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Dianne Newman's Lecture Part 1: Microbial Diversity and Evolution

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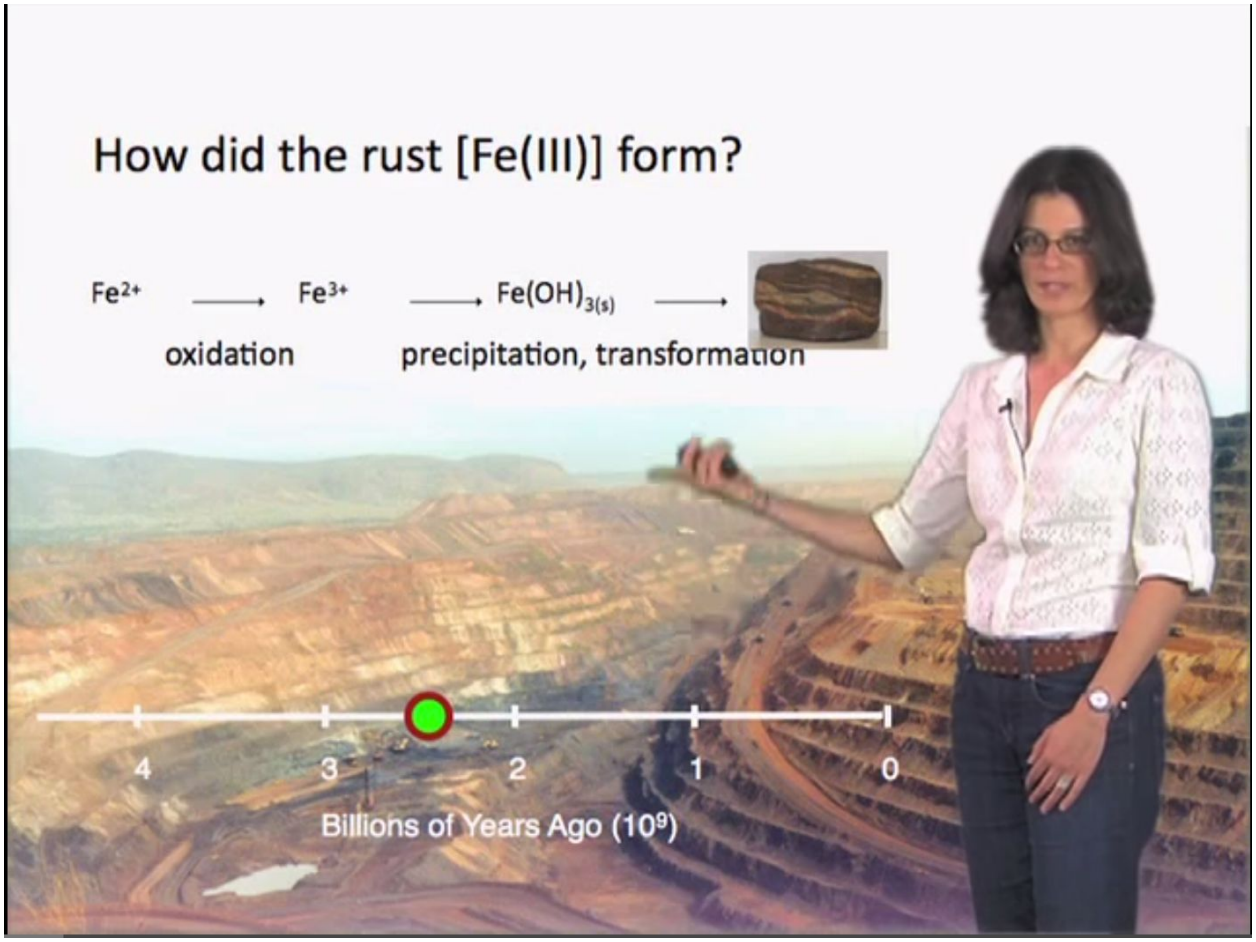
1. Keywords and Terms

microorganisms, evolution, diversity, metabolism, geochemistry

2. Lecture Notes

In this talk, Dr. Dianne Newman gives an overview of microbial diversity and evolution. According to Dr. Newman, there are at least 4 important points that must be considered when investigating microorganisms and their history.
Microbes are ancient, numerous, ubiquitous, and diverse.



