

Schrodiner's Apology

He was the first physisit to step into the "What is life?" question. He wrote an apology for not knowing any biology during his book on it.

Introduction

We accept evolution as the best explanation for the source of all life. Supposidly there was a last universal common ancestor (LUCA). Life is broken up into eukaryotes (multi cell life), archaea, and backteria (single cell life). This doesnt explain where that LUCA came from (the origin of all life).

When did life begin

A stramatolite is a blob, rock looking thing in the ocean. Its layers of sediment mixed with layers of microbes. Autotrophs are bacteria near the top of the layer that take in sunlight and make organic compounds (like sugars). The next layer down has hertotrophs that use those sugars to create water and co₂ that the autotrophs use. These two types alternate layers since they cycle the same stuff. Inside the layers in the stromatolites there are microcosms that represent life on earth.

When you cut open really old rocks they have similar layers to stromatolites which might make you think they might be dead stromatolites but those layers could be completely inorganic. Carbon 12/13 ratio is usually around 89:1 but life is better at metabolizing carbon 12. So if the carbon 12/13 ratio is different we can conclude that organisms were there to eat up the c12. So we can determine which of these layered rocks had life in them. They date back to about 3.5 billion years which gives us a sort of date for the origin of life. But at that point we already had complex life (able to photosynthesize) which means that life is much older than that. Earth is only 4.6 billion years old so life is really fucking old.

Microfossils would be an awesome find. But its really hard to find these super old rocks that haven't been disturbed (re-introduced into the rock cycle) which would destroy the microfossils in them. Its also very hard to tell what is a microfossil and what is just a crystal or other geologic figure. Our current oldest microfossil is around 3.4 billion years old. We think its organic because it displays clustering behavior, it has messed up c12/c13 ratios within and without the cell, and sulfur isotope ratios are also messed up which implies it might have been metabolizing sulfur.

The oldest rocks with messed up c12/c13 ratios is on the island of akilia off the coast of Greenland at about 3.85 bya. We can also see other isotopes that get messed up by the presence of life that we can look at (see above sulfur comment).

The current evidence is that life evolved shortly after the late heavy bombardment (which happened at 4.1 bya). This could mean that life is very prevalent in the universe instead of just a lucky event.

Where did life begin?

DNA mutates; thats just what it does. There is a predictable and measurable rate of evolution based on those mutations in dna. By comparing genomes of organisms we can tell how close their common ancestor was, from doing this we build a tree of life.

We can track back dna to show that sharks branched out first and using the tree of life we can find that most early life was extremophiles.

Where did life begin?

Geological Evidence:

- Did life originate on **land**? Unlikely:
 - ✓ All life today requires **water** as a solvent for chemical reactions. Cell = “bag of water”
 - ✓ Early atmosphere had no O₂ ⇒ no ozone (O₃) layer to protect from Sun’s **intense UV**
- Did life originate in Darwin’s “**warm little pond**”?
 - ✓ Organic compounds can form spontaneously...
 - ✓ Tides (bigger back then!) and wetting/evaporation would have increased their concentration, spurring reactions that may have led to life
 - ✓ Perhaps volcanic hot springs offered the energy to support an origin of life?
 - ✓ **Problem:** not much protection from UV...

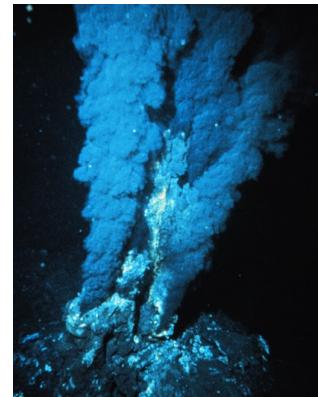


We're pretty sure life evolved in water because water is hella important to life. Darwin thought that life may have evolved in a very warm tide pool randomly. We kind of dismiss this theory because concentrated UV rays might have messed that up.

Where did life begin?

Geological Evidence:

- Back to deep-sea vents or underground:
 - ✓ Protection from Sun's UV
 - ✓ Plenty of chemical energy to fuel reactions that may have led to life (for underground hypothesis: reactions between water & minerals in rock)
- ✓ Even if life arose in "Darwin's ponds", lunar evidence of asteroid/comet impacts of the "late heavy bombardment" would have destroyed all life that didn't migrate to the deep-sea (or underground)



So exactly where life began is still a mystery...

For life to evolve we need some protection from UV rays which we can get deep in the ocean. Another point against the warm puddle theory is that the late heavy bombardment would have vaporized any life there unless it was living underground or deep in the sea.

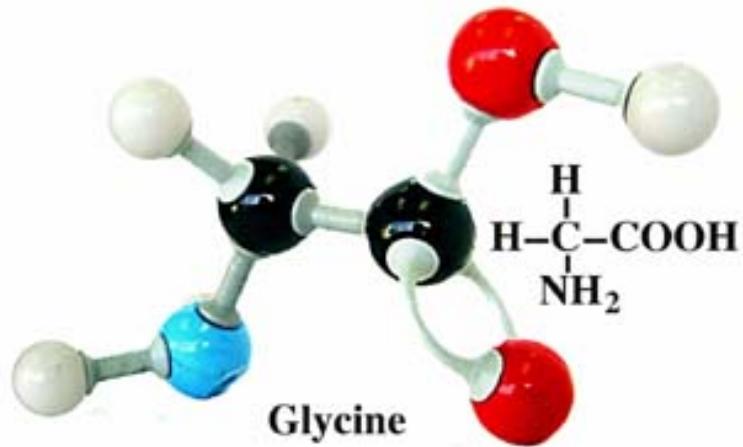
How did life begin?

Life is (at least) very complex chemistry:

Amino acids are the building blocks of life. More than 100 amino acids occur in bacteria and plants, but only about 20 are commonly found in animals.

