Biomolecules and Prebiotic Information Systems

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Prebiotic information systems exist in three forms: analog, hybrid, and digital. The Analog Information System (AIS), manifested early in abiogenesis, was expressed in the chiral selection, nucleotide formation, self-assembly, polymerization, encapsulation of polymers, and division of protocells. It created noncoding RNAs by polymerizing nucleotides that gave rise to the Hybrid Information System (HIS). The HIS employed different species of noncoding RNAs, such as ribozymes, pre-tRNA and tRNA, ribosomes, and functional enzymes, including bridge peptides, pre-aaRS, and aaRS (aminoacyl-tRNA synthetase).

coevolution of biomolecules and information systems

1. Introduction

One of the most enduring mysteries of modern science has been the origin of life on Earth and its information systems. The clues for the origin of life come from astrobiology, the early Earth, biochemistry, molecular biology, and laboratory experiments. Because information permeates life, any study of abiogenesis must address the origin of biological information systems as well. Information is one key property, perhaps the key property, that separates life from nonlife. It is the logic of life that makes a living system more organized, ordered, and complex. The way the information flows through and between biomolecules and cells is unique in nature [1]. Earth's biological and informational evolution are intertwined and inseparable. Life and its information systems form a closely coupled entity, influencing each other in a complex feedback loop. Life is an information processing system that can store and process information necessary for its growth, metabolism, and self-reproduction. Life transmits heritable information to its progeny and undergoes Darwinian evolution. This is how life begets life and creates biodiversity. The information does not change whether it is encoded in nucleic acids or proteins: information is substrate independent. The concept of information is central to a meaningful description of biological processes, but its status as a physical entity remains elusive. Darwinian evolution tends to lead to an increase in information content and a decrease in randomness during abiogenesis.

It is generally believed that two kinds of biological information, analog and digital, emerged about four billion years ago during abiogenesis [1][2][3]. De Duve [4] viewed pathways of life as both determinate and directional, where the vector of evolution lies in the structural, informational, and catalytic molecules. It is well-known in biochemistry that biomolecules are very sensitive to the changes in their environment—changes in pressure, temperature, pH concentration, ATP concentration, molecular count, etc. These elements are in constant flux, enabling and forcing biomolecules to be a dynamic and flexible system to adapt and respond quickly to the changes in the environment.

Biomolecules have a reconfigurable internal structure that enables them to change in the best way to face the environment and solve the problem. They must also deal with limited resources and time. Analog computing is better suited for such a situation. It requires fewer parts, fewer resources, less energy, and less time than digital computing. Therefore, biomolecules—large and small—are analog machines with their own embedded analog information system. They perform analog computing. It is very instructive to understand the nature of a molecular analog information system. An analog information system's internal structure is not fixed like a digital information system. Instead, an analog information system's internal structure is reconfigurable and solves the problem (or situation) by changing its structure in a suitable way [5].

Each molecular unit has its own information and information system, meaning that 'the information comes from within'. In other words, the molecular units may receive signals from the environment, but they contain their own information to process the signal. Each molecular unit performs its function using its own structure, information, and the information-function interdependency rules [6]. Researchers assert that information contained and used by various molecular units is in the form of four major categories—time, space, control, and energy. The time information consists of temporal elements such as rate, clock, etc. The space information consists of spatial elements such as pattern, proximity, attractiveness, sequence, etc. The control information includes signal and regulatory elements. The energy information includes potential energy, charge differences, etc. The molecular units use, consume, and produce this information.

Molecular information systems began early in the interstellar medium in the building blocks of life, which were delivered to young Earth by meteorites during the heavy bombardment period. Analog information systems appeared first in abiogenesis, followed by digital information systems. These two information systems, operating separately and in close cooperation, streamlined the prebiotic synthesis from chaotic molecular assemblages and provided directionality to the flow of information.

