Evolutionary Dynamics
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Week 01
Lecture 03

Hi, let's continue our discussion on the story of life on Earth.

And in this one, in this video, we'll discuss how the first cell or LUCA came about.

But before we do that, we ended our last video on the story of life on Earth in the last four billion years.

So, and there were these.

Two different experiments.

These are experiments in life that happened as life played out on the planet called Ediacaran Fauna roughly 560 million years ago, the Cambrian explosion 541, and the best-preserved samples that we have of the Cambrian explosion.

Evidence for the Cambrian explosion is present all around the planet.

But one of the best-preserved samples comes from the Burgess Shale in Canada.

And I just wanted to show you this is a depiction of the biological diversity that is thought to have existed in the Ediacaran fauna.

And I just want to show this so as to.

Communicate how fantastical some of these life forms are.

It's almost like an artist's view of just fantastical life forms that could have existed.

Interestingly, all these life forms are thought to have existed.

Let me also share this great reference called Wonderful Life by the late paleontologist and evolutionary biologist Stephen Jay Gould.

This is a wonderful book to read.

Particularly about what happened in the Burgess Shale, Stephen J. Gould, one of the most remarkable writers on evolution in the late 20th century, is extremely accessible for any layperson, not a specialist in the area, to read and enjoy.

Interestingly, one of the themes that we will visit later in the course was introduced by Stephen Jay Gould around this time.

And Gould asks a rhetorical question.

The question he asks is about what we have just seen on the previous slide, which is 4.6 billion years ago.

And life was allowed to evolve.

Earth went through this period of time, and we see life forms of today.

Human beings, all the other species that we see, the life forms we see.

So all this evolutionary process.

A time of roughly 4 billion years of life somewhere here, all this time has led to the diversity of life forms that we see around us.

And Gould rhetorically asks the following question.

Imagine a hypothetical scenario where we again go back to the start of the formation of the planet and let the planet evolve for another 4.6 billion years.

Then two questions arise.

One, will we see life or

Will we see life or will we not see life, which means that in an independent run of the planet, having spent four and a half billion years of its life, we do not see life.

That means, in some sense, it's very lucky to have evolved.

And for us, we've been very lucky to be alive in this particular run of the planet and not in this one.

And secondly, if life does evolve, will it?

Will life Follow the same structure as we see now?

And what that means is that will the morphological forms that exist on this parallel earth,

Be the same as the morphological features that we see today?

Will there be plants?

Will there be fish?

And so on and so forth.

So Gould calls this experiment replaying the tape of life.

And

In a few weeks' time, we will see how in lab experiments of evolution, we can actually test this idea of replaying the tape of life and how much of evolution is dictated by necessity, which would be the case if life on this planet was exactly the same as life on the planet as we know it today.

That is dictated by necessity.

Physical constraints, what is called evolutionary convergence, that life forms must be of a certain particular type versus

Chance, that it's chance events which dictate it.

And the argument would be that if the Permian extinction had not taken place, then dinosaurs wouldn't be around.

If the KT extinction had not taken place, then mammals wouldn't have come into being, and we wouldn't be here.

So it's these freak events of a meteorite colliding with the earth that lead to the evolution of the life forms as we see today.

And there are no necessities.

Life could have taken any path that it wanted to.

So it's this debate between chance events and necessity about which of these is the more prevailing force in dictating evolutionary forces.

And as I said, we'll discuss experiments that test these in laboratory settings now.

All right, so how did LUCA come into being?

So imagine you have to build a cell.

So my question to you is, pause the video for a few minutes and ask, what does it take to build a cell?

Suppose we have just chemicals floating around in a pond, and there are reactions taking place, and something is being converted into something.

Two chemicals meet to make something else, and so on and so forth.

But it is all happening in a pond.

So out of this, if life has to arise, then what are the necessary conditions for life to come?

One that I will list is to give you a sense of what the question is, because it's an abstract question in some sense.

