{t/t_{1/2}} - 1\right)$$

Two minerals example

We live at time t and can measure N and D. Suppose the rock contains two minerals, A and B. Then the measurements for these minerals will be related by

$$D_A = D_0 + N_A\left(2^{t/t_{1/2}} - 1\right) \qquad D_B = D_0 + N_B\left(2^{t/t_{1/2}} - 1\right)$$

We do not know t or D_0, but we know that it is the **same** D_0 for both minerals. This is two equations with two unknowns. We are mostly interested in t, the time since the rock froze. Find it by subtracting the two equations (eliminating D_0) and solving for t.

$$t = \frac{t_{1/2}}{\ln 2} \ln\left(\frac{D_A - D_B}{N_A - N_B} + 1\right)$$

You need to know how to use this formula.

Two minerals example

The half-life of ^{87}Rb is measured in the lab to be

$$t_{1/2} = 4.99{\times}10^{10}\ \text{years}$$

Example: Samples of two minerals from the same igneous rock from northern Ontario are analyzed in a mass spectrometer, with these results for the number ratios *N* and *D*:

Mineral	^{87}Rb/^{86}Sr (N)	^{87}Sr/^{86}Sr (D)
Plagioclase (B)	0.0755	0.7037
Pyroxene (A)	0.3280	0.7133

How old is the rock?

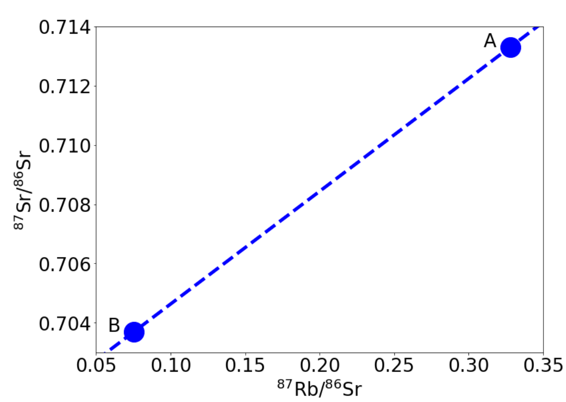
Two minerals example

Solution:

$$t = \frac{t_{1/2}}{\ln 2}\ln\left(\frac{D_A - D_B}{N_A - N_B} + 1\right)$$
$$= \frac{4.99{\times}10^{10}\ \text{years}}{0.693} \times \ln\left(\frac{0.7133 - 0.7037}{0.328 - 0.0755} + 1\right)$$
$$= 2.7{\times}10^{9}\ \text{yr}$$

The *y*-intercept gives the value of *D* that the rock had at the time it froze:

$$D_0 \equiv \frac{n(^{87}\text{Sr})}{n(^{86}\text{Sr})} = 0.7008$$



What do we get when we make these measurements on rocks?

The oldest rocks turn out to be meteorites. All meteorites are **nearly the same age**.

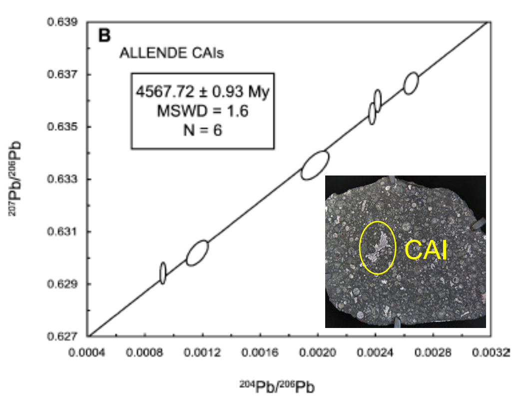
The very oldest are the "CAI" parts of certain primitive meteorites called **carbonaceous chondrites**: these all solidified precisely $4.5677 \pm 0.0009 \times 10^9$ years ago.

Nearly all meteorites come to us from the asteroid belt or the comets, so they are members of the Solar System. Thus, the Solar System has to be at least **4.5677×10^9 years old**.

