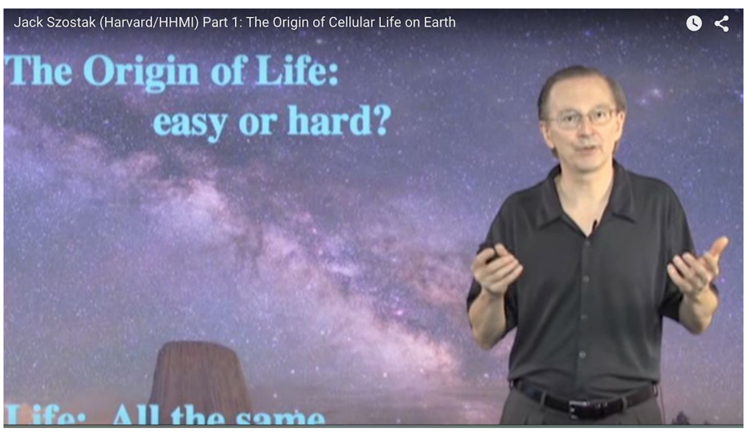
Session 5: Chemical Evolution

Overview:
Scientists have wondered for years how the very first life form may have evolved. How did the Earth go from an environment of simple molecules to primitive cells? Dr. Szostak presents evidence for the “RNA world” hypothesis and explains how lipids, nucleotides and amino acids could all have formed from molecules in the early atmosphere if energy (for example lightening) was added. Once formed, these molecules could have been enclosed in a membrane to form a primitive, self-replicating protocell. After several billion years of evolution, prokaryotes ruled the Earth. In a short video clip, Newman explains how ancient rock formations provide insights into the critical role that photosynthesizing bacteria played in the evolution of the Earth’s atmosphere and modern life.

First video:
Title: The Origin of Life on Earth
Speaker: Jack Szostak



Questions for Part 1:

1. What characteristics of fatty acids make them ideal candidates for the composition of membranes of protocells?
    a. Fatty acids allow membranes to have a high level of disorder.
    b. The permeability of membranes composed of lipids is low and does not allow nucleotides to cross the membrane.
    c. Fatty acids cannot spontaneously form a double layer membrane.
    d. Fatty acids are generally found close to nucleotides.
    e. None of the above.

2. Which of the following molecules is most likely to have been the original building block for life and why?
    a. RNA, because its bases have special properties that allow for chemical reactions to occur.
    b. DNA, because it is a good source of gene storage.
    c. RNA, because its sugar can be used to catalyze chemical reactions.
    d. Amino acids, because they allow for different chemical reactions to be catalyzed in diverse proteins.
    e. Both A and C are correct.

3. The main difference between a protocell and a cell is that
    a. the protocell does not possess complex organic molecules.
    b. the cell is able to catalyze polymerization reactions.
    c. the protocell cannot replicate itself.
    d. the protocell is not subject to evolution.
    e. None of the above is correct.

4. The Miller-Urey experiment was trying to mimic conditions on the early Earth and prove the possibility of a chemical origin of life. Which molecules were created in the experiment? (Select all the answers that apply.)
    a. Amino acids
    b. RNA
    c. DNA
    d. Lipids
    e. A and B are correct
    f. B and C are correct

5. Which of the following characteristics would NOT have been needed for the early protocells to evolve into living cells?
    a. A membrane-like boundary separating the external environment from an internal environment.
    b. Polymers capable storing information.
    c. Polymers capable of enzymatic activity.
    d. Self-replication
    e. Internal segregation of different metabolic activities.

For questions 6-8 determine if the statement is true or false.

6. Miller and Urey were able to determine the ideal conditions for the development of life.

7. Chemical evolution allows for the development of new complex organic molecules with a specific function.

8. The Miller-Urey experiment was able to produce amino acids used in modern cellular organisms.

9. Describe two methods by which spontaneous polymerization of molecules may have occurred. Briefly explain each hypothesis.

10. Describe the main characteristics of RNA that allow us to hypothesize that it was the chemical basis for early life. Compare and contrast these characteristics with protein.

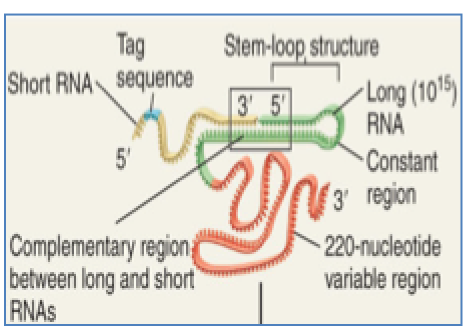
11. Most organisms use DNA to store their genetic information. Why is DNA NOT thought to be the molecule that created life?

12. Silicon (Si) is in the same group as carbon in the periodic table and many organic molecules can be synthesized using Si instead of C. However, researchers did not include Si in the mixture of elements they used to test their ideas of life arising from the early atmosphere. Why not?