12 can be synthesized by the human body. The remaining 8 must come from our diet (they are called *essential* amino acids).

Amino acids make up **proteins**, the second-largest component of human muscles, cells and other tissues (water is the largest)



N=blue, C=black, O=red, H=white

How Did Life Begin?

Amino acids are the building blocks of life. They have a carbon backbone which is why we call ourselves carbon based life forms. We really are only made of about 20 amino acids. We can synthesize 12 of them so we only really need the other 8 from our diet. We combine these amino acids into more complicated molecules, usually proteins. Long chains of molecules can be formed randomly.

How did life begin?

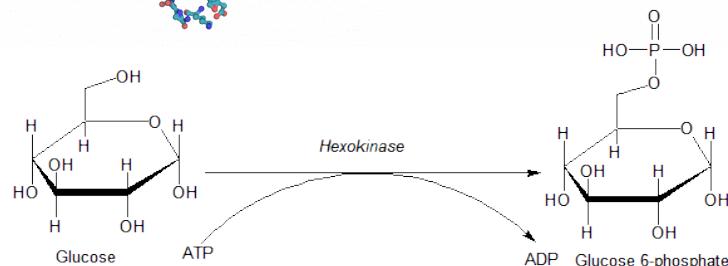
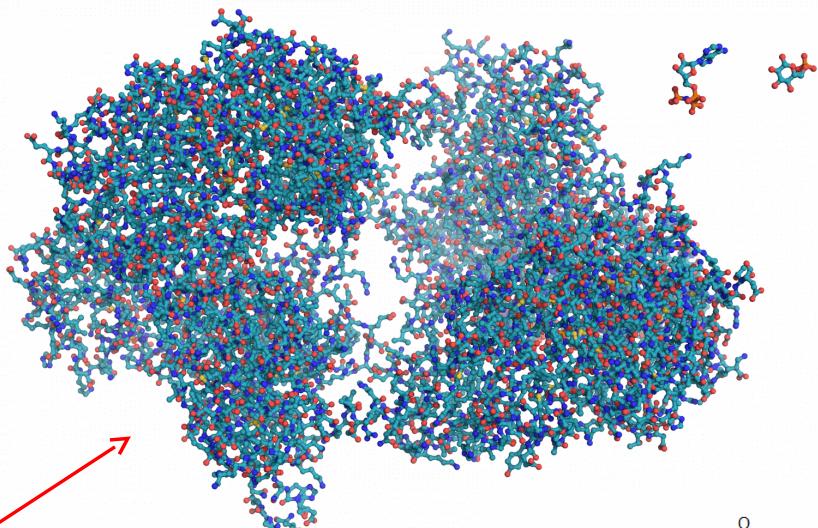
Life is very complex chemistry:

Proteins are long chains of amino acids, folded up in a complicated **3D structure**, both of which determine the protein's function.

Functions include:

- Catalyzing metabolic reactions (enzyme)
- DNA replication
- Responding to stimuli (e.g., tissue repair)
- Transporting molecules around

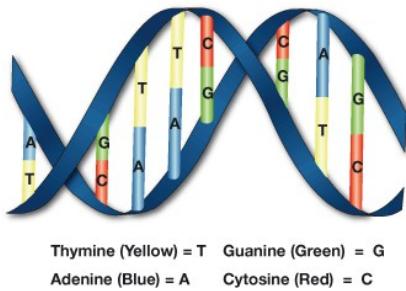
Typical example of an enzyme (hexokinase) ... involved in converting glucose to glucose 6-phosphate



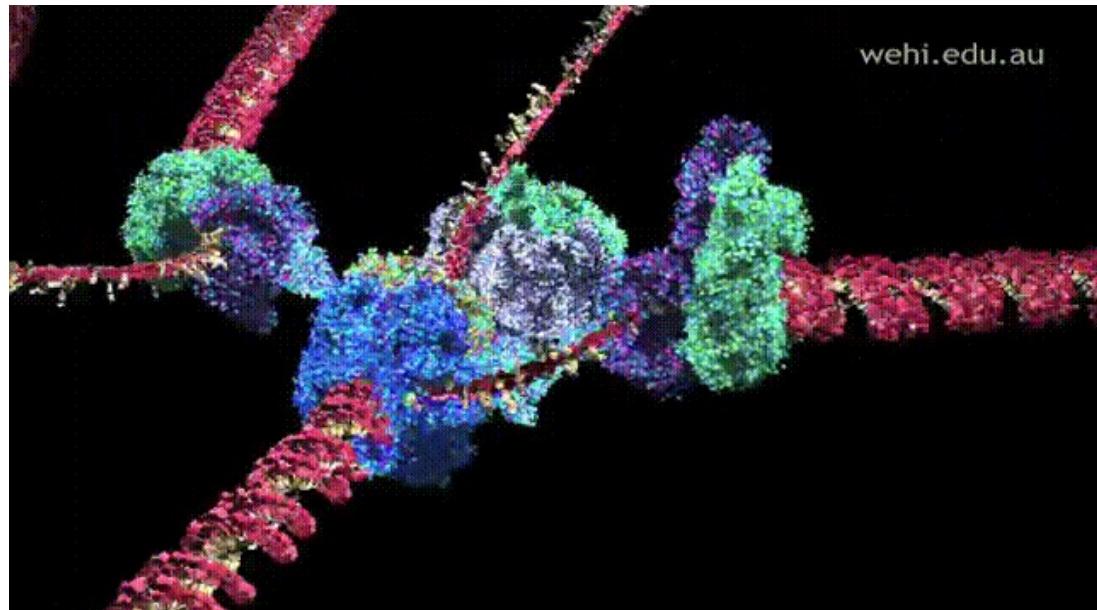
Proteins are formed from long chain of amino acids taht get folded up into 3D shapes. Proteins are primarily used for catalyzing complex metabolic reactions. Most molecules rest in a comfortable state so we have to push on them to form a gap where other molecules can snap into it. This can happen on its own but is very slow (too slow for life). Enzymes (a type of protine) speeds up this process. They provide pockets for the two molecules that we want to combine. To get into those pockets they have to bend and snap into place. They do this because the nearby water molecules that keep coliding with them. A water molecule bumps into a molecule and makes it bend into the protine. At this point ATP comes into play that can harnes this mechanical energy.