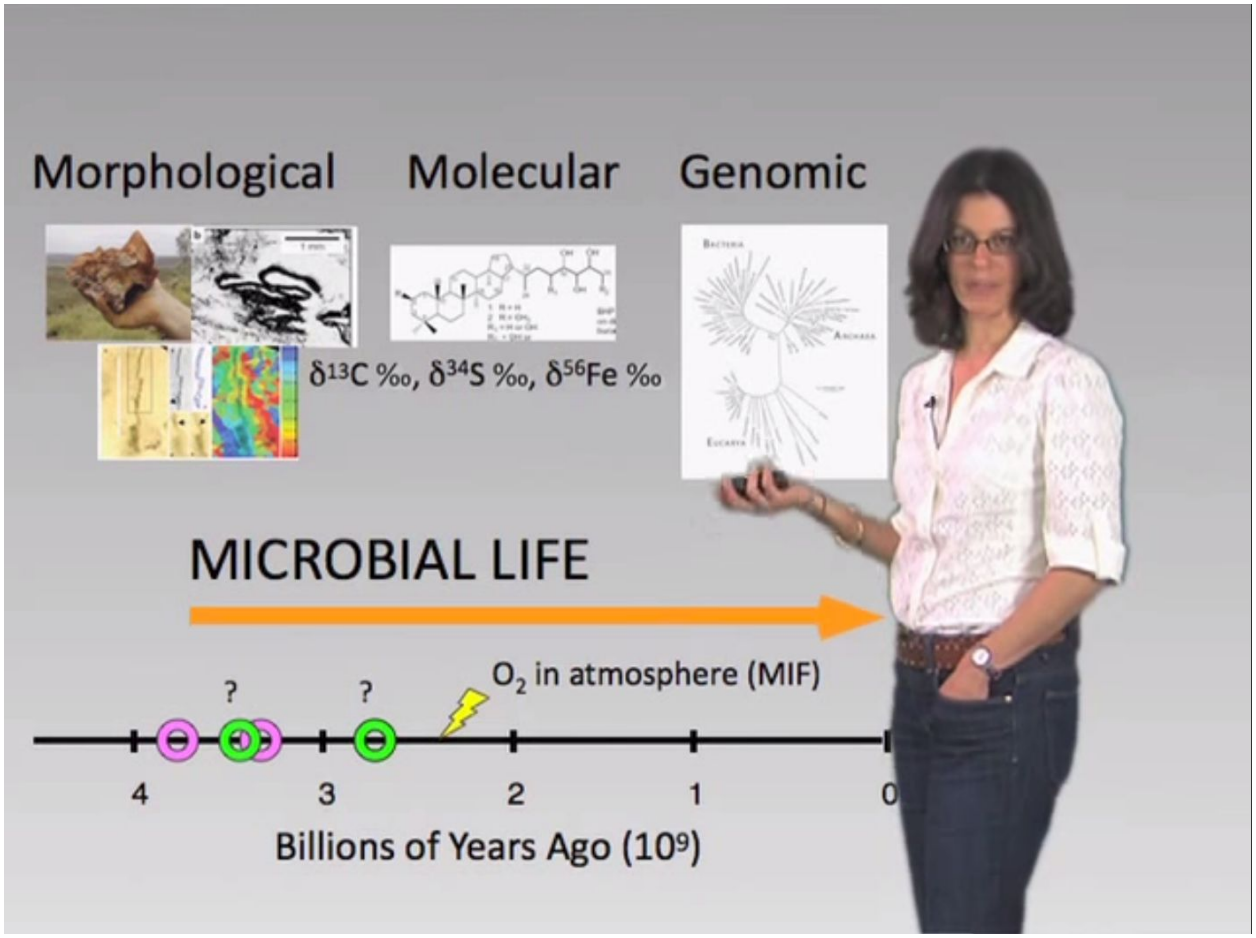
Fossils provide us evidence of ancient, often now extinct, life, and by doing so record the history of the evolution of metabolism.

In rocks from 3.8 billion years ago, ore deposits are present that are records of microbial activities that literally transformed the planet.

When asking how the rust in banded iron formaCons formed, two possible scenarios are considered for the initial oxidation step:

- Scenario 1: anoxygenic photosynthesis
- Scenario 2: oxygenic photosynthesis

Future experiments to help distinguish between the two scenarios will shed light on the evolution of oxygenic photosynthesis.