One necessary ingredient of life, I think, has to be a separation between self and environment.

Separation between self and environment.

And in life as we know it, this is accomplished via membranes.

That's what a cell membrane does.

It separates the inside of the cell from the outside of the cell.

And hence, that's a prerequisite for this first cell to be built.

So as I said, take a few minutes and see what all you come up with, and we'll go through the list that I have here.

All right.

So hopefully you have something, you have put something there which you think are necessary constituents of building a cell.

But let's just go through this.

Let's go through this.

So one is.

There should be genetic material or some material which is related to heredity.

Because when I have offspring, I have to communicate the properties that I have to my offspring, and only then can natural selection act.

So how does this work? There has to be some chemical medium of communication of information from one generation to another.

So this is necessary for the communication of information.

From one generation to the next.

And obviously, in our cells, this is accomplished via DNA.

In human beings, for instance, half the DNA comes from the father, and half comes from the mother.

And that's how that information is conveyed from one generation to another.

It doesn't have to be DNA, but in any imaginary life form that we are building here, in any imaginary cell we are building here, some chemical entity, which is this unit of communication, has to be there.

A cell has to have entropy and has to have a source of energy generation.

This is just because our bodies are great ordered machines.

And the second law of thermodynamics tells us that entropy increases with time.

But our bodies are maintained in order, and hence we are fighting entropy.

We are maintaining order, which is against the second law of thermodynamics.

And this requires us to invest energy, and hence there must be a source of energy around us.

Catalysts are very important.

Many of the reactions that take place often occur. Some of you might have seen this: this is the energy of a molecule, and reactions are often depicted like this.

Like this, these are the reactants.

Reactants have this much energy.

Products have this much energy.

So this reaction is favorable because you are going from a high-energy state to a low-energy state.

However, for this reaction to be carried out, there is a large energetic barrier that is stopping it from taking place.

What the presence of a catalyst does is it changes this landscape from a large barrier to a relatively small barrier.

Now this reaction becomes much more feasible because the energetic barrier, which used to be this much, is now only this much.

Now this becomes a much more feasible reaction.

This role of catalysts is played by proteins in the cell.

We'll look at what proteins are in the subsequent lecture.

It doesn't have to be a protein.

Some mRNAs also catalyze reactions, but by and large, proteins catalyze reactions.

We need a membrane.

We already discussed this.

We need to separate self from the environment.

Hence, we don't have to call it a membrane, but some boundary has to be there which differentiates between me and non-me as a cell.

And whatever the constituent elements of this cell are, if it's carbon-based life, then I need carbon, oxygen, nitrogen, sulfur, and phosphorus.

All elemental sources have to be supplied.

I have to develop mechanisms to pick these up from the environment that I'm living in and then subsequently use and assimilate them in my body.

And I need some sort of replication machinery.

This is necessary for replicating the genetic material, which has to be passed on to the progeny that I'm going to produce.

So these are broadly the requirements that we have when we think about making a cell.

All right, so what have been the ideas that have been floated around regarding the start of life on Earth?

In 1871, Kelvin proposed that germs of life might have been brought to Earth by some meteorite.

But that's a very unsatisfactory explanation because it merely transports the problem of the origin of life from having happened here to having happened on that meteorite.

So this is a very unsatisfactory type of explanation.

However, this remained a fringe notion and was not taken much seriously up until 1969, when in Australia, a really old meteorite, which contained 74 different types of amino acids, complex sugars, and nucleotides, was found.

It landed on the planet.

And we'll see that amino acids are obviously what constitute proteins.

And we'll see the significance of this later.

So, post this discovery of a meteorite having brought essential constituents of what life has, as we know it, this was sort of a fringe notion.

But having said that, as time goes on, our estimates of how old life is on the planet itself are undergoing revisions.

In the 1960s, life was thought to be less than 600 million years old.

In the 1970s, it was thought to be at least 2.5 billion years old.

And currently, it is around 3.5 billion years old.

And some estimates say it is even older than that.

