*Interdisciplinary Description of Complex Systems* 14(3), 314-321, 2016

# A ROADMAP FOR A COMPUTATIONAL THEORY OF THE VALUE OF INFORMATION IN ORIGIN OF LIFE QUESTIONS

**Soumya Banerjee**

Broad Institute of MIT and Harvard
Cambridge, USA

Ronin Institute
Montclair, USA

Complex Biological Systems Alliance
North Andover, USA

DOI: 10.7906/indecs.14.3.4
Regular article

*Received:* 19 March 2016.
*Accepted:* 31 May, 2016.

## ABSTRACT

Information plays a critical role in complex biological systems. Complex systems like immune systems and ant colonies co-ordinate heterogeneous components in a decentralized fashion. How do these distributed decentralized systems function? One key component is how these complex systems efficiently process information. These complex systems have an architecture for integrating and processing information coming in from various sources and points to the value of information in the functioning of different complex biological systems. This article proposes a role for information processing in questions around the origin of life and suggests how computational simulations may yield insights into questions related to the origin of life.

Such a computational model of the origin of life would unify thermodynamics with information processing and we would gain an appreciation of why proteins and nucleotides evolved as the substrate of computation and information processing in living systems that we see on Earth. Answers to questions like these may give us insights into non-carbon based forms of life that we could search for outside Earth.

We hypothesize that carbon-based life forms are only one amongst a continuum of life-like systems in the universe. Investigations into the role of computational substrates that allow information processing is important and could yield insights into: 1) novel non-carbon based computational substrates that may have "life-like" properties, and 2) how life may have actually originated from non-life on Earth. Life may exist as a continuum between non-life and life and we may have to revise our notion of life and how common it is in the universe. Looking at life or life-like phenomenon through the lens of information theory may yield a broader view of life.

## KEY WORDS

origin of life, artificial life, life-like systems, information theory, reaction-diffusion systems

## CLASSIFICATION

JEL: O10, O35

*Corresponding author, $\eta$: soumya.banerjee@ronininstitute.org; +1 505 277 3122;
Department of Computer Science, 1, University of New Mexico, Albuquerque, NM, 87131, USA

## INTRODUCTION

Information plays a critical role in complex biological systems. Complex systems like immune systems and ant colonies co-ordinate heterogeneous components in a decentralized fashion. How do these distributed decentralized systems function? How is the immune system able to find rare amounts of pathogens in infections and mount a response to eliminate them without any centralized control? One key component is how these complex systems efficiently process information. Previous research highlights the need for:

1) Specialized physical structures (called lymph nodes) that facilitate the otherwise serendipitous encounter of rare pathogen-specific immune system cells with their fated pathogens
2) Signals (chemicals called chemokines) that help in detecting pathogens and guiding immune system cells towards them, and
3) Associated infrastructure like receptors on cell membranes and signalling networks ("hardware") for interpreting these diverse cues and orchestrating a response that is both decentralized and robust [1-4]. These complex systems have an architecture for integrating and processing information coming in from various sources and points to the value of information in the functioning of different complex biological systems. This paper proposes a role for information processing in questions around the origin of life.

It has been suggested previously that information processing capabilities distinguish life from other so-called non-living matter [5, 6]. Information processing is one amongst many key ingredients for life. We propose computationally testing the value of information in origin of life questions using spatially explicit models.

Living systems are complex adaptive systems. Physical space plays an important role in life. Specialized structures, for example cell membranes ("hardware"), serve both as an effective compartment as well as to integrate information ("software") from extra-cellular and intracellular sources. The software and hardware of life have co-evolved to achieve efficient information processing.

Investigations novel computational substrates that allow information processing is important and could yield insights into novel non-carbon based computational substrates that may have "life-like" properties [7, 8]:

1) systems of oil droplets exhibit life-like properties: they are able to replicate and consume energy [9, 10]. Oil droplets also have been engineered to have compartments and derive propulsive power from an external energy source [11],
2) stars have an energy source and compartments. Disturbances from stars that undergo supernova at the end of their lifetimes lead to star formation in neighbouring galactic clouds and nebulae (which is conceptually similar to replication),
3) spherical droplets, self-propelled colloids [12] and motile crystals [13] move about in remarkably life-like ways. Microscopic beads of artificially engineered materials exhibit swarming behaviour under the influence of an electric field [12],
4) reaction-diffusion systems like the Belousov-Zhabotinsky (B-Z) reaction are chemical oscillators and also display complex properties reminiscent of life (Figure 1).Reaction-diffusion systems have been exploited to construct computational systems called "reaction-diffusion computers" [14, 15],
5) quantum systems are capable of transferring information like spin and have "life-like" properties [16], and
6) finally weather systems like hurricanes persist for long times [7]; even weather systems on other planets like the Great red spot on Jupiter has persisted for a very long time and displays complex behavior.