How did life begin?

Life is very complex chemistry:



DNA replication: More than a dozen enzymes are involved in unzipping the DNA, checking and correcting errors, and re-zipping the duplicated DNA



Proteins are also used in the replication of dna. One splits the dna in half (into 2 single helixes). Things are duplicated and then its zipped together to form a new strand of dna.

How did life begin?

Initial Puzzles:

- At the very least we need:
 - ✓ **Amino acids** (building blocks of proteins)—where do these come from?
 - ✓ **Lots of time** (for something interesting to happen)
- ...then we can start to think about how simple organic compounds gave rise, over time, to complex, replicating life. **Having the notes is not the same as having the music!**

Amino acids are all over the place. Even in space, on asteroids. They need a ton of time to combine into these weird things called life.

How did life begin?

Early Earth

- Age of the Earth & concept of “deep time”:
 - ✓ Theology □ a few thousand years to infinite, or cyclical; commonly 5,000–10,000 years
 - ✓ Starting in 1700s: **Rock erosion, sedimentation, salt in oceans** □ 10–100 million
 - ✓ 1856—Helmholtz: Assume Sun’s energy from **gravitational collapse** □ 22 million
Too small because it ignored the real energy source of the Sun: **fusion**
 - ✓ 1862—Lord Kelvin: **Cooling of initially molten Earth** □ 20–400 million
Too small because it ignored heating due to **radioactivity** of the rocks
 - ✓ By later 1800s, **geology & evolution** argued for much older (billions) □ bitter disputes...

[In first version of *On Origin of Species*, removed by Kelvin, head of Royal Society]

When we were first looking at ancient earth we looked at all the sedimentary layers. Physists eventually got involved and found that the earth can't be older than the sun. So they tried to calculate the age of the sun. They did this by looking at the size of the sun and assuming that it created energy through gravity. He didn't know that it worked through fusion so his age was way off. They we looked at how long it would have taken molten earth to cool to the state that its at. This ignored radioactive rocks in earth which give off heat that extended the age of earth.

Biologists were arguing that the age of the earth was much older than that. Darwin's original Theory of Evolution stated that the earth must be billions of years old but the physists made him remove that.

How did life begin?

Early Earth

- Age of the Earth & concept of “deep time”:
 - ✓ 1904—Ernest Rutherford:
 - Realized **radioactivity** could heat the Earth (age could be much greater than Kelvin's 1897 revised estimate of 20 million)
 - Took first step towards **radiometric dating** of the Earth
 - ✓ 1927—Arthur Holmes: “The Age of the Earth, an Introduction to Geological Ideas” gets 1.6-3.0 billion years...

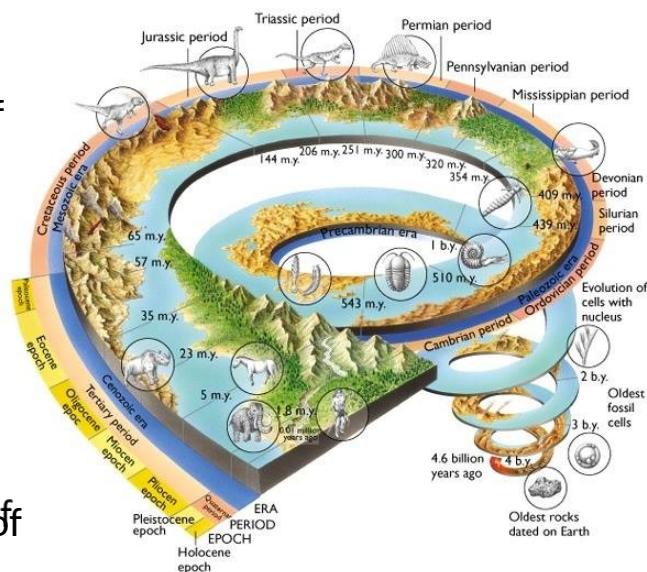
Eventually we learned more about earth and the geologists got to a number that more closely matched what the biologists knew.

How did life begin?

Early Earth

- Today we know Earth is **4.54 ± 0.05 BYO**:
- ✓ Radiometric dating (e.g., Potassium-40 to Argon-40) off **meteorites** left over from Solar System formation → **4.567 BYO**
- ✓ ...consistent with radiometric dating of **oldest Earth rocks** (zircon crystals in Australia) → **4.404 BYO**
- ✓ ...consistent with radiometric dating of the **oldest Apollo Moon rocks**
- ✓ ...consistent with comparing the mass and luminosity of Sun to those of **other stars**

Mind Warp: Deep Time!



As radioactive elements in a rock decay they do so at a steady rate. This allows us to look at ratios between two elements and that will tell us how long it has been since that rock solidified (else the gases would have escaped).

It is believed that a mars sized body collided with earth near its birth which caused it to break apart which formed the moon. If we look at the oldest rocks on the moon we see that they are roughly the same age.