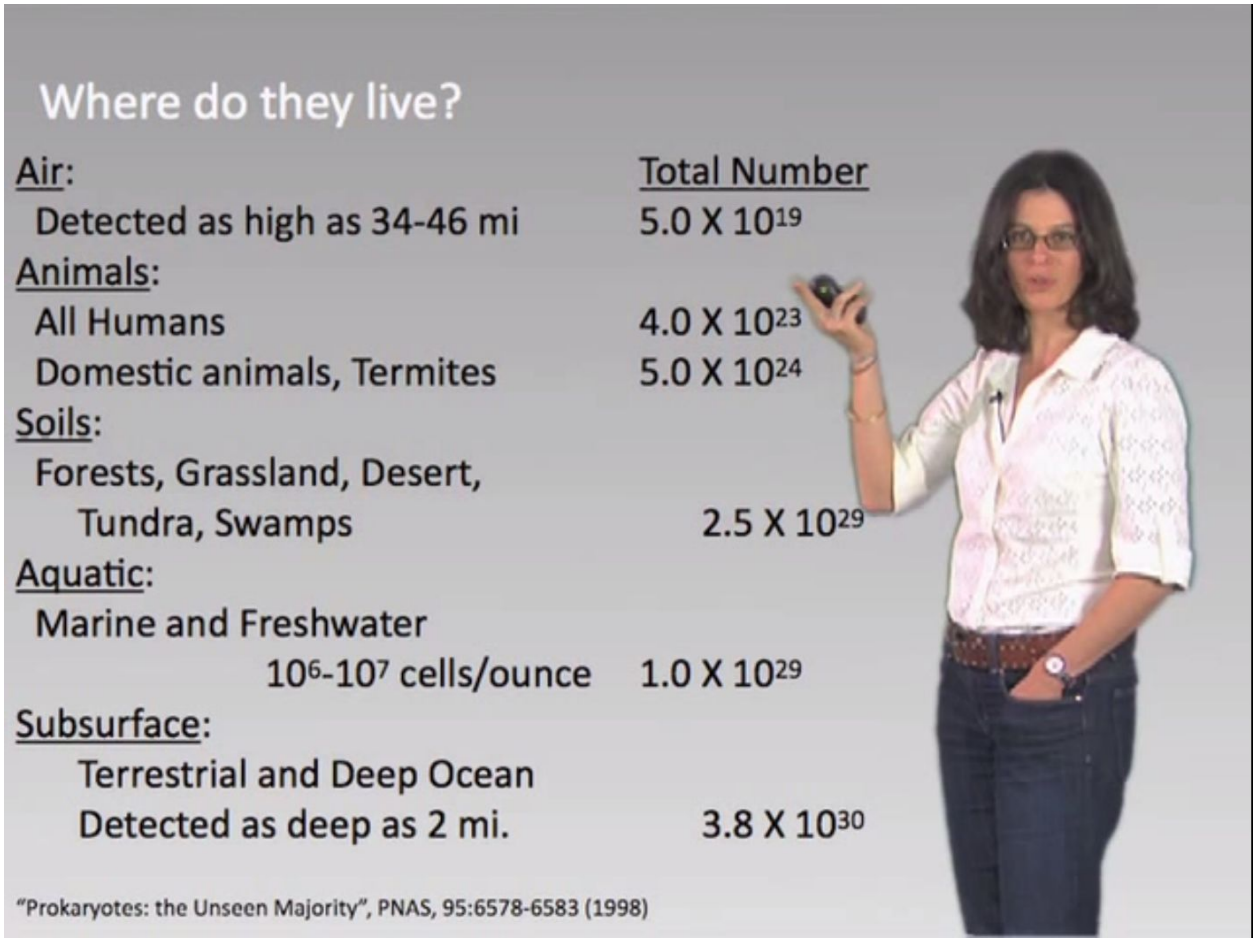
So, what experiments can be performed to decipher when particular microbial metabolisms evolved and what types they were?

There are 3 primary ways to gain insight into microbiology of the past: morphological, molecular, or genomic biosignatures.

Particular rock forms have been interpreted as vestiges of ancient life, but it is difficult to come up with robust biomarkers based on morphology.

Molecular biomarkers (i.e. ratio of isotopes in a sample) have traditionally been considered the best way to gain more specific insights into ancient metabolisms.

Now, genes are also thought of as fossils, and genomics help piece together the relatedness of evolution of enzymatic functions and metabolisms.