There are good reasons to think that small bodies were all molten when the Solar System formed, so this is essentially the same as the Solar System's age.

Age of the Solar System

Age of the oldest bits of Allende (1969) meteorite, derived from U-Pb radioisotope dating (Connelly et al. 2008). U-Pb is the isotope system currently favored for use on the oldest meteorites, as Rb-Sr is for the oldest terrestrial and lunar rocks.



Inset credit: Wikimedia Commons

Ages of the surfaces of Earth and Moon

The radioisotope ages of lavas are comfortingly close to the real ages of recent (e.g. Mauna Loa) and historically-attested (e.g. Vesuvius, Etna) eruptions.

Igneous rocks in Earth's crust show ages all the way from very recent to about $\mathbf{3.8{\times}10^9}$ **years**; none are older.

- …though some minerals are older. Some small zircons, found embedded in younger rock, are as old as the meteorites. Zircon has a particularly high melting point.

Moon rocks, on the other hand, are all older than $3.2{\times}10^9$ years and range up to nearly the age of the meteorites.

Age of the surfaces of Earth and Moon

The lunar highlands (light parts) are clearly older than the maria (dark parts), as the cratering record also shows.

So the Moon started solidifying about 700 million years before the Earth did.

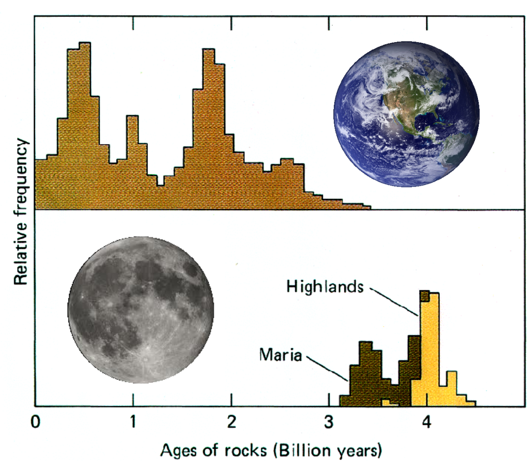


Figure from Jay Frogel

Age summary

So we have these experimental **facts**:

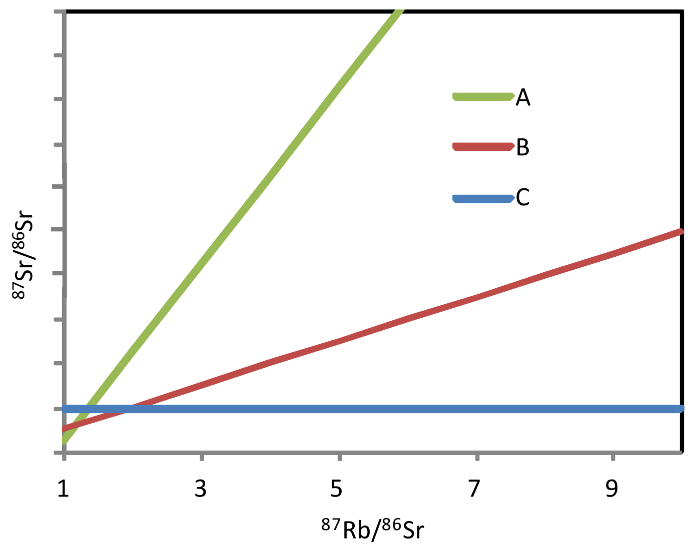
- The Universe is 13.7 billion years old, give or take about 0.1 billion.
- The Milky Way galaxy is about 13.5 billion years old; certainly it cannot be younger than the oldest white dwarfs it contains, which are 10 billion years old.
- The Solar System – Sun, planets, asteroids, etc. – is 4.5677 billion years old, give or take about a million years.
- The Earth's surface solidified about 3.8 billion years ago.

These time spans are **much** longer than the age the world was thought to have in Darwin's time. This has expanded dramatically the scope of the slow processes of **evolution**.

Review question!