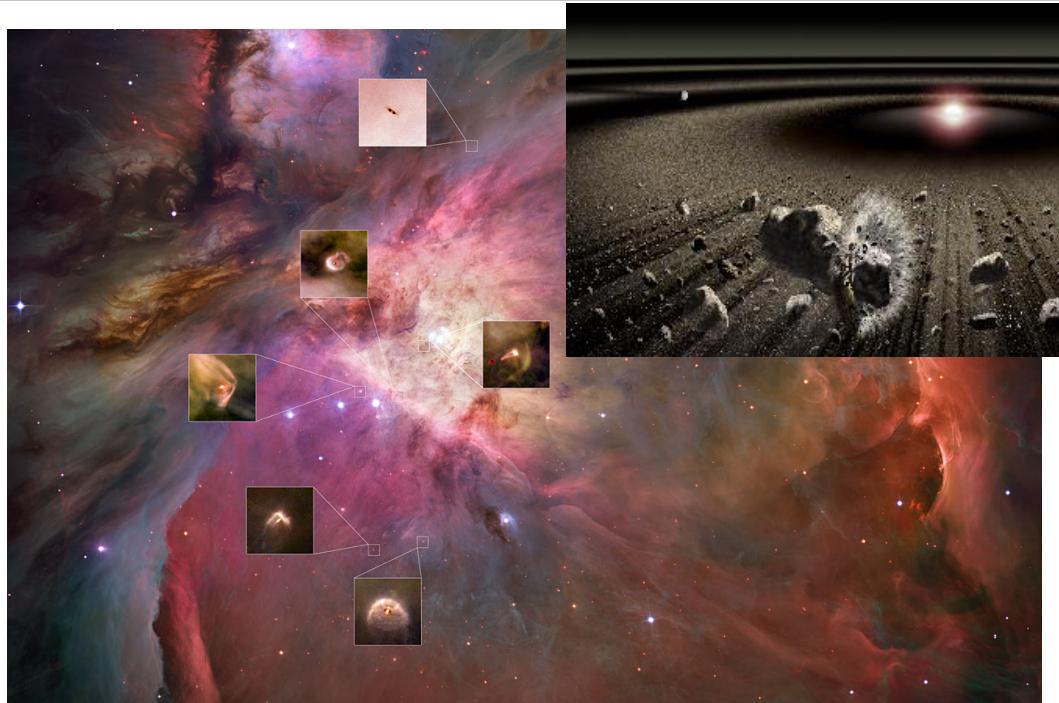
We can also see that stars that are similar to the sun brighten at a constant rate over time. This lets us look at other stars in the system (that are similar to the sun) and age them. From this we get that the sun is about as old as earth.

How did life begin?

Early Earth

The **Sun formed** from the gravitational collapse of a small part of a giant molecular cloud (H + He + heavier elements a.k.a. "dust", i.e., "stardust")

The **Earth formed** in a few million years by electrostatic then gravitational accretion of this dust into grains □ clumps of grains □ planetesimals (~10 km) □ planet size



Embryonic solar systems in the Orion Nebula

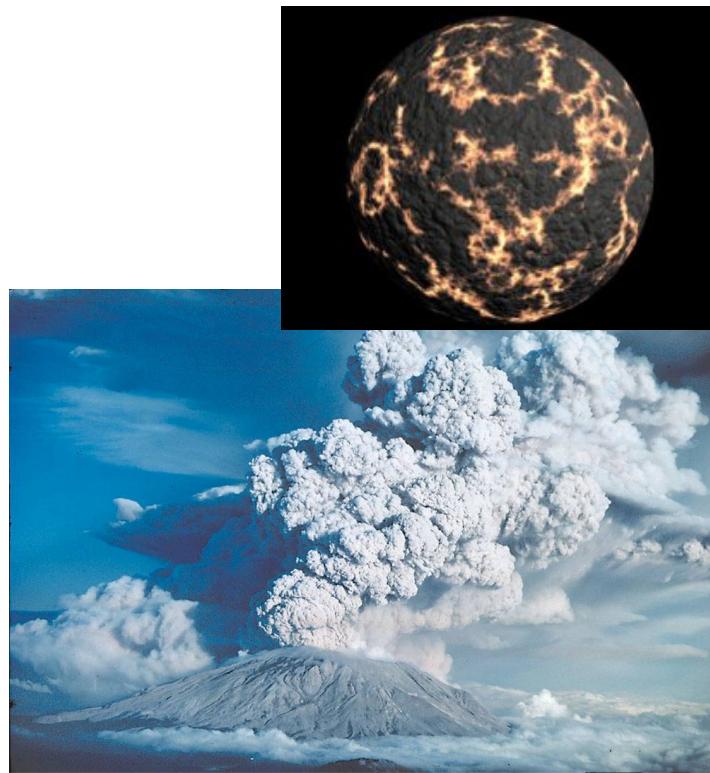
When the universe first formed it really only made hydrogen and helium. It is in the cores of the stars that heavier elements are formed (still only about 2% heavier elements).

Eventually rocks are formed by electrostatic and gravitational pull making larger and larger clumps of molecules.

How did life begin?

Early Earth

- Initially the Earth had **no oceans or atmosphere**:
 - ✓ Made from **rocky/metallic** planetisimals (icy planetisimals formed further out from Sun)
 - ✓ To small & warm to hold onto H or He gasses, and too little other gasses around
- Current models suggest:
 - ✓ **Rocky/icy** planetesimals far from Sun later flung inward by gravitational encounters
 - ✓ Trapped water and gas in this rock was later outgassed by volcanos (when Earth cooler)
 - ✓ Water vapor condensed to form oceans
 - ✓ Gasses (mainly CO₂; also N₂, H₂S, SO₂, H₂) formed early atmosphere



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Rocky/metalic planets form near the center of solar system since they are made of heavier elements (and icey elements would have evaporated in the heat). At first it had no atmosphere (it isn't big enough to have the pull to do it like jupiter does). We get our atmosphere from water vapor being spewed by volcanoes (we think). Another theory about the origin of the atmosphere is that the thing that collided with us did so with such force that it released a bunch of water that was sealed inside rocks.