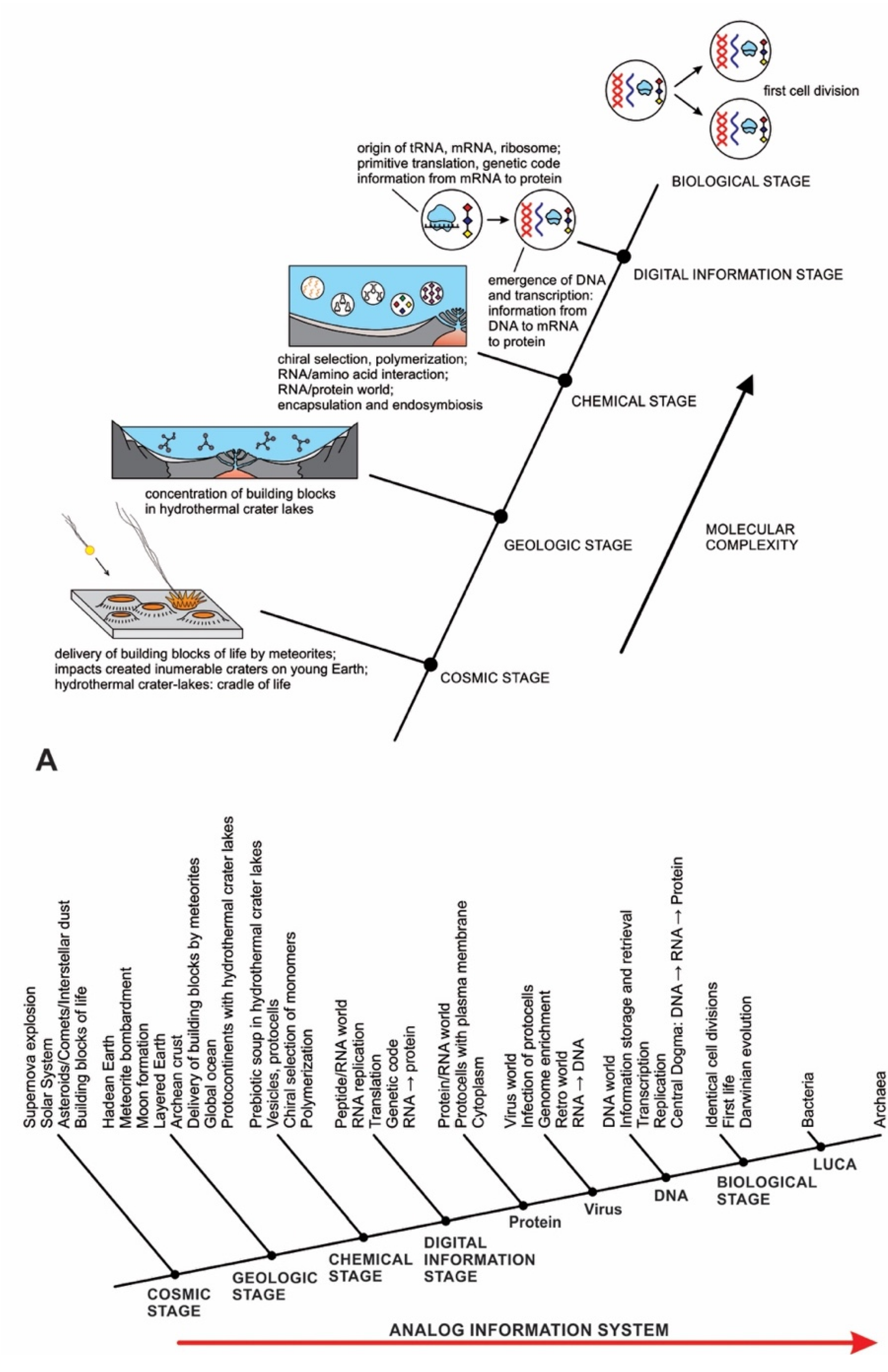
A Digital Information System (DIS) includes the genetic information built slowly by the coded sequences of nucleotides in mRNA in the peptides/RNA world. It is a latecomer in abiogenesis. Digital information is discrete and is encoded in linear sequences of nucleotides in mRNA and later in DNA. The sequence of nucleotides in mRNA and DNA determines the information content of the molecules. Digital information processing in translation, genetic code, and transcription are familiar to researchers. Less appreciated are the analog aspects of information processing.

The dichotomy between analog and digital information is not clear-cut. Researchers show that between analog and digital, there is a transitional information stage, which researchers call the Hybrid Information System. The identification of these three systems helps researchers to document the coevolution of biomolecules and information systems during abiogenesis. These new approaches to prebiotic information systems are necessary for understanding the origin of life.

Living things collect and store information from the environment for survival. They adapt to their environment by using the information to harvest energy and evade equilibrium. Life is characterized and sustained by several information-rich biological processes that govern cellular functions and significantly contribute to its overall complexity. Information is an important prerequisite for the onset of life. Prebiotic information would undoubtedly have been much simpler and was built incrementally over time.

2. Hierarchical Origin of Life and Information Systems

In previous publications, researchers discussed the hierarchical origin of life in a bottom-up approach [7][8][9]. In researcher's model, life arose about four billion years ago through five hierarchical stages of increasing molecular complexity in terrestrial hydrothermal crater basins, the likely cradle of life. These stages are cosmic, geologic, chemical, digital information, and biological. **Figure 1** shows a schematic model for the origin of life and its information systems. An information-processing application to the origin of life is more robust than the purely chemical evolution of life.