Radioisotope dating can be used to determine

A. How long ago the elemental ingredients – silicon, oxygen, magnesium, iron… - of the rocks were made.
B. How long ago an igneous rock was last melted.
C. How long ago the ingredients of a sedimentary rock were deposited on the ocean floor.
D. How long ago the last radioactive atom in the rock decayed.



Review question #2

One of these sets of experimental measurements of Rb and Sr ratios is of lava from a recent eruption of Mauna Loa. Which one?

The emergence of life and intelligence: Drake's equation

So how did life and its components come into existence during the billions of years of the past?

During the rest of the semester, we will be guided by the equation formulated in the 1960s by Frank Drake as an accounting measure for the universal factors important in the emergence of life and civilization in the Universe.

- Drake phrased the expression in terms of the number of civilizations with which we could eventually communicate, but each **factor** in the equation is related to the development of an important component of life as we have tentatively defined it.
- Also of importance but not a term in the equation: *r*, the average distance to the nearest civilizations.

No astronomy or biology in it, just bookkeeping, but it is a useful way to think about Life.

The Drake equation

$$N = R_* f_p n_e f_\ell f_i f_c L$$

N = number of communicable civilizations in our Galaxy

R_* = rate at which stars form

f_p = fraction of stars that have planetary systems

n_e = number of planets that are suitable for life per planetary system

f_l = fraction of planets suitable for life on which life actually arises

f_i = fraction of life-bearing planets on which intelligence develops

f_c = fraction of intelligence-bearing planets which develop a technological phase during which there is a capacity for, and interest in, interstellar communication

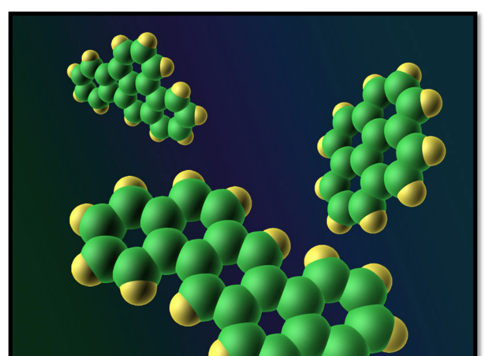
L = average lifetime of communicable civilizations

The result after 13.7 Gyr: LAWKI

As far as we know, things that are alive are composed of **organic molecules**, based upon long chains and rings of carbon atoms, and **water**.

- This endows living things with a distinctive mix of ion-molecule and neutral-neutral chemical processes, as we will discuss in the middle third of the course.
- It might also seem like an eccentric choice, considering how Earth's surface differs from the rest of the Solar System.

Abbreviation: Gyr = 10^9 years = 1 billion years



PAHs: Green = carbon, Gold = hydrogen (SSC/NASA)

Chemical composition of LAWKI

Much like LAWKI (Life As We Know It) is similarly composed.

By atom, per hundred oxygen atoms,

Element	Bacteria	Human
Hydrogen	217.2	234.6
Carbon	22.1	40.4
Nitrogen	4.8	9.2
Oxygen	100.0	100.0
Phosphorus	0.4	0.5
Sulfur	0.2	0.5
Calcium	< 0.2	0.9

i.e. CHONSP, as you might have seen in high school biology

Element	Interior	Crust	Ocean	Air	Human
Hydrogen		4.8	200.1	0.002	232.0
Carbon	< 0.1	0.1	0.004	0.1	37.9
Nitrogen		0.0		372.1	5.8
Oxygen	100.0	100.0	100.0	100.0	100.0
Sodium		4.2	0.9		0.2
Magnesium	30.4	3.0	0.1		0.1
Aluminum	2.8	10.3			
Silicon	28.6	33.9			
Phosphorus		0.1			0.8
Sulfur	4.8	0.1	0.1		0.2
Chlorine		0.0	1.0		0.1
Argon				2.2	
Potassium		2.3			0.3
Calcium	2.0	3.1			0.9
Iron	30.6	3.1			
Nickel	1.6				

Different from Earth's composition …

(by atom, per 100 oxygen atoms)