So all of this is undergoing continuous revision.

Still, it doesn't tell us how life came to Earth.

Darwin in 1871 wrote the following sentence, and he says, 'But if—and what a big if—we could conceive in some warm little pond, with all sorts of ammonia and phosphoric salts, light, heat, electricity present, that a protein compound was chemically formed, ready to undergo still more complex changes.'

So the idea is that, what if we give all these constituents and add some heat, light, and electricity, would molecules of biological relevance come out of the chemical reactions that take place?

And this was the classical experiment that I was taught when I was in school: the experiment by Stanley Miller.

This was a paper that was published in 1953.

1953 is also the year when the DNA structure was published by Watson and Crick.

But when these discoveries happened in '53, the structure paper was published.

It was important, but what really grabbed the attention of people was the Stanley Miller experiment.

And the Miller experiment we've seen is that you have some water and some methane gas.

There is some nitrogen.

There is water, some phosphorus salts, and so on and so forth.

And if you just heat these slightly, you provide some electricity to mimic cloud formation and then electricity in the clouds, and so on and so forth.

What Stanley Miller saw was that within a few days,

the color of the liquid changed from just pure water to slightly pinkish.

And as the time of the experiment proceeded further, the liquid got darker and darker.

And when the chemical analysis of this dark liquid was done, it was found that amino acids, among other things, were present in the liquid.

And this was extremely interesting because if, in a matter of simply analyzing,

a few weeks, you could have amino acids being brought into a liquid pond like this, then all you needed was a mechanism to link these amino acids together, and then you would have a chain of amino acids, which are proteins, and these could come together. Proteins form structures, functions, they are catalysts, and they're indispensable to life. So if, in a matter of a few weeks, you had

amino acids come into being, this was a really good indication of how life could have come into being.

And everything that was supplied in this experiment is actually very reasonable to expect as something that might be going on in oceans or ponds.

In fact, this led to Urey, who was already a Nobel Prize winner by that time, to comment that if God didn't do it this way, he missed a good bet.

That this was such an excellent way of leading to the evolution of life.

And this experiment was a classic experiment.

And it led to this experiment being repeated in different ways, shapes, and forms across the globe.

And every single time, you would get the same result: that in a very short amount of time, these molecules of biological relevance come into being.

However, there is a problem with this idea that if the hypothesis is that this happened in the open ocean,

The problem is, how do I concentrate them?

How do I concentrate these biological molecules so as to force them to come together?

So if this is one amino acid, this is another amino acid, and this is another one.

In an open ocean, it's really hard to get these biological monomers to come together to such a high concentration that this type of a chain of amino acids would be formed.

And unless you have these types of reactions happening, that from these monomers, you have these biologically relevant polymers come into being,

Until that step is figured out, it's really hard to see how life could have come out of a process like this.

So there are some ideas which talk about this, about how it could have happened.

But the sort of the most, the modern view of this, and this is sort of how our thoughts have been shaped in the last 15 to 20 years, is the following.

But to get to that, we have to understand how living cells make ATP.

ATP is the energy currency of a cell.

And there is a surprising mechanism which all life forms use to make ATP.

Essentially, the mechanism goes as follows.

We eat food.

Food is an electron donor.

Food gives electrons.

These electrons.

So if you are talking about our cells, this is happening in the mitochondria.

If we are talking about simple bacteria, this is happening on the bacterial cell membrane.

This is inside the mitochondria.

This is outside the mitochondria.

So we eat food.

Food gives electrons to these red circles, which are proteins in the mitochondrial membrane.

These proteins pass those electrons from one to another.

And in that process, the energy that the electron is losing is being used to pump protons from inside the mitochondria to outside the mitochondria.

So all that is happening is that we have these electrons flowing down a potential gradient.

And in that process, protons are being pumped out of the cell.

Eventually, what that leads to is a proton gradient.

You have a high proton gradient outside the cell and a low proton concentration inside the cell.