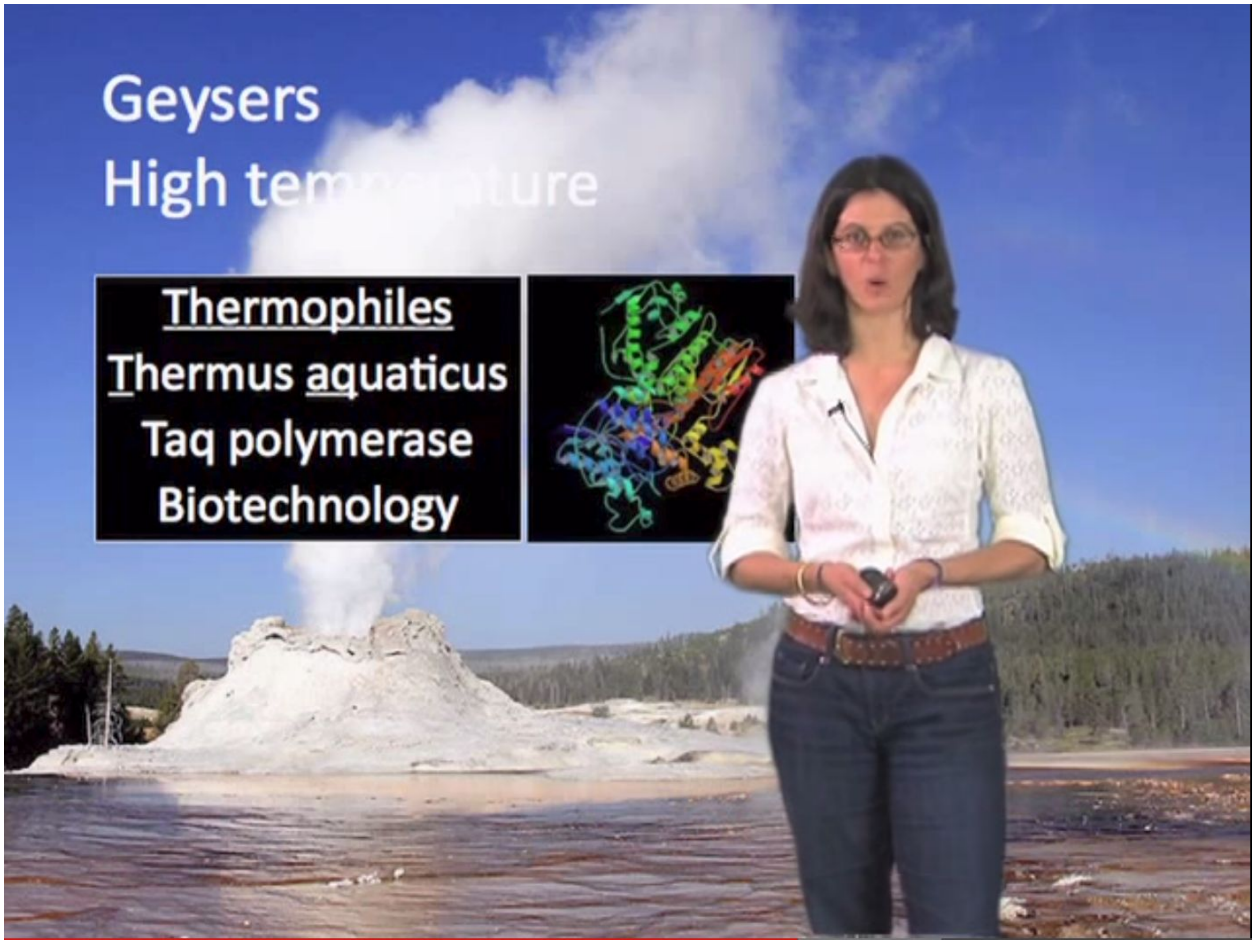


Microbes are incredibly numerous, with the worldwide population estimated to be ~ 5 * 10^{30} cells.

Microbes live everywhere from the depths of the ocean to the outer reaches of Earth's atmosphere.

Microbial life is most active in the subsurface, both in terrestrial and oceanic environments.

Humans can even be thought of as walking microorganisms, as bacterial cells outnumber human cells by ~ 10:1 in the body.