Element	Earth	Sun	Comets	Human
Hydrogen		147058.8	200	232.0
Carbon	< 0.1	44.1	44.1	37.9
Nitrogen		13.4	13.4	5.8
Oxygen	100.0	100.0	100.0	100.0
Sodium		0.3	0.3	0.2
Magnesium	30.4	4.3	4.3	0.1
Aluminum	2.8	0.3	0.3	
Silicon	28.6	3.7	3.7	
Phosphorus		0.03		0.8
Sulfur	4.8	1.4	1.4	0.2
Potassium		0.02		0.3
Calcium	2.0	0.3	0.3	0.9
Iron	30.6	1.2	1.2	
Nickel	1.6	0.2	0.2	

Closer to the Solar System

(by atom, per 100 oxygen atoms)

Carbon and silicon atom can both make four covalent bonds. There is a lot more silicon on Earth's surface than carbon. Why are we not instead made of silicon?

A. Life began in comets, not on Earth's surface.
B. Life must have evolved on a planet with more carbon and then been transplanted.
C. Silicon life came first and was gradually replaced by carbon life.
D. Long molecules made of silicon chains are unstable; basically, it was carbon-chain molecules or nothing.

Take a guess!

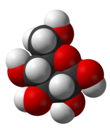
We will find out in a few weeks!

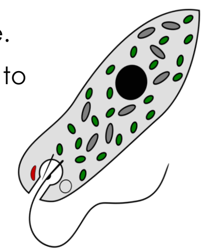
☺

Other prominent attributes of LAWKI

In addition, living things tend to…

- …engage in **metabolism**, thus requiring supplies of chemicals and chemical energy.
- …**reproduce**.
- …**mutate**: they adapt and evolve.
- …exhibit **sensitivity**: they respond to changes in their environment.





Wikimedia Commons; Caltech Archives

What is life?

We will take these five attributes as a **provisional definition of life**, and use them to guide our search. But we must remember that…

- …it is really life as we know it.
- …as we explore the Universe, we find many unexpected environments in which things could have progressed quite differently, considering the billions of years they had to do so.
- …even as we explore Earth, we find **extremophiles**: life forms adapted to chemicals and environments way past where we thought the limits were.

Grand Prismatic Spring, Yellowstone National Park, where a lot of interesting extremophiles live.

Identify the correct statement

A. After visiting Pluto, the New Horizons probe is on its way back to Earth with the samples it collected.

B. There have been five mass extinctions in Earth's history, and a sixth might be underway.

C. On average, 55% of our DNA was inherited from the Neanderthals.

D. The "RNA World" picture of the origin of Earth's life has been decisively disproven.

Exceptions to the LAWKI-based definition

Mules and hinnies are undoubtedly alive but do not reproduce (very often, anyway).

Fire is undoubtedly not alive, but all it would seem to lack is organic composition.

Viruses are considered by most to be a life form, but they do not metabolize or exhibit sensitivity.

Robots are not considered alive, but: we can endow them with sensors; program them to build other robots (reproduce) or change themselves or others (mutate, adapt). They require energy and materials to keep going (metabolism).

Data from Star Trek

A definition exercise – water

Let us see what happens when we try to make a sharper, more general definition to guide us. An exercise in this activity:

Suppose that this is the 17th century. Although we have great experience with the physical and chemical world, we cannot identify individual atoms or molecules and do not know for sure that matter is made of such things.

What is water?

Water, as we know it

To take it as is from the terrestrial environment:

Colorless, odorless clear liquid
- Except seawater, pond water, lake water…

Vaporizes at T = 373 K under 1 atmosphere pressure
- Except if not particularly clear and colorless

Freezes at T = 273 K under 1 atmosphere pressure
- Except if not particularly clear or colorless

Nonpoisonous; quenches thirst; very mildly flavored
- Except with certain special trace additives

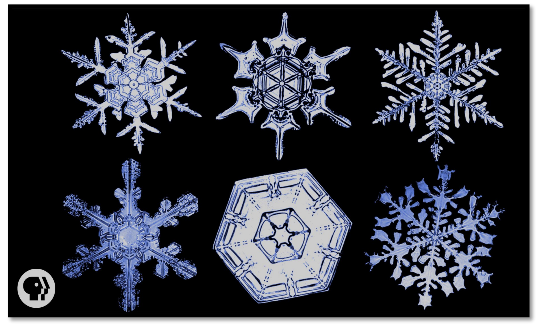
Many exceptions! Is there an **essence** of water that we may seek in a more sophisticated fashion?