first cell division
BIOLOGICAL STAGE
origin of tRNA, mRNA, ribosome; primitive translation, genetic code information from mRNA to protein
emergence of DNA and transcription: information from DNA to mRNA to protein
DIGITAL INFORMATION STAGE
chiral selection, polymerization; RNA/amino acid interaction; RNA/protein world; encapsulation and endosymbiosis
CHEMICAL STAGE
concentration of building blocks in hydrothermal crater lakes
GEOLOGIC STAGE
MOLECULAR COMPLEXITY
delivery of building blocks of life by meteorites; impacts created inumerable craters on young Earth; hydrothermal crater-lakes: cradle of life
COSMIC STAGE
A
Supernova explosion
Solar System
Asteroids/Comets/Interstellar dust
Building blocks of life
Hadean Earth
Meteorite bombardment
Moon formation
Layered Earth
Archean crust
Delivery of building blocks by meteorites
Global ocean
Protocontinents with hydrothermal crater lakes
Prebiotic soup in hydrothermal crater lakes
Vesicles, protocells
Chiral selection of monomers
Polymerization
Peptide/RNA world
RNA replication
Translation
Genetic code
RNA → protein
Protein/RNA world
Protocells with plasma membrane
Cytoplasm
Virus world
Infection of protocells
Genome enrichment
Retro world
RNA → DNA
DNA world
Information storage and retrieval
Transcription
Replication
Central Dogma: DNA → RNA → Protein
Identical cell divisions
First life
Darwinian evolution
Bacteria
Archaea
LUCA
BIOLOGICAL STAGE
DNA
Virus
Protein
DIGITAL INFORMATION STAGE
CHEMICAL STAGE
GEOLOGIC STAGE
COSMIC STAGE
ANALOG INFORMATION SYSTEM

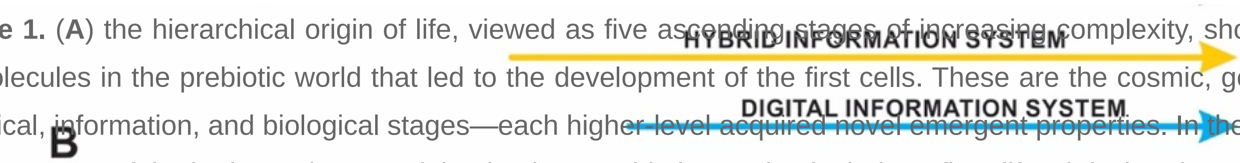


Figure 1. (**A**) the hierarchical origin of life, viewed as five ascending stages of increasing complexity, showing the biomolecules in the prebiotic world that led to the development of the first cells. These are the cosmic, geological, chemical, information, and biological stages—each higher-level acquired novel emergent properties. In the dark hot environments of hydrothermal crater lake basins, prebiotic synthesis led to first life. (**B**) the three ways of processing information in life are analog, hybrid, and digital, shown against the hierarchy of life.

The origin of life is a unique product of two worlds: the building blocks of life from space and abiogenesis in the cradle of researcher's planet. In the *cosmic* stage, a star explosion nearby the solar nebula cast the building blocks of life into interstellar space. During the Late Heavy Bombardment period, the comets and carbonaceous chondrites produced within that nebula transported water and organic molecules to young Earth. Carbonaceous chondrites, when impacted by young Earth, delivered a suite of building blocks of life and water that triggered abiogenesis. Meteorite impacts shipped these ‘seeds’ of life to young Earth along with water. Asteroid collisions created numerous hydrothermal crater lakes on the Archean crust, crafting cradles for prebiotic chemistry.

References

1. Walker, I.W.; Davies, P.C.W. The algorithmic origin of life. J. R. Soc. Interface 2012, 10, 20120869.
2. Koonin, E.V. Why the central dogma: On the nature of the great biological exclusion principle. Biol. Dir. 2015, 10, 52.
3. Baum, D.A.; Lehman, N. Life’s late digital revolution and why it matters for the study of the origins of life. Life 2017, 7, 34.
4. de Duve, C. Singularities: Landmarks on the Pathways of Life; Cambridge University Press: New York, NY, USA, 2005.
5. Ulman, B. Analog Computing. Oldenbourg Wissenschaktsverlag. 2013. Available online: https://ereader.perlego.com/1/book/654438/20 (accessed on 20 December 2021).
6. Kunnev, D. Origin of life: The point of no return. Life 2020, 10, 269.
7. Chatterjee, S. A symbiotic view of the origin of life at hydrothermal impact crater lakes. Phys. Chem. Chem. Phys. 2016, 18, 20033–20046.
8. Chatterjee, S. From Stardust to First Cells—The Origin of Life. In Encyclopedia of Geology, 2nd ed.; Alderton, D., Elias, S.A., Eds.; Academic Press: London, UK, 2021; Volume 3, pp. 555–560.
9. Chatterjee, S. The hydrothermal impact crater lakes: The crucibles of life’s origin. In Handbook of Astrobiology; Kolb, V.M., Ed.; CRC Press: Boca Raton, FL, USA; Taylor & Francis: Boca Raton, FL, USA, 2018; pp. 265–295.