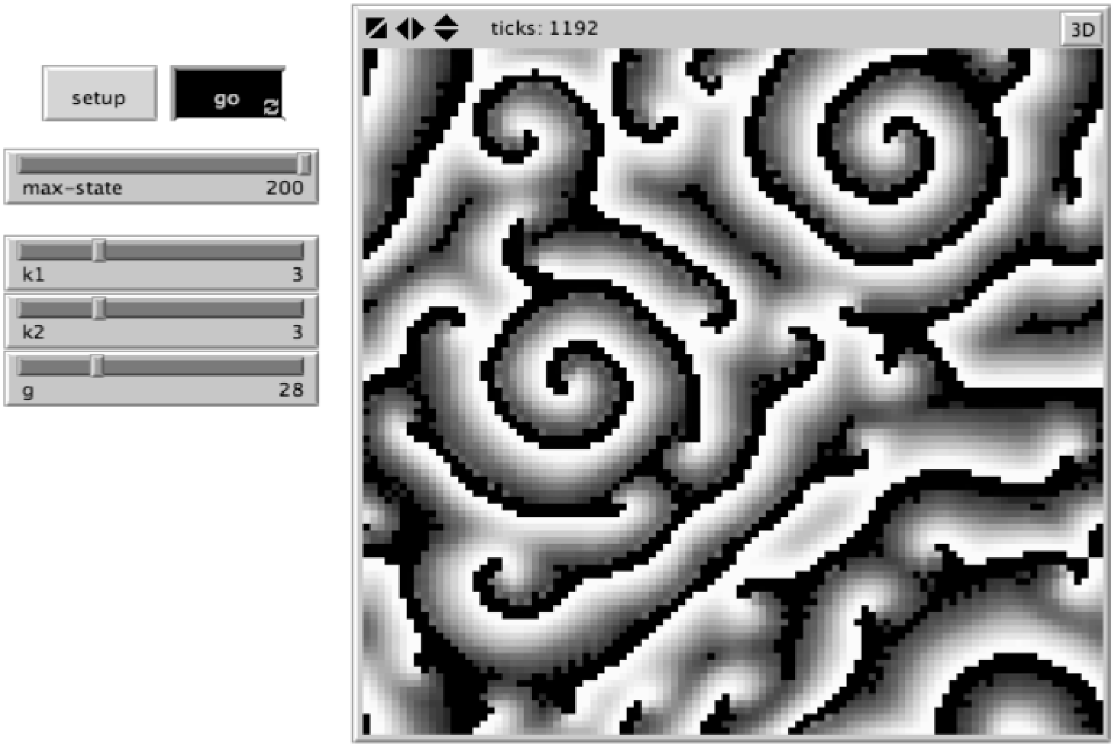


**Figure 1.** Screenshot from the NetLOGO simulation tool for the Belousov-Zhabotinsky (B-Z) reaction showing wave like patterns that persist [17, 18].

Our ultimate aim is to develop a framework for an information theoretic definition of life that is independent of the subjective definitions of only carbon-based life. What life-forms could conceivably arise in our known universe subject to the known laws of physics? We hypothesize that carbon-based life forms are only one amongst a continuum of life-like systems in the universe.

Investigations into the role of computational substrates that allow information processing is important and could yield insights into novel non-carbon based computational substrates that may have "life-like" properties [7, 8] and even how life may have actually originated from non-life on Earth.

## AN INFORMATION THEORY OF THE ORIGIN OF LIFE

We hypothesize that the key components of an information-theoretic view of life are:

1) information processing (software),
2) information storage (memory),
3) the physical substrate (hardware) and the role of physical space,
4) information transfer (across both physical space and time),
5) persistence of information, and
6) energy and thermodynamics (energetic limits on information processing and life).