How did life begin?

Early Earth

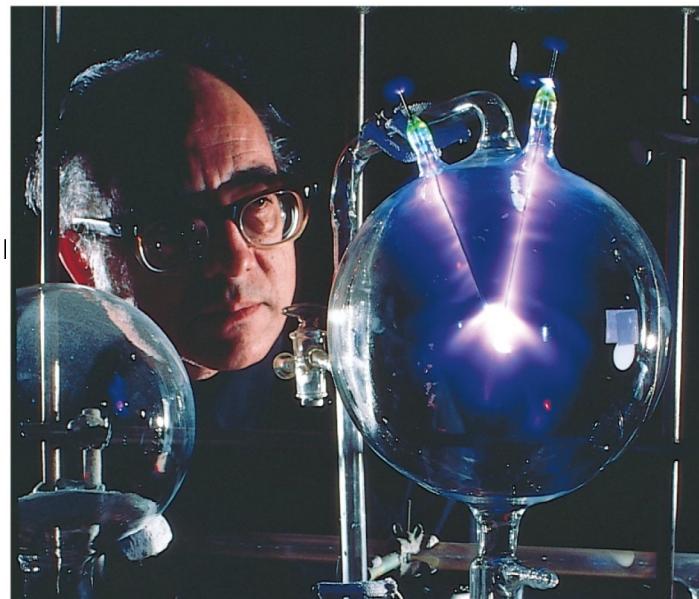
- Zircon evidence suggests Earth possibly had **continents, oceans and atmosphere** as soon as 100 million years after the planet first formed (!)
 - ✓ U-Pb dating □ solid zircon 4.4 BYA
 - ✓ O isotopes □ solidified in presence of water
 - ✓ Radioactive rocks, or impact that made Moon □ accelerated heating □ outgassing?
- **Note:** Life arose in a nearly **oxygen-free** environment
 - ✓ O₂ is highly reactive □ prevents complex organic molecules forming outside cells
 - ✓ So “life as we know it” **could not form** in the **present** environment on Earth



How did life begin?

Origin of Organic Molecules

- Famous **Miller-Urey experiment:**
 - ✓ Assumed (wrongly) early Earth atmosphere was methane and ammonia, and energy driving the chemical reactions was lightning
 - ✓ Readily synthesized **amino acids** (building blocks of life) and other organic molecules
 - ✓ Similar experiments today...problem: Don't know exact composition of the early atmosphere, especially H₂ content
- Other sources:
 - ✓ Chemical reactions between water and minerals near deep-sea vents
 - ✓ Material from space: Asteroids & comets, UV from Sun acting on dust in solar nebula



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These two guys put what they thought was the atmosphere of early earth and waited. Eventaully amino acids formed. The problem with this is that the early atmosphere was actaully co₂ based. Out current experiments show that the kind of amino acids formed depends on the ratio of carbon in the air.

Moral of the story amino acids are easy to produce.

How did life begin?

Chemistry ≡ Biology?

- Plenty of organic molecules around, but how do these form living/replicating cells?
- **Random chance is virtually impossible ≡ must be a *natural mechanism*. But what?**
- Looking for high probability “chemical pathways”...

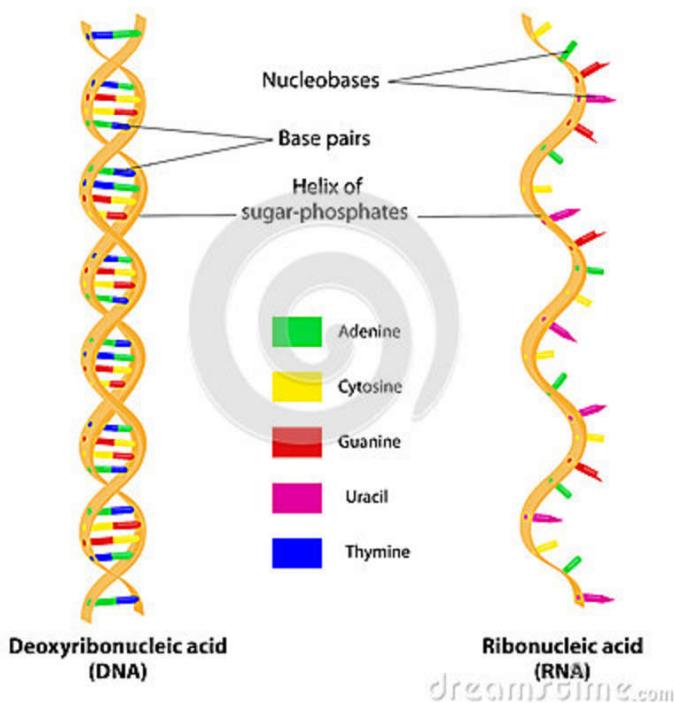
There are a bunch of different natural path ways that we need to explore that could have resulted in the change between amino acids to true biology.

How did life begin?

Chicken & Egg Paradox #1

- **Problem:** Modern DNA cannot replicate without catalysing proteins (enzymes), and enzymes cannot be made without DNA. **Which came first?**
- **Possible Solution:** 1980s (Thomas Cech and colleagues—Nobel prize 1989): RNA *itself* can catalyse many cellular biochemical reactions, including (partially) *their own replication!*
- This supports the idea of an earlier “**RNA World**”, where RNA serves as **both** genetic *and* catalysing molecule

Structure of DNA & RNA



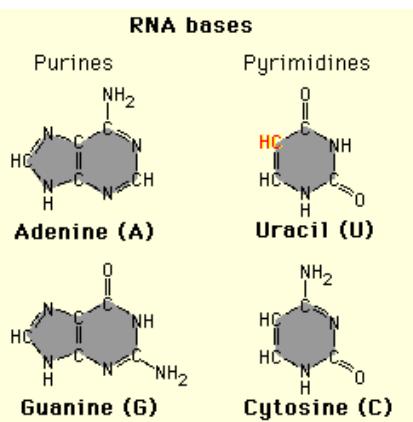
Modern dna doesnt replicate itself without proteins. On the other side we know that proteins cannot be made without dna. The solution to this is that RNA can behave like a protein to help rna self replicate without the use of proteins. This lead to the notion that early life was just rna called the rna world.