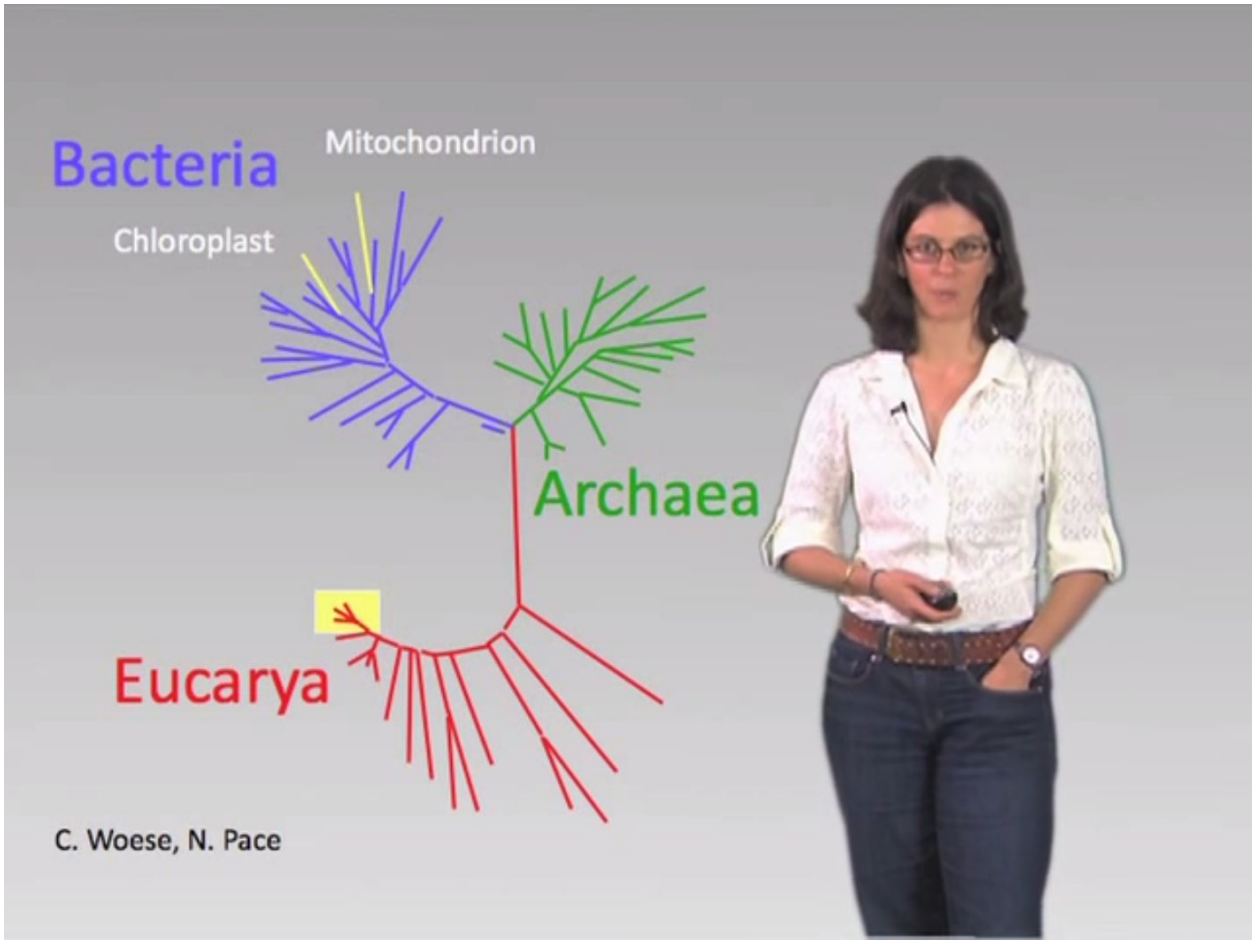


Microbes are utterly ubiquitous and can be found living in essentially every environment imaginable.

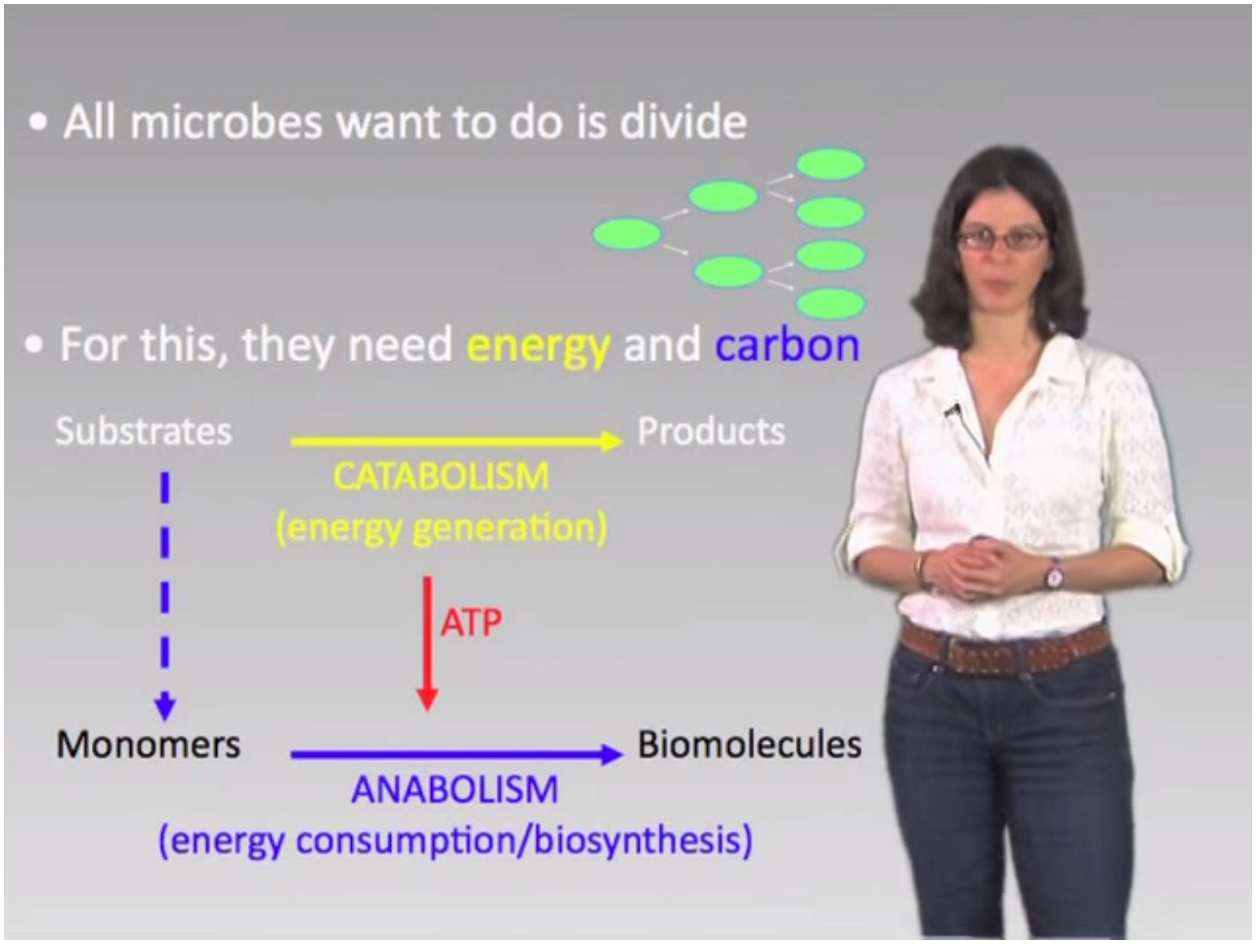
Microbe-rich environments, such as pond scum and soil, provide a diversity of metabolism that has helped shape the chemistry of earth for billions of years.