13. Explain why compartmentalization was required for chemical evolution to occur.

14. To determine if RNA could catalyze polymerization reactions, Bartel and Szostak performed an experiment. They synthesized long RNAs in which the 5' end was constant region (identical sequences, shown in green below), and the 3' end was variable (orange). Each molecule of RNA contained a different sequence on the variable end. They took a large pool of the long RNAs and added identical short RNAs (yellow) containing a sequence that was complementary to part of the constant region. The short RNAs also contained a tag sequence (blue) that allowed the short RNA to be identified and purified. They hypothesized that some of variable regions might contain enzymatic activity to catalyse the formation of a phosphodiester bond between the 5' end of the constant region of the long RNA and the 3' end of the short RNA.

(Bartel DP & Szostak JW (1993) Isolation of new ribozymes from a large pool of random sequences. Science 261(5127):1411-8)



a. How could Szostak and Bartel identify long RNAs in which the variable region was able to catalyze the formation of the 5' to 3' bond between the constant region and the short RNA?

b. Using a similar assay, how could Szostak and Bartel identify the variable RNA sequences that have the best catalytic activity? (Note: Enzyme proficiency is determined by how quickly and efficiently a reaction is catalyzed)

Second video:
Title: Primitive Photosynthesis
Speaker: Diane Newman

Questions for Part 2:

1. Which of the following processes would the microorganisms that oxidized iron 2.4 billion years ago have been able to perform? Choose all of the answers that apply.
    a. Oxygenic photosynthesis.
    b. Anoxygenic photosynthesis.
    c. Compartmentalization of organelles.
    d. Replication
    e. All of the above.

2. How did plants develop the ability to undergo oxygenic photosynthesis?
    a. An ancient cell engulfed a bacteria that evolved to be a mitochondrian.
    b. An ancient cell engulfed a bacteria that evolved to be a chloroplast.
    c. A cyanobacteria evolved to become a simple plant.
    d. Scientists don't know how plants undergo oxygenic photosynthesis.

For the following question, determine if the statement is true or false. If the statement is false, change one word or phrase to make it true.

3. Scientists think that oxygenic photosynthesis evolved after anoxygenic photosynthesis.

4. List one thing that oxygenic and anoxygenic photosynthesis have in common and one thing that is different between these process?

5. How did the the evolution of oxygenic photosynthesis impact the Earth's atmosphere? Speculate about how this change influenced the evolution of life.

Answers for Session 5:

Questions for Part 1:

1. What characteristics of fatty acids make them ideal candidates for the composition of membranes of protocells?
    a. **Fatty acids allow membranes to have a high level of disorder.**
    b. The permeability of membranes composed of lipids is low and does not allow nucleotides to cross the membrane.
    c. Fatty acids cannot spontaneously form a double layer membrane.
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2. Which of the following molecules is most likely to have been the original building block for life and why?
    a. RNA, because its bases have special properties that allow for chemical reactions to occur.
    b. DNA, because it is a good source of gene storage.
    c. **RNA, because its sugar can be used to catalyze chemical reactions.**
    d. Amino acids, because they allow for different chemical reactions to be catalyzed in diverse proteins.
    e. Both A and C are correct.

3. The main difference between a protocell and a cell is that
    a. the protocell does not possess complex organic molecules.
    b. the cell is able to catalyze polymerization reactions.
    c. the protocell cannot replicate itself.
    d. the protocell is not subject to evolution.
    e. **None of the above is correct.**

4. The Miller-Urey experiment was trying to mimic conditions on the early Earth and prove the possibility of a chemical origin of life. Which molecules were created in the experiment? (Select all the answers that apply.)
    a. **Amino acids**
    b. RNA
    c. DNA
    d. Lipids
    e. A and B are correct
    f. B and C are correct

5. Which of the following characteristics would NOT have been needed for the early protocells to evolve into living cells?
    a. A membrane-like boundary separating the external environment from an internal environment.
    b. Polymers capable storing information.
    c. Polymers capable of enzymatic activity.
    d. Self-replication
    e. **Internal segregation of different metabolic activities.**

For questions 6-8 determine if the statement is true or false.

6. Miller and Urey were able to determine the ideal conditions for the development of life.
   False.

7. Chemical evolution allows for the development of new complex organic molecules with a specific function.
   True.

8. The Miller-Urey experiment was able to produce amino acids used in modern cellular organisms.
   True.

9. Describe two methods by which spontaneous polymerization of molecules may have occurred. Briefly explain each hypothesis.
   a. **Solid mineral surfaces: Clay could have provided the surface for polymerization. Chemical building blocks (amino acids or nucleotides) bind with high affinity to clay. This brings them into close proximity (higher local concentration) increasing the likelihood of reactions between the molecules.**
   b. **Hot pools: Spontaneous polymerization may have occurred when water evaporated and increased the local concentration of chemical building blocks.**
   c. **Hydrothermal vents: iron and nickel at the deep ocean vents could have catalyzed the polymerization of amino acids.**
   d. Cold/icy environments: Extremely cold environments results in the concentration of molecules in ice and therefore aids polymerization.

10. Describe the main characteristics of RNA that allow us to hypothesize that it was the chemical basis for early life. Compare and contrast these characteristics with protein.