How did life begin?

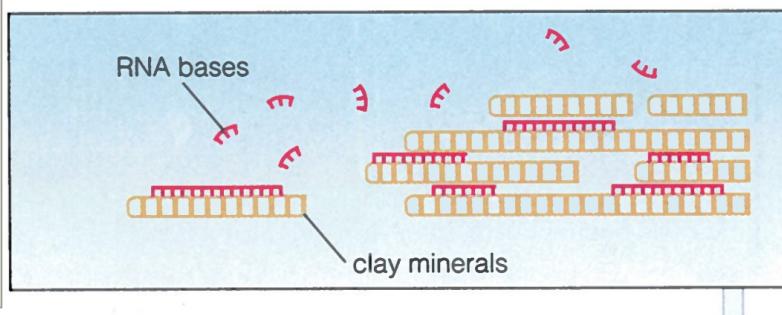
RNA World

- **Experiment:**

- ✓ Inorganic minerals (a kind of “clay”) can facilitate self-assembly of RNA bases
- ✓ Quickly and easily produces RNA strands up to **a few dozen** bases in length
(Note: zircon grain analysis suggests “clay” was widespread 4.4 billion years ago)



1. Clay minerals catalyze the formation of RNA strands up to a few dozen bases long.



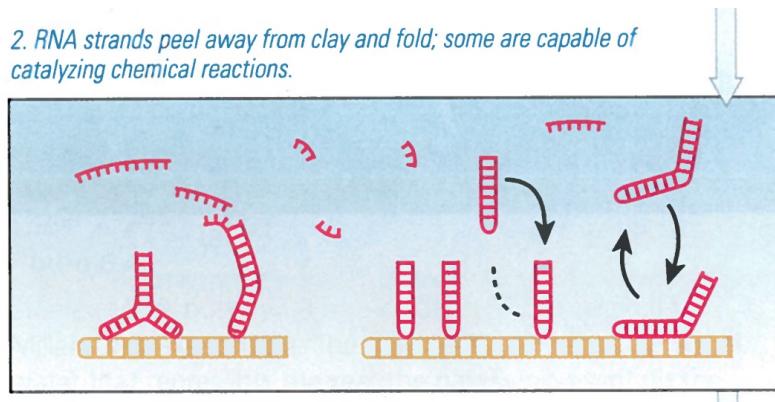
You have some rna bases floating around in water (you can made these randomly). Within zircon chips that are hella old (near the beginning of earth) there are these inclusions of "clay". If you add this clays to the water with rna bases the clay spontaneously acts like an enzyme so the rna bases slots into these pockets in the clay by random chance and snap together.

How did life begin?

RNA World

- **Experiment:**

- ✓ But need **length > 165 bases** for RNA to be able to catalyse its own replication
- ✓ Note 1: Short strands easily peel away from the clay & fold in ways that promote joining
- ✓ Note 2: Strands as small as 5 bases are able to catalyse various chemical reactions

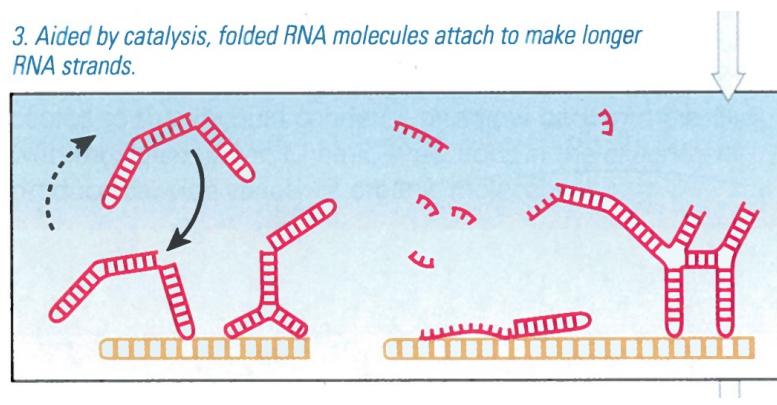


How did life begin?

RNA World

- **Experiment:**

- ✓ But need **length > 165 bases** for RNA to be able to catalyse its own replication
- ✓ Note 1: Short strands easily peel away from the clay & fold in ways that promote joining
- ✓ Note 2: Strands as small as 5 bases are able to catalyse various chemical reactions
...like joining short strands into longer strands

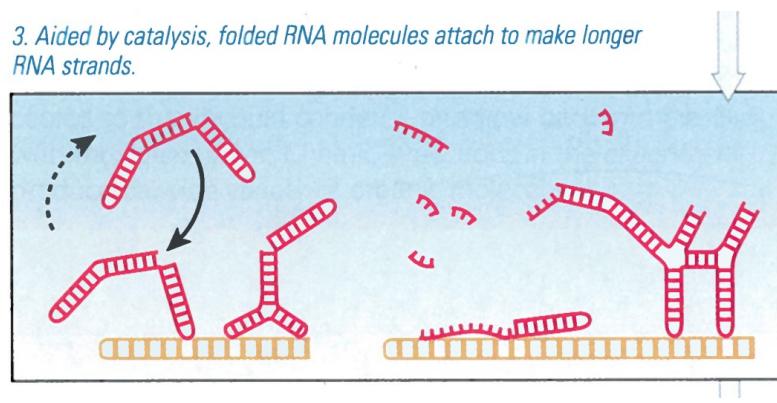


How did life begin?