Microbes are also capable of living in more extreme environments, such as extreme acidity or pressure, where the microorganisms again play a significant role in shaping the local chemistry.

‘Extremophile’ microbes have been used to derive enzymes, such as Taq polymerase, whose unique properties makes them ideal for use in research and industrial settings.



The diversity of microbial life is evident at various levels of characterization.
Microbes encompass significant Phylogenetic diversity.
Phylogenetic trees map evolutionary distance between different organisms using ribosomal RNA (a universal and highly conserved protein) as a molecular comparison between domains of life.
With the use of more sophisticated cell biology techniques, microbes are being found to have almost boundless morphological diversity in addition to Phylogenetic diversity.



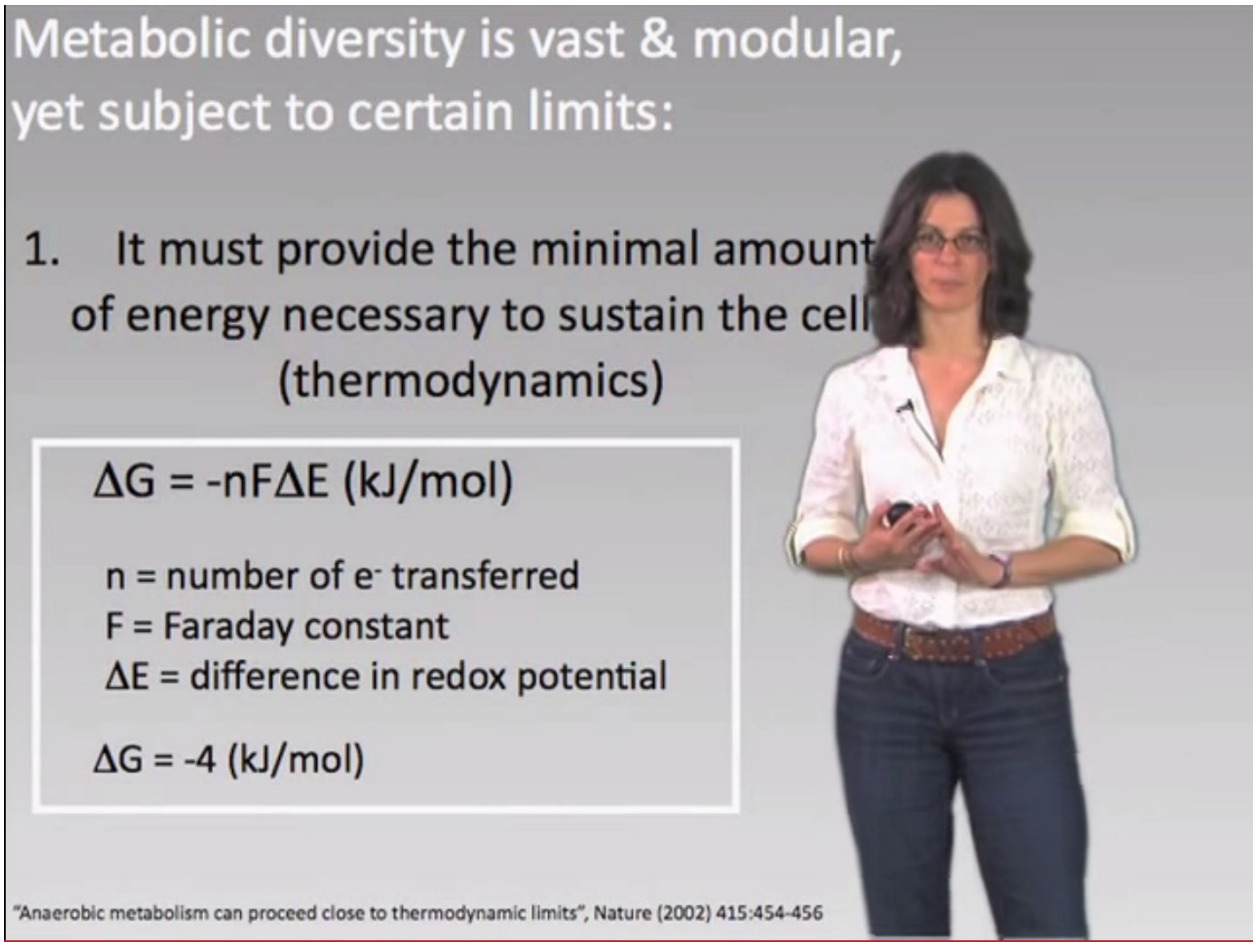
Microbes have evolved an amazing array of chemistry to collect the energy and carbon that they need to divide.

