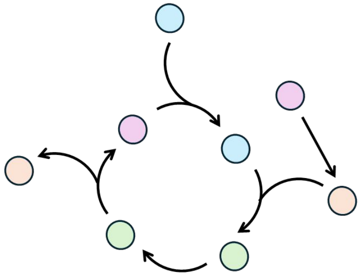
DARES Focus Area 1:

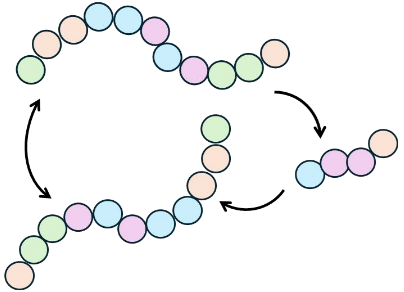
Protometabolism and synthesis / function of macromolecules in planetary environments

Primary: Laurie Barge
Secondary 1: Saurja DasGupta
Secondary 2: Laura Rodriguez

Focus Area #1: Overview

Origin of life (OoL) is a crucial part of the definition of astrobiology (the study of the **origin**, evolution, distribution, future of life).





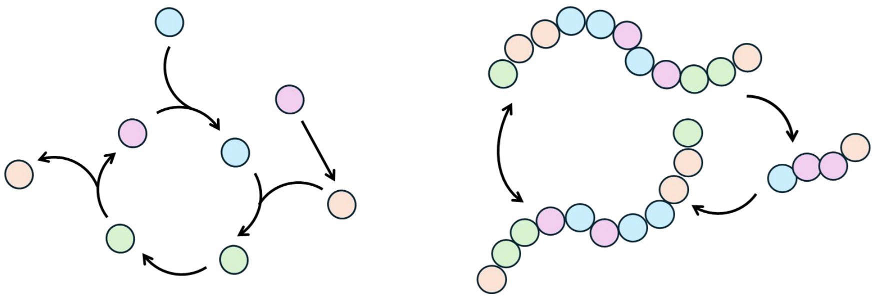
Studies of the origin of life on Earth focus on the co-evolution of **primitive metabolic systems** and **informational and functional polymers**. The next leap forward will be understanding how these two components co-evolved and were integrated, within primordial cell-like **compartments ('protocells')** at the origins of life.

OoL is essential to astrobiology:

- *Evolution of life:* OoL studies can help illuminate the role of the geological environment in driving Earth's emergence of life, and connect properties of our extant biosphere to how life began. How would this be different on other planets; to what degree does the properties of extant life reflect the mechanisms by which it originated?
- *Distribution of life:* OoL is a prerequisite for life to exist on a world - therefore OOL research is critical for identifying where life might arise in the universe. The lack of OoL could explain why a planet may be habitable but yet uninhabited. OoL also represents complex abiotic chemistry which can be useful for mission / instrument efforts to detect biosignatures.

Focus Area #1: Overview

Origin of life (OoL) is a crucial part of the definition of astrobiology (the study of the **origin**, evolution, distribution, future of life).



Studies of the origin of life on Earth focus on the co-evolution of **primitive metabolic systems** and **informational and functional polymers**. The next leap forward will be understanding how these two components co-evolved and were integrated, within primordial cell-like **compartments ('protocells')** at the origins of life.

Importance to the community:

- The last decade has seen many advances in OoL research, for example advances in studies of:
    - Prebiotic polymers (for example, depsipeptides which may have been a prebiotic precursor to peptides)
    - Proto-metabolic networks, where abiotic (sometimes mineral-driven) organic reactions of small molecules can approach aspects of the earliest metabolic pathways or cycles.
    - Laboratory evolution of catalytic nucleic acids (especially, ribozymes that carry out RNA assembly reactions) including those with non-natural building blocks (XNAzymes)
    - Integrating compartmentalization with functional biopolymers and protometabolic reactions in the form of lipid vesicle- and coacervate-based protocells.

Focus Area #1: Why this Focus Area now?

Previously in the 2015 Astrobiology strategy – the OoL focus was “Goal 2: Synthesis and function of macromolecules in the origin of life”

Now:
The new Astrobiology Strategy can expand to incorporate the state of the art in OoL research: from protometabolism and macromolecules in prebiotic chemistry and the emergence of life, the emergence of compartmentalization, and including latest research in the field that represents the role of the environment in directing prebiotic chemistry.

RNA studies:

- Recent work has achieved a significant integration between functional RNAs and protocells
- We have seen major strides in the creation of non-natural nucleic acids with diverse functions
- Studies of the catalytic capabilities of RNA have expanded significantly in the last ten years.