RNA World

- **Experiment:**

- ✓ Given the countless clay grains, and that the RNA enzyme for joining is very simple, it is not unreasonable to expect very long RNA strand to form *naturally (spontaneously)*

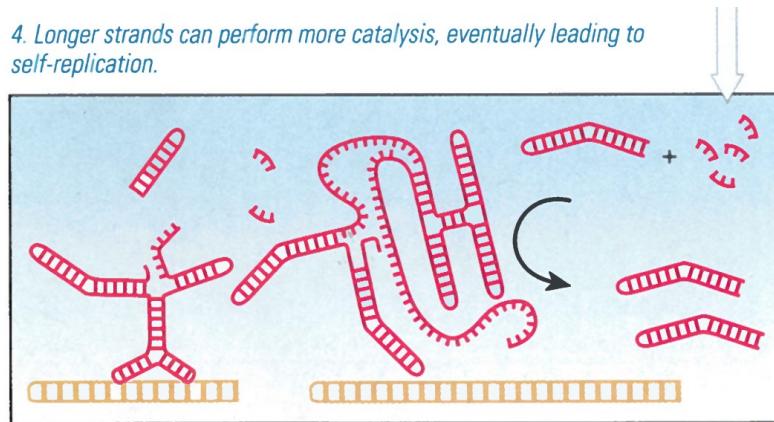


How did life begin?

RNA World

- **Experiment:**

- ✓ This natural mechanism for creating longer RNA strands would have dramatically increased the chance of getting an RNA molecule **long enough to self-replicate**
- ✓ Once this happens, growth is exponential...



These diagrams show steps through which self-replicating RNA may have originated as RNA bases (created by mechanisms like those in the Miller-Urey experiment) and interacted with clay minerals. (Adapted from Briones, Stich, and Manrubia, "The Dawn of RNA World," *RNA Journal*, May 2009.)

How did life begin?

Exponential Growth

- Once you have **one** self-replicating molecule, its numbers grow **exponentially**:
 - ✓ $1 \rightarrow 2 \rightarrow 4 \rightarrow 8 \rightarrow 16 \rightarrow 32 \rightarrow 64 \rightarrow \text{etc.}$
 - ✓ After only a few hundred self-replications, they could (given enough “raw material”) fill the entire volume of the Earth’s oceans!
 - ✓ Even with minutes, hours, days, or even years between self-replications, this would be a “blink of an eye” on geological timescales (“deep time”)
 - ✓ Exponential growth starts slowly, but in not too long it “skyrockets”

We now have short strands of base pairs just floating around. These can clip together or serve as the substrate to facilitate other strands to snap together.

The ocean has tons of these clay grains and rna chunks floating around we can see that there are tons of combinations being formed which eventually forms a strand of rna long enough to self replicate (165 bases). At this point growth becomes exponential growth.

How did life begin?

Chicken & Egg Paradox #2

- **Problem:** Which came first: the **cell membrane**, or its **contents**: genes (RNA/DNA) and proteins?
- **Possible Solution:** Scientists have known for decades that cooling a warm-water **solution of amino acids** can cause them to bond to form a spherical shell “**pre-cell**”. **Lipids** (fats) in water also form pre-cells on the surface of the **same clay minerals** that help assemble RNA molecules. Some pre-cell membranes exhibit **real cell membrane behaviors** like:
 - ✓ Selective molecule transport across the membrane
 - ✓ Electrostatic energy storage and discharge
 - ✓ Growth and splitting into “daughter” spheres

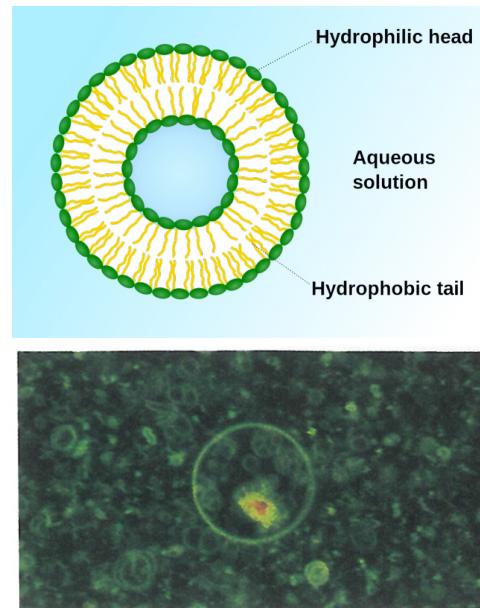


Figure 6.6

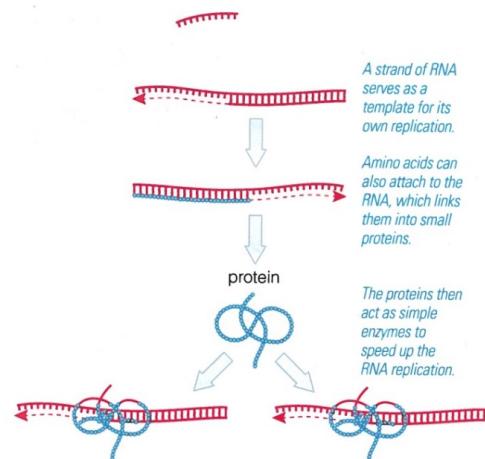
This microscopic photo (made with the aid of fluorescent dyes) shows short strands of RNA (red) contained within lipid pre-cell (green circle), both of which formed with the aid of catalysis by clay minerals beneath them.