Catabolic processes generate energy by turning substrates (chemical or sunlight) into products.

Anabolic processes consume energy to turn carbon, often in monomeric form, into more complex biomolecules.

The energy “currency” used in these exchanges is adenosine triphosphate (ATP).

ATP can be made through substrate-level Phosphorylation or oxidative phosphorylation.



While microbial metabolic diversity may seem boundless, it does have certain limits. Microbial metabolism must provide the minimal amount of energy necessary to sustain the cell.
Microbial metabolism must utilize substrates that are bioavailable.
The substrates and products of microbial metabolism must not be toxic.

3. Review Questions

1. When did oxygenic photosynthesis evolve?
    a. 2.5 billion years ago
    b. 4 billion years ago
    c. 1 billion years ago
    d. The date is still unknown
2. What are the 3 primary ways to gain insight of microbiology of the past?

3. What is the ratio of bacterial cells to human cells in the body?

    a. 100:1
    b. 10:1
    c. 1:1
    d. 1:10

4. What cellular component's sequence is used to develop phylogenetic trees?

5. _____ utilize chemical substrates for catabolism, and _____ utilize sunlight as the substrate for catabolism.

6. What are the limits on microbial metabolic diversity?

4. Answers to Review Questions

1. d. The date is still unknown

2. Morphological, molecular, and genomic biosignatures.

3. b. 10:1

4. ribosomal RNA

5. Chemotrophs ; phototrophs.

6. It must provide the minimal amount of energy necessary to sustain the cell. The substrates must be bioavailable. The substrates or products must not be toxic.

5. Discussion Questions

1. Compare and contrast the insights into ancient microbial metabolism given by morphological, molecular, or genomic biosignatures. Is one the best?

2. How might our growing knowledge of the human 'microbiome' (there are actually more bacteria cells than human cells in our body) change how we treat disease?

3. This lecture presents many examples of communities of microorganisms living within more advanced multicellular organisms. Why do you think that this is such a common theme in nature?

4. After hearing about the diverse and ubiquitous nature of microbial life on Earth, are you more or less confident that extraterrestrial life exists?

6. Answers to Discussion Questions

1. Morphological biosignatures are characteristic rock forms that are classified visually, and they were the original biosignatures used to decipher microbiology of the past. Morphological biosignatures can be concretely linked to the rocks they are found in, which themselves can be dated. While particular rock forms have been interpreted as vestiges of ancient life, it is a challenge to come up with distinct, robust biosignatures simply based on morphology. Molecular biosignatures can be inorganic or organic. The most commonly measured form of inorganic biosignatures is the ratio of isotopes in a sample, whereas organic biosignatures are often molecular fossils of lipids, which degrade very slowly. The molecular biosignatures left in the rock can help researchers decipher whether the remaining chemistry in the rock was originally carried out uniquely by some biological process. Genomic biosignatures are their own class of organic molecular biosignatures in which genes are thought of as fossils. The genomic record has helped establish the diversity of life on Earth, and also aids our understanding of the relatedness of the evolution of enzymatic functions and metabolisms; however, genomic biosignatures don't give dates to specific evolutionary events, but can only help indicate relative order. While Dr. Newman indicates that molecular biosignatures may be the best way to gain more specific insight into different types of ancient metabolisms, combining all these types of biosignatures will likely be necessary to solve remaining open questions in the realm of metabolic evolution.

2. There are 10 bacterial cells for each human cell in the body, and we are only just beginning to appreciate the implications of this astounding statistic. Drugs exert their therapeutic effects by engaging a target, or sometimes multiple targets; however, almost all drugs have known 'off-target' effects that can cause adverse effects. The balance between on-target and off-target effects will determine whether a molecule is an effective, safe drug, and this balance must be considered on a drug-by-drug basis. Recently, the pharmaceutical industry has also realized that the on-target vs. off-target balance for a given drug must also be considered on a patient-to-patient basis due to genetic differences. Moving forward, potential drugs will need to be checked for desired and undesired effects on microbial targets, and this information will need to be incorporated with knowledge of patient-specific microbial populations. The list of targets that must be considered for on-target and off-target drug effects will likely need to be expanded to include all microbial target, which will be completely paradigm shifting for the drug industry.

3. There are numerous examples in nature of microorganisms thriving within larger multicellular organisms, and the simplest explanation for this pattern is that both sides of the relationship are imbued with a competitive advantage. Cooperative relationships between microorganisms and multicellular organisms are abundant in nature and come in many forms, and these mutualistic or symbiotic relationships tend to be evolutionarily conserved. The initial impetus for the establishment of these relationships can be traced to the fact that microorganisms were a foundational component of Earth's environment well before the emergence of multicellular organisms. As multicellular life evolved, it is conceivable that nature found it 'easier' to simply incorporate microbes with well established functions into emerging multicellular hosts than it would have been to evolve entirely new capabilities. The 'space' of microbial chemistry available to evolving multicellular hosts was almost unimaginably large, so it makes sense that there are now so many examples of mutually beneficial relationships between microbes and multicellular organisms.