These protons then flow through this potential gradient that has been created through a machine called ATP synthase.

And as they rush through this ATP synthase, it is akin to viewing this process as a water mill turning; this flux of protons rotates a water mill, and the energy generated in the process leads to ADP being converted to ATP.

This was discovered in the 1960s and 70s.

And it's a long, fascinating story in itself about how this came into being.

But the point from our context is that this is such an unintuitive mechanism of making ATP.

Why not just have X react with ADP?

And this gets converted to Y, and you have ATP produced with some phosphate.

People really thought that it just needed to be a chemical reaction.

Why does it have to be so complex?

In fact, the requirement of a membrane to generate ATP was the focus of Peter Mitchell's work.

Again, from our context, the point is that every life form that we know of uses this particular mechanism to make ATP.

And if every life form is using a proton gradient as a source of energy, then the proton gradient is the source of energy for every life form.

What that means, or what that strongly suggests, is that the first life form that came onto the planet must have used a proton gradient as a source of energy, and every subsequent life form has simply inherited that mechanism as a source of energy.

Hence,

When we are looking at a place on the planet's ecological niche where life could have evolved, we are looking at places where this proton gradient is available as a source of energy, which cells simply tapped because of its geochemical availability there.

And obviously, this proton gradient is not present in the free ocean.

So this search led to what are called alkaline hydrothermal vents.

This is a discovery from 2000, although they were assumed to have existed even before they were discovered.

But what happened is that alkaline hydrothermal vents were discovered in the year 2000.

And they are formed at the bed of the sea, and they look like structures like this, which are several meters high.

And this happens when there are fissures in the bed of the ocean.

So water rushes in, but as water rushes in, its temperature increases, pressure increases, and it suddenly vaporizes and reacts with the constituents and comes back up with force.

As it comes back up with force, it brings material onto the surface, which, as it comes up, cools down and solidifies.

And we have these porous membrane-like structures, which are present on the bed of the ocean.

Subsequent studies after 2000 have indicated that these structures are present everywhere on the Earth's bed.

Their temperature is 75 degrees Celsius, and they crystallize to form these rocks.

And what happened is that over geological time, the oceans were acidic.

So you had outside here, the H^+ concentration is high.

And the gases that are flowing through these porous membrane structures are alkaline in nature.

So the H^+ concentration

that is coming through them is low.

The ocean's H+ concentration is high.

So you have this constant availability of a proton gradient that is there for you to tap into and use as an energy source.

Moreover, the walls of these structures have metal ions embedded in them.

Because they are coming from the reactions that happened underneath the ocean bed.

And these metal ions serve as catalysts.

Many catalysts are metal ions.

So overall, it's thought that these alkaline hydrothermal vents are

the place where Luca came into being, where life first originated on the planet.

A greater discussion on this is sort of beyond our scope, but this is our current understanding and the most promising hypothesis of where life could have evolved on Earth.

And just to wrap up this discussion, what I will say is that these are sort of pictures from Nick Lane's group at University College London, where these hydrothermal vents are actually being made.

So instead of not being able to go to the ocean bed and conduct an experiment, we can make these porous structures in the lab.

This liquid pool is sort of ocean water.

And these are structures that we now know what these hydrothermal vents, crystalline structures look like.

So we recreate them and we pass gas through them here, just as gases pass through in alkaline hydrothermal vents.

And then we try to record what is happening in these, what sort of biological molecules are getting formed and getting accumulated because spaces are confined now.

So not only do we solve the problem associated with the use of H+ ions as an energy source, but we also solve the problem of concentration because every biological molecule that is formed is now present in a confined space, and hence they can be brought close to each other, making reactions much more feasible. But this is sort of an early phase of this research, and it will be a while before we know the details of this. Nick Lane also has this book called The Vital Question

which talks about, and the vital question is, how did LUCA come into being, dealing with that question historically and bringing us up to alkaline hydrothermal vents?

It's a great read, and I recommend it to those of you who are interested.

Thank you.