    RNA is a good candidate for the original building block of life because it can carry information, catalyze chemical reactions and fold into diverse 3D structures. The 2' OH group on the ribose ring of RNA makes it much more reactive than DNA, which lacks this OH group. This allows RNA to catalyse various enzymatic reactions including self replication. The ability of RNA to fold into complex 3D shapes allows for specificity in the chemical reactions it catalyses.

    Protein can form complex structures and perform enzymatic reactions, however, it cannot store genetic information.

11. Most organisms use DNA to store their genetic information. Why is DNA NOT thought to be the molecule that created life?
    The chemical basis of life requires the following characteristics:
    a. Enzymatic activity
    b. The ability to quickly self-replicate
    c. The ability to fold into different three-dimensional shapes to allow enzymatic specificity.

d. **Because evolution requires the ability to mutate, the molecule would need to be able to replicate itself with some (albeit small) degree of error.**

   DNA cannot self-replicate or catalyze reactions. It is stable with a fairly low rate of mutation (one of the features that makes it a good molecule to store genetic information). It is capable of one structure; the double helix. Therefore, DNA does not match the requirements to be the first molecule of life.

12. Silicon (Si) is in the same group as carbon in the periodic table and many organic molecules can be synthesized using Si instead of C. However, researchers did not include Si in the mixture of elements they used to test their ideas of life arising from the early atmosphere. Why not?
    Although Si can form the same macromolecule structures as carbon, this element is not present in any of the building blocks of today's living systems. This does not eliminate the possibility that in other environments (such as another planet), Si could be the basis of the building blocks for life.

13. Explain why compartmentalization was required for chemical evolution to occur.
    Compartmentalization is required because it allows for the enrichment of a molecule that has evolved a specific advantage. For example, if an RNA has evolved that is faster at replicating or is somehow better than other RNAs, it is not helpful if most of the RNAs that it encounters and replicates do not include the same advantage. If the RNA is compartmentalized inside a protocell, the chance of it copying a molecule that is related greatly increases. With time this will generate an advantage for the protocell.

14. To determine if RNA could catalyze polymerization reactions, Bartel and Szostak performed an experiment. They synthesized long RNAs in which the 5' end was constant region (identical sequences, shown in green below), and the 3' end was variable (orange). Each molecule of RNA contained a different sequence on the variable end. They took a large pool of the long RNAs and added identical short RNAs (yellow) containing a sequence that was complementary to part of the constant region. The short RNAs also contained a tag sequence (blue) that allowed the short RNA to be identified and purified. They hypothesized that some of variable regions might contain enzymatic activity to catalyse the formation of a phosphodiester bond between the 5' end of the constant region of the long RNA and the 3' end of the short RNA.

a. How could Szostak and Bartel identify long RNAs in which the variable region was able to catalyze the formation of the 5' to 3' bond between the constant region and the short RNA?
If the variable region was able to catalyze the formation of a 5' to 3' bond, the short and long RNAs would be covalently bound. Using the tag, Bartel and Szostak could then purify the short RNA containing molecules. By looking at the size of the RNA molecules, they could distinguish between short RNAs alone and short-long RNA complexes. The scientists could then sequence the long RNAs to determine which variable regions had enzymatic activity.

b. Using a similar assay, how could Szostak and Bartel identify the variable RNA sequences that have the best catalytic activity? (Note: Enzyme proficiency is determined by how quickly and efficiently a reaction is catalyzed)
Scientists could stop the polymerization reaction at different times, and select for RNAs that were able to catalyze the formation of the 5' to 3' bond faster.

Questions for Part 2:

1. Which of the following processes would the microorganisms that oxidized iron 2.4 billion years ago have been able to perform? Choose all of the answers that apply.
    - **a. Oxygenic photosynthesis.**
    - **b. Anoxygenic photosynthesis.**
    - c. Compartmentalization of organelles.
    - **d. Replication**
    - e. All of the above.

2. How did plants develop the ability to undergo oxygenic photosynthesis?
    - a. An ancient cell engulfed a bacteria that evolved to be a mitochondrian.
    - b. **An ancient cell engulfed a bacteria that evolved to be a chloroplast.**
    - c. A cyanobacteria evolved to become a simple plant.
    - d. Scientists don't know how plants undergo oxygenic photosynthesis.

For the following question, determine if the statement is true or false. If the statement is false, change one word or phrase to make it true.

3. Scientists think that oxygenic photosynthesis evolved after anoxygenic photosynthesis.
True.

4. List one thing that oxygenic and anoxygenic photosynthesis have in common and one thing that is different between these process?
    a. **Both forms of photosynthesis produce biomass (carbon based molecules)**
    b. **Anoxygenic photosynthesis does not produce O_2 but oxygenic photosynthesis does.**

5. How did the the evolution of oxygenic photosynthesis impact the Earth's atmosphere? Speculate about how this change influenced the evolution of life.
   Oxygenic photosynthesis changed the Earth's atmosphere to one based on oxygen. The early Earth had a highly reducing atmosphere (remember the Miller-Urey experiment) and oxygen would have been toxic to early life forms. As microbes such as cyanobacteria produced O2, and the atmosphere and oceans became oxygenated, early life would have to have evolved to live in this new environment. Next time you take a breath, thank an ancient microbe!