Proto-metabolism studies:

- The past decade has shown many advances in recapitulating protometabolic cycles and pathways in a prebiotic setting
- Studies of the effects of minerals or metals on prebiotic reactions have helped to narrow down the role of the environment or geochemical influence on the emergence of life, which is important for understanding whether OOL is likely to have occurred on other worlds.

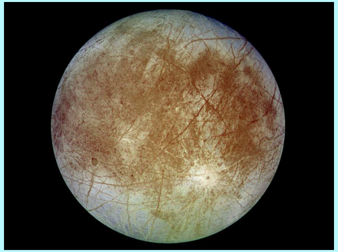
Focus Area #1: Why this Focus Area now?

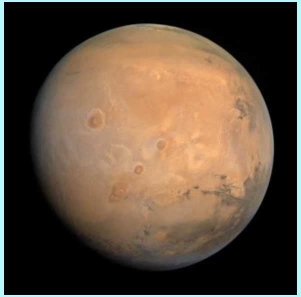
For astrobiology missions that search for life: going forward we need a stronger consideration of OoL on other worlds even if that OoL is not Earth-like – and need to consider OoL potential for mission development / life detection

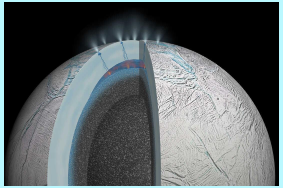
OoL research is necessary in order to provide astrobiology motivation for exploration of other worlds with life detection missions, because **OoL is a prerequisite for life and may be more restrictive than habitability.**

For example, it is important for ocean world missions to determine whether life could emerge on an ocean world with no land (even if we learn that land was involved with the OoL on Earth) in order to justify looking for life on Europa or Enceladus.

The reason for this is because OoL is not guaranteed to occur, and we are still in the process of understanding how constrained or rare OoL is. What are the bottlenecks? Can a planet be 'stuck' in a prebiotic state? The probability of OoL is unknown but is a crucial part of biosignature strategy.







Focus Area #1: Why this Focus Area now?

Increase synergy with exoplanet discoveries: OoL research can help us understand conditions that might enable the OoL on planets in general – building an OoL metric for the universe analogous to the definition of habitability (conditions that enable life to exist).

This concept of “OoL potential of a world / environment” needs more refinement in the coming decade so that it can be most useful to astrobiology missions interested in searching for life.

OoL research can go beyond Earth-centric studies, and explore not just “what happened to start our biosphere” but “what are other ways life could start in the universe”

Studies in this area can make “OoL potential” metrics that are relevant to all types of worlds not just Earth, and in a paradigm that does not make too many assumptions about specific planetary environments (since the conditions that environments contain is an active area of discovery in Earth & planetary science)

This idea is going to be very relevant to exoplanet studies as increasing numbers of terrestrial exoplanets are discovered

Focus Area #1: Why this Focus Area now?

Synergy with planetary science missions. The increased emphasis on OoL in the 2023-2032 "Origins, Worlds, Life" Planetary Science & Astrobiology decadal survey underlines how OoL is an even more significant area for astrobiology / planetary science than in the last decade.

OoL was always a big part of astrobiology but - given the increased OWL focus on prebiotic chemistry themes - in this new astrobiology strategy we should make sure there's even more emphasis on OoL's connections to planetary science missions.

OWL - OoL relevant examples

- **Q9.1 What Were the Conditions and Processes Conducive to the Origin and Early Evolution of Life on Earth, and What Do They Teach Us About the Possible Emergence and Evolution of Life on Other Worlds?**
- **Q9.1c What Is the Boundary Between Abiotic and Biotic Phenomena and How Does That Boundary Change with Earth's Overall Geochemical and Biological States?**
- **Q11.1 Path to Biogenesis: What Is the Extent and History of Organic Chemical Evolution, Potentially Leading Toward Life, in Habitable Environments Throughout the Solar System?**

Examples:

- Prebiotic chemistry research can help to define the abiotic / biotic threshold for instrument measurements; providing an example of complexity beyond what we observe in Earth samples

- (Related to FA #2): What abiotic chemistry could emerge on a world with no life; what complex molecules could form from organic chemical evolution on solar system bodies e.g. Ceres, Mars, ocean worlds?