4. First off, there is definitely not a right answer to this question. In one sense, the discovery of microorganisms thriving in a diverse range of extreme Earth environments supports the idea that life could have developed in other extreme conditions elsewhere in the universe. These examples of life adapting to hostile, extreme environments show the remarkable extent of life's colonization of Earth, and it can be argued that this suggests that extraterrestrial life likely exists. It is difficult to consider how the diversity and ubiquity of microbial life on Earth could be used as an argument against the existence of extraterrestrial life, but someone surely could argue the point. The fact that all life discovered on Earth utilizes the same basic genetic code could be pointed to as evidence that life has only arisen once, and that it was only able to do so under particular Earth-specific conditions.

7. Explain or Teach These Concepts to a Friend

1. Explain how phylogenetic trees are constructed
2. Explain the difference between a symbiotic, mutualistic, and parasitic relationship
3. Compare and contrast oxygenic and anoxygenic photosynthesis

8. Questions for Discussion Paper

Discussion Paper:

For the paper: Wu, C.-H., Bialecka-Fornal, M., and Newman, D.K. (2015). Methylation at the C-2 position of hopanoids increases rigidity in native bacterial membranes. Elife: 4:e05663.

1. How might the 2-methylation of hopanoids permit adventitious adaptation?
2. Why are the findings of previous hopanoid studies not likely to reflect the true roles of hopanoids in vivo?
3. What evidence suggests that methylation at the C-2 position of hopanoids promotes fitness under environmental stress?
4. What are the challenges to interpreting the meaning of any ancient molecular fossil?

9. Answers to Questions for Discussion Paper

1. For 2-methylation of hopanoids to permit adventitious adaptation, the modification must confer some sort of selective advantage to the host organism. One possibility is that 2-methylation of hopanoids provides biosynthetic precursors for further modification into novel components for signaling pathways. The likelihood of such a scenario is supported by the fact that sterols, which are often seen as the eukaryotic hopanoid analogues, serve as biosynthetic precursors for steroid hormones that play important signaling roles. Another possibility is that 2-methylated hopanoids may fulfill the geometry requirements of curve membranes and facilitate cell division. In this case, 2-methylation would clearly give a selective advantage because it would allow for more rapid and effective cell division. Given our still fairly limited knowledge of the effects of 2-methylation of hopanoids, it is conceivable that 2-Me-hopanoids bestow selective advantage through an entirely unanticipated mechanism.
2. Previous biophysical studies have provided insights into the functions of hopanoids, but it is unclear how relevant their findings are. Prior studies utilized model membranes as the context within which to study the role of hopanoids and the effect of 2-methylation. The lipid compositions and concentrations used in previous studies have not been consistent and do not necessarily provide a good model of in vivo cellular systems. If it is the case that the effect of hopanoid 2-methylation depends on membrane context, which is suggested by the findings of the Wu et al. paper, then it would be necessary for in vitro studies to mimic cellular composition as closely as possible. Furthermore, sterols, the eukaryotic hopanoid equivalent, are known to differently modulate membranes depending on their lipid context. This indicates that in vitro studies will only be able to shed light on the in vivo role of

hopanoid 2-methylation if there are able to fully replicate the relevant in vivo lipid environments.

3. Prior to the Wu et al. paper, there was already multiple lines of evidence suggesting that 2-Me-hopanoids promote fitness under environmental stress. 2-Me-hopanoids are enriched in the outer membrane of akinetes, the stress resistant cell type of the cyanobacterium Nostoc punctiforme. A stress-responsive pathway has been shown to upregulate the HpnP methylase in *R. palustris*, and this enzyme is responsible for methylating hopanoids at the C-2 position. Spikes in the 2-Me-hopane index (ratio of methylated hopanes to total hopanes) throughout time are correlated with oceanic anoxic events, which signify environmental stress. Lastly, in modern environments, the capacity for 2-Me-hopanoid production correlates with organisms, metabolisms, and environments that favor symbiotic plant-microbe interactions. The finding of Wu et al. that hopanoids differentially modify native membrane rigidity as a function of their methylation state supports the interpretation that 2-Me-hopane levels in fossils may reflect episodes of particular environmental stresses.

4. Molecular fossils hold rich details about early life, past environments, and evolution, but precautions must be taken in their interpretation. For a given molecular fossil to be interpreted, at least three criteria must be met. First, potential ancient sources for the fossilized compounds must be identified, with the necessity for unambiguous chemical parity between modern and ancient sources. Second, it is important to understand whether particular environmental conditions regulate the production of variants of the molecular fossil. Finally, it is critical to identify specific biological functions for the modern counterparts of molecular fossils, and then to evaluate whether the role of the molecular class has been conserved through evolution.