



Written by Brittanie McQueen  
Resofield Inc, PBC

# Conditions of Emergence: The Role of Energy, Medium, and Cyclical Constraint in the Formation of Complex Systems

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## Abstract

The emergence of life and complex systems is not random but contingent upon specific environmental and physical conditions. This paper examines three foundational requirements observed across origin-of-life research and systems science: (1) a continuous energy input, (2) a medium that enables interaction, and (3) cyclical or constraining processes that organize variation. Using early Earth as a primary case study, with emphasis on solar energy, aqueous environments, and lunar-driven tidal cycles, this paper proposes that emergence occurs when energy flows through a medium under structured variation. While grounded in physical science, this framework may also provide a useful lens for understanding pattern formation in broader complex systems.

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## 1. Introduction

The origin of life on Earth represents one of the most significant questions in science. While substantial research has focused on biochemical pathways and environmental conditions, less attention has been given to identifying general structural requirements that enable emergence.

Rather than focusing solely on specific chemical pathways, this paper examines the broader conditions under which complexity arises. It proposes that emergence consistently depends on the interaction of three elements:

energy input, a material medium, and cyclical or constraining processes

This framework is explored through early Earth conditions and evaluated for its applicability to complex systems more generally.

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## 2. Energy as a Driver of Complexity

Life requires a sustained source of energy to drive chemical reactions and maintain non-equilibrium conditions.

On early Earth, primary energy sources included:

- solar radiation from the Sun
- geothermal energy from hydrothermal systems
- electrical energy (e.g., lightning)

Solar energy, in particular, played a dominant role in shaping Earth's surface environment. It drives atmospheric circulation, temperature gradients, and ultimately photosynthesis—the foundation of modern ecosystems.

From a thermodynamic perspective, life exists far from equilibrium and depends on continuous energy flow to maintain structure and organization (Schrödinger, 1944; England, 2013).

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## 3. Water as a Medium for Interaction

Water is widely regarded as essential for life due to its unique chemical properties:

- it acts as a universal solvent
- it allows molecular mobility and interaction
- it stabilizes complex molecules such as proteins and nucleic acids

Early life is hypothesized to have originated in aqueous environments, including:

- hydrothermal vents
- shallow pools
- tidal zones

These environments enable repeated molecular interaction, increasing the probability of complex chemical organization (Deamer & Dworkin, 2005; Lane, 2015).

Thus, water serves as a medium through which energy-driven processes can produce increasingly complex structures.

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## 4. Cycles and Environmental Constraints

While energy and medium are necessary, they are not sufficient on their own. Emergence also requires structured variation, often provided by cyclical processes.

Key early Earth cycles include:

- day–night temperature fluctuations
- seasonal variation
- wet–dry cycles
- tidal cycles influenced by the Moon

These cycles create:

- repeated opportunities for chemical reactions
- concentration and dilution of molecules
- environmental constraints that select for stability and persistence

For example, wet–dry cycles have been shown to facilitate polymer formation, a key step in the origin of life (Deamer et al., 2019).

Similarly, tidal forces—driven by the gravitational interaction between Earth and the Moon—may have contributed to early environmental variability critical for molecular evolution.

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## 5. The Sun–Earth–Moon System

The emergence of life on Earth can be better understood by considering the interaction of the Sun, Earth, and Moon as a coupled system.

- Sun → energy input
  - Provides continuous radiation that drives atmospheric and chemical processes
- Earth → medium
  - Provides liquid water and chemical environments for interaction
- Moon → cyclical modulation
  - Contributes to tidal forces and long-term stabilization of Earth's axial tilt

The Moon's gravitational influence produces tidal cycles, which generate dynamic coastal environments. These environments are hypothesized to have supported prebiotic chemistry by creating repeated cycles of concentration and reaction.

Additionally, the Moon stabilizes Earth's axial tilt, reducing extreme climate variability and contributing to long-term environmental stability (Laskar et al., 1993).

Together, this system illustrates how energy, medium, and cycles interact to create conditions conducive to emergence.

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## 6. A General Framework for Emergence

From the preceding analysis, a general pattern can be identified:

Emergence occurs when energy flows through a medium under cyclical or constraining conditions

This framework can be interpreted as:

- Energy → drives change and enables reactions
- Medium → allows interaction and transformation
- Cycles / constraints → organize variation and enable stability

This pattern is consistent with observations in:

- non-equilibrium thermodynamics
- self-organizing systems
- biological evolution

Importantly, this framework does not propose a universal law, but rather a recurring structural relationship observed across complex systems.

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## 7. Discussion

The implications of this framework are twofold:

1. Emergence is not purely stochastic; it depends on identifiable conditions
2. Cycles and constraints are as critical as energy and matter in enabling complexity

Traditional models often emphasize chemical composition or energy sources in isolation. However, without structured variation—introduced through cycles and constraints—complex systems may fail to stabilize or evolve.

This suggests that the search for life beyond Earth should consider not only energy and water, but also the presence of dynamic environmental cycles.

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## 8. Conclusion

The emergence of life on Earth can be understood as the result of interacting conditions rather than isolated factors.

Energy input, a medium for interaction, and cyclical or constraining processes together enable the formation of complex systems.

This framework provides a grounded, interdisciplinary perspective that integrates physics, chemistry, and planetary science, while offering a basis for further exploration into the conditions necessary for emergence in both natural and artificial systems.

This paper expands on an idea I explored more informally here:

[What Conditions Does Life Actually Need?](#)

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## References

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