We run into another chicken and egg problem with the cell membrane did it form before or after is genes. If you put a bunch of lipids in water they will form a cell membrane spontaneously because they have hydrophobic tails that slot themselves on the inside. If you run this experiment in the presence of the zircon clay it will act as a catalyst to speed up the formation of cells.

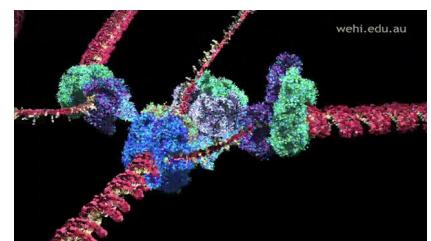
How did life begin?

Chicken & Egg Paradox #2

- **Confining RNA & other organic molecules in pre-cells would facilitate the origin of life:**
 - ✓ Keeping molecules concentrated **increases reaction rates** and likelihood of creating a self-replicating RNA
 - ✓ Suppose a self-replicating RNA emerges that codes for a **replicating enzyme**. The pre-cell would keep this enzyme inside where it would help this particular RNA (and no others) to replicate faster → **dominate**.
 - ✓ Experiments suggest relatively high early RNA mutation rates → many opportunities for **natural selection** of more efficient self-replication pathways and increased complexity



a This diagram shows a self-replicating RNA molecule that has evolved the capability to produce a primitive enzyme that helps its own replication.



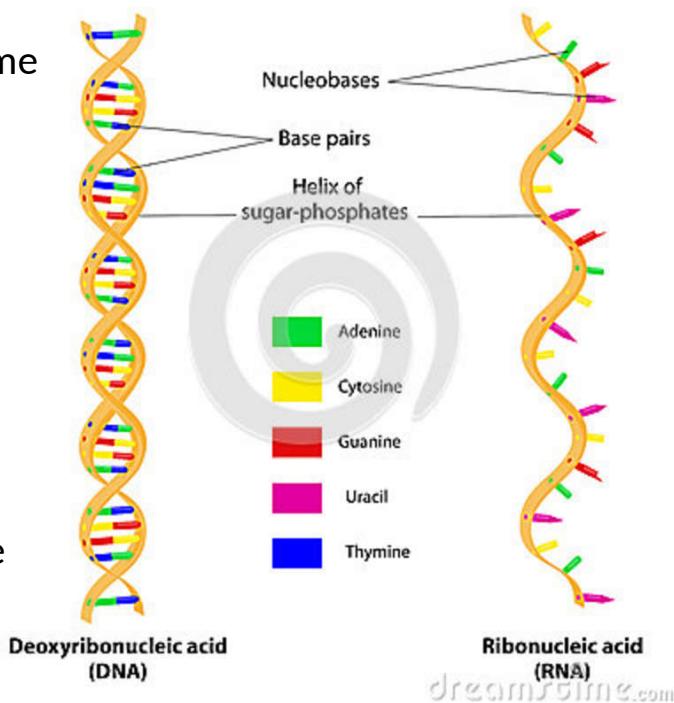
These cell membranes can form randomly they can form around some rna strands. This makes the chemistry in the cell concentrated until the cell swells and splits into daughter cell. This concentration speeds up the process. Because this replicates at an exponential speed it dominates over everything else.

How did life begin?

RNA World ⇌ DNA World

- **Gradually**, these “RNA organisms” would have become “alive”, or “biological”, in the sense we think of now
- Biological natural selection could then take over, resulting eventually in a “DNA World”:
 - ✓ Similarity between RNA & DNA
 - ✓ DNA is a more durable hereditary material
 - ✓ DNA is less prone to copying errors
- RNA also served other functions in the cell, and so would stay, with now DNA serving the hereditary role

Structure of DNA & RNA



DNA is much more solid than RNA which is more prone to errors.

Summary

Summary of “RNA World”

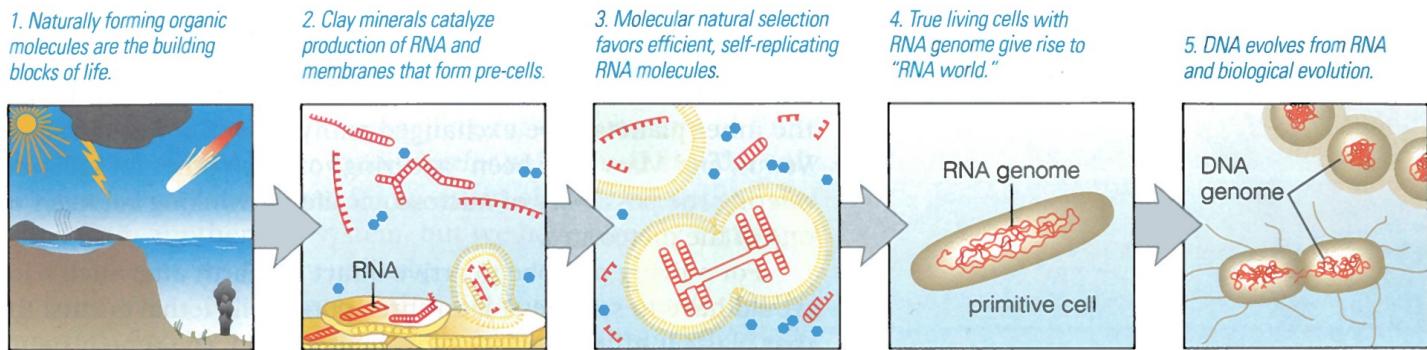


Figure 6.8

A summary of the steps by which chemistry on the early Earth may have led to the origin of life. (Adapted from Campbell, Reece, Simon, *Essential Biology*.)

Summary:

- amino acids are really easy to make
- clay that is super common can act as a catalyst to form rna
- rna links together to become large enough to self replicate
- cell membranes can form randomly around rna strands
- dna evolves from rna and is better at continuing so it takes over