The one true water

We can make **distilled** water by boiling ordinary water and re-condensing the vapor under clean conditions. Then, we get:

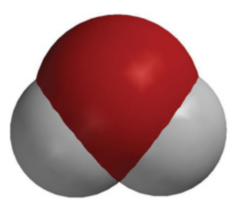
- Colorless, odorless clear liquid
- Vaporizes at T = 373 K under 1 atmosphere pressure
- Freezes at T = 273 K under 1 atmosphere pressure
- Nonpoisonous; quenches thirst; flavorless
- When cooled below 273 K under suitable conditions, crystallizes in a distinctive hexagonal pattern as seen, for example, in snowflakes

In all, a restrictive definition but perhaps still not uniquely definitive.

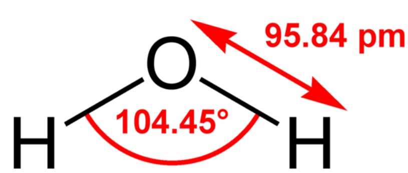


The true essence of water

With 19th century hindsight, of course, we know that water is a molecule which contains two hydrogen atoms and one oxygen atom, covalently bonded as shown.



Does life admit to such a uniquely restrictive definition? How might we find out if it does?



Are there better ways to define life?

Many have tried to come up with more general definitions that have fewer exceptions. Notable is Claire Folsome (1979, quoting Onsager and Morowitz), who focused on life as an ecological process:

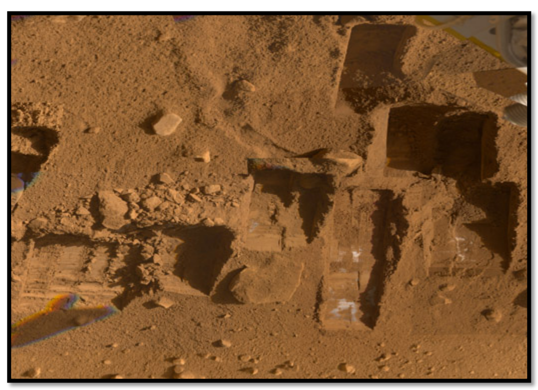
> Life is that property of matter that results in the coupled cycling of bioelements in aqueous [watery] solution, ultimately driven by radiant energy to attain maximum complexity.

Biosphere 2

Are there better ways to define life?

And Feinberg and Shapiro (1980):

> Life is fundamentally an *activity* of the biosphere. A biosphere is a highly ordered system of matter and energy characterized by complex cycles that maintain or gradually increase the order of the system through an exchange of energy with its environment.



Digging for ice on Mars (Phoenix / U. Ariz.)

Are there better ways to define life?

Perhaps the ultimate nerdy definition, from famous physicist Erwin Schrödinger (1944):

> Life is a class of phenomena in open thermodynamic systems, able to decrease their internal entropy at the expense of increasing the entropy of its surroundings, and avoids the decay into equilibrium.

(Entropy is a measure of disorder in a physical system; according to the second law of thermodynamics, entropy can never decrease in a closed system.)

Schroedinger (Nobel Foundation)

Is there an essence to life?

Is there a unique, definitive descriptor for life, analogous to the atomic composition of water?

We don't know for sure. But:

The idea that the basic attributes of life, like the five for LAWKI, could be **encoded** in the contents may suggest a way to look for an essence.

So, as suggested by many scientists over the last 150 years, we may look for analogues and generalizations of the **genetic code** common to LAWKI, as an essence of life.

- Schrödinger, again, suggested such a generalization in the form of "aperiodic crystals" a decade before Watson and Crick found the structure for DNA.