FINDINGS

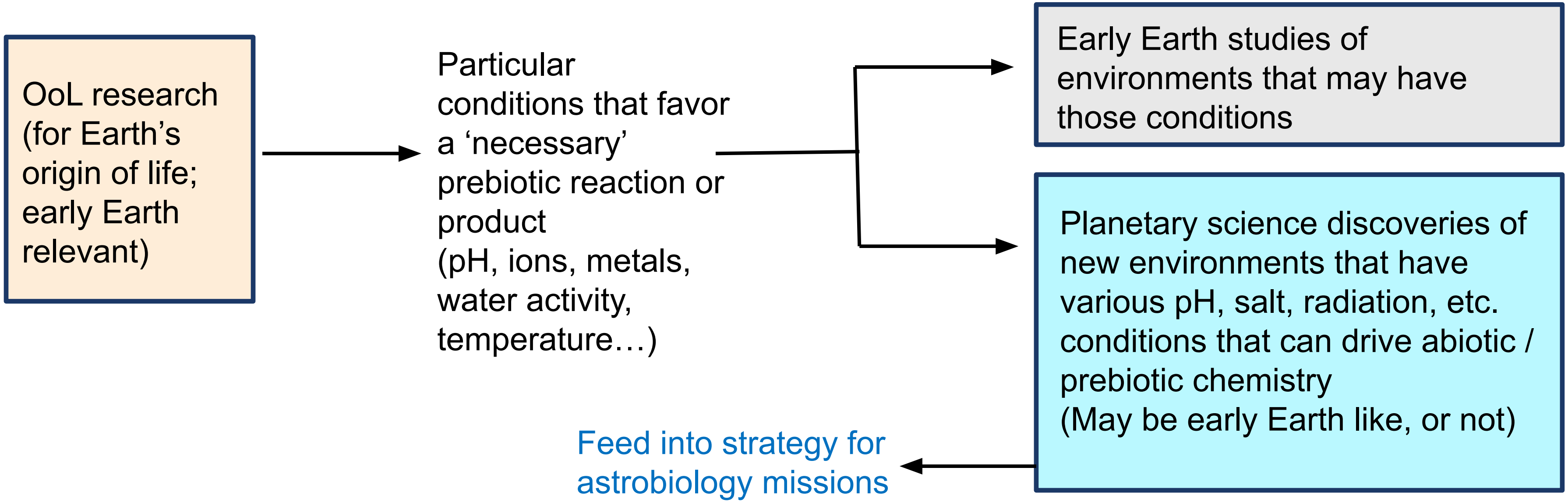
Finding 1: For origin of life studies to best benefit astrobiology missions, it is essential to link prebiotic reactions to planetary **conditions** that favor them (e.g., a pH requirement). However it is most helpful not to link prebiotic reactions overly to specific **environment types** (e.g., lake, vent), as we do not yet know all the conditions a particular kind of environment contained on the early Earth, or which environments might host which specific conditions on other planets.

Finding 2: Studies of organic chemical evolution can help elucidate conditions conducive to the emergence of life on other planetary bodies, are critical for ascertaining the abiotic baseline of different worlds, and can elucidate how life as we don't know it could begin. (Relates to Focus area #2)

Finding 3: Environments / conditions that favor the origin of life (as we know it) may be more constrained than those that are habitable. This is why a habitable world might be uninhabited - because for life to exist, the origin of life must also have occurred.

FINDINGS

Finding 1: For origin of life studies to best benefit astrobiology missions, it is essential to link prebiotic reactions to planetary **conditions** that favor them (e.g., a pH requirement). However it is most helpful not to link prebiotic reactions overly to specific **environment types** (e.g., lake, vent), as we do not yet know all the conditions a particular kind of environment contained on the early Earth, or which environments might host which specific conditions on other planets.



FINDINGS

Finding 2: Studies of organic chemical evolution can help elucidate conditions conducive to the emergence of life on other planetary bodies, are critical for ascertaining the abiotic baseline of different worlds, and can elucidate how life as we don’t know it could begin. (Relates to Focus area #2)

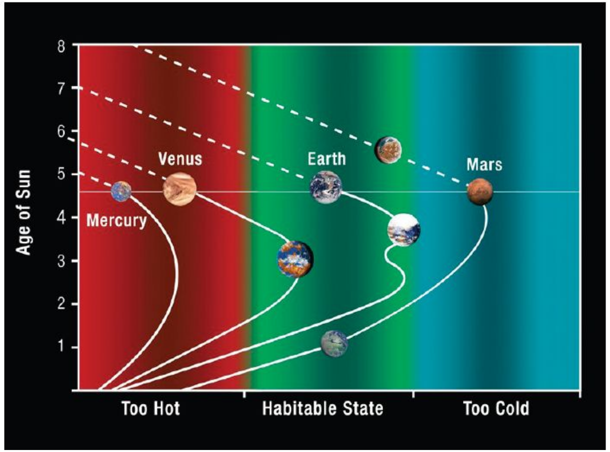
- Abiotic chemistry is also essential to studies of the OoL. Abiotic chemistry can be “prebiotic”, aka leading to processes that drive the OoL, or it can just be complex / abiotic but still an important part of understanding the prebiotic landscape.

- Life as we don’t know it : OoL studies can help inform what alternative biospheres might look like, alternate energy utilization strategies, biochemistries, etc. If life inherited some of its functions from its origin, then “OoL as we don’t know it” is also essential to understanding the diversity of biological systems that might exist elsewhere.

FINDINGS

Finding 3: Environments / conditions that favor the origin of life (as we know it) may be more constrained than those that are habitable. This is why a habitable world might be uninhabited - because for life to exist, the origin of life must also have occurred.

This is related to the 2019 NASEM astrobiology strategy finding:
“Finding: Planetary conditions that may be habitable today or in the past are not necessarily the same as those that could have fostered the emergence of life. Both are important for the search for life.”



NASEM 2019 Astrobiology Strategy
“Dynamic Habitability”

OoL can be weaved into this concept of dynamic habitability: when is a world able to support the OoL; how does this intersect with habitability over time; and what does this mean for life detection?

Focus Area #1: uncertainties, areas for more discussion

- Prebiotic chemistry represents an example of highly complex / advanced abiotic chemistry and it is also not guaranteed that a prebiotic system must ever transition to actual life if there are bottlenecks. So, **how should we best incorporate prebiotic / abiotic complex chemistry into the life detection focus areas, and mission / technology discussions?**

- **How best to distribute studies of Early Earth, LUCA, and early life evolution on Earth in the next astrobiology strategy?** Some of LUCA and early Earth studies are OoL relevant and might make sense in FA #1. But other LUCA and early Earth / early life studies are more “evolution” of life and should be represented in the Focus Area about evolution of biospheres.

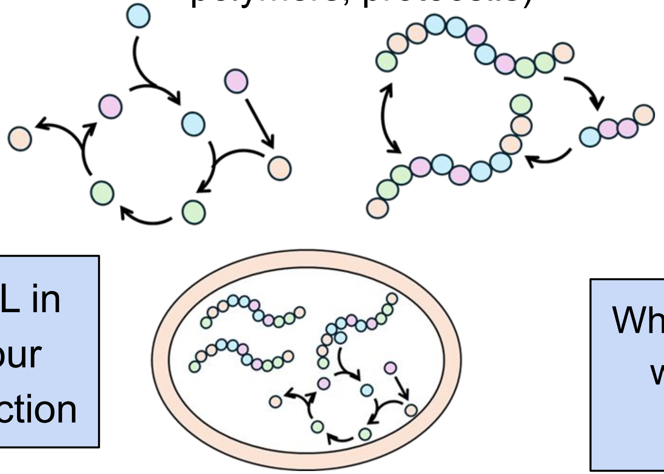
Focus Area #1: other astrobiology connections

What conditions were necessary for OoL on Earth? What are the implications of this for other planets?

To what extent is the evolution of a biosphere related to how that life originated?

How common or rare is OoL in the universe? → defines our general chances of life detection

OOL research (protometabolism, polymers, protocells)



Prebiotic chemistry helps to define the abiotic / biotic threshold for instrument measurements

For ocean worlds – can OoL occur on worlds with no land?

Exoplanets – search for terrestrial planets with OoL potential

What can chemistry of uninhabited worlds (Ceres, Titan) teach us about prebiotic chemistry?

Focus Area #1: Take Aways

Origin of life (OoL) is a crucial part of the definition of astrobiology (the study of the **origin**, evolution, distribution, future of life in the universe).

The last decade has seen many exciting advances in OoL research (proto-metabolism, polymer studies, compartmentalization) and these directions should be woven into the astrobiology strategy.

OoL research is going to be increasingly important for planetary science and astrophysics missions going forward: we can increase synergy with exoplanet science as terrestrial planets continue to be discovered; and we should work to connect OoL with planetary science / solar system missions (both those that have life detection aspects, and those that have organic chemical evolution aspects)

OoL research can advance our knowledge of ‘life as we don’t know it’, and also, provide valuable perspective for narrowing down where life should exist elsewhere.