We expand on the possible properties of the substrate that allows information processing, information storage and information propagation:

1) Information processing. Systems of oil droplets are capable of complex behavior like replication [9, 10, 19]. Computational simulations of these systems may shed light on whether these systems would be capable of information processing. The system can be evolved using a genetic algorithm. The artificial "genome" would be the size of the droplet, its speed, charge on its surface, ambient air pressure and temperature. One test for

information processing would be verifying if an oil droplet can divide based on whether there are two other droplets in contact with it (this would function like a primitive AND gate). Such a simple model of information processing may allow for the emergence of co-operative behavior that would enhance survival. Similar approaches have been used in reactiondiffusion systems without compartments [14, 15].

2) Information storage and memory. Information storage and memory are critical components of life and life-like systems. We suggest testing if systems of oil droplets would be capable of storing information persistently. These systems are capable of a limited form of heredity [8] and some limited form of memory [10]. We suggest incorporating other factors in order to ensure that these systems remember their shape and have persistence. These factors would be additional physical structures (resembling a cellular cytoskeleton that would provide aphysical scaffold on which to store information) and compartments that would allow richer dynamics within droplets to be coupled to cues outside the surface (similar to biological cell compartments and cell membranes).
3) The physical substrate (hardware) and the role of physical space. Physical space and structures play a role in facilitating information processing. We suggest testing if there are special shapes of oil droplets that may allow efficient information processing and propagation.

   In the immune system, dendritic cells with a large surface area and protrusions specialize in information transfer (by maximizing the surface area over which interactions occur and the number of interactions with other cells). Computational simulations may yield oil droplets with specialized shapes that are optimal for information transfer.

   The immune system also has physical structures called lymph nodes that are information processing centers: the facilitate the interaction and information transfer between immune system cells and pathogens. Additional constraints in the oil droplet simulation that allows for physical structures ("artificial lymph nodes") would also facilitate information propagation between different types of oil droplets that are also spatially separated (discussed below).
4) Information transfer and propagation in space and time. Simulate propagation of information and the evolution of co-operative behavior. We recommend computationally simulating other "species": smaller droplets that can propagate and relay information faster (like small molecules called chemokines in the immune system that are specialized for carrying information). It would also be fruitful to investigate the effect of introducing these "species":
   a) specifically testing if this would allow for the emergence of co-operative behavior and co-operative information processing amongst different droplets,
   b) testing if faster propagation of information is good for the whole system since beneficial mutations can spread fast but so can deleterious mutations, and
   c) testing the role of both short-range and long-range interactions in spreading innovative mutations (where mutations would be changes to the virtual "genome" mentioned earlier).
5) Persistence of information. A strong requirement for life and life-like systems is that information should persist. This would result in selection of attributes that may also be heritable. We note that conceptually, selection and heredity, and memory and persistence of information, are similar and point to the survivability and robustness of these systems.Thinking about the B-Z system we note that certain model parameters that lead to persistent wave-like patterns (Figure 1) may have a selective advantage, i.e. these behavior or parameters may become dominant in a population. Computational exploration of the

parameter space of these systems may give insights into if these systems are capable of long-term persistence and if there are particular behaviours or model parameters that have a “selective” advantage.

6) Energy: energetic limits on information processing. We suggest computationally simulating the energetic demands of systems like oil droplets. The simulations would have an explicit energy term, which would be varied over a realistic range. The effects of changing energy on the resulting dynamics and information processing capabilities of the system can then be readily observed.

   Such a computational model should allow us to test:

   a) if features of information processing should emerge faster, and
   b) the rate of information processing itself is faster based on the energy or temperature of the system.

There may be an optimal range of energy and temperatures for information processing to be viable: too cold and molecular motion would cease; too hot and critical physical structures capable of sustaining information processing would dissociate faster than they would arise. Thermodynamics is thought to play an important role in the evolution of life and life-like systems [8, 20]. Simulations like these may help eventually unify thermodynamics and information processing under a common theory.

## DISCUSSION

One key characteristic of life is the ability to process information. We suggest a framework and roadmap of computational experiments that will give insights into the role of information processing and storage in non-living systems and life-like systems. This may yield insights into how the transition from non-life to life occurred on Earth and give insights into questions like:

1) How common is life in the universe? If information is fundamental to life [5, 6] then energetic limits on information processing and a physical substrate capable of supporting and storing information may be vital constraints on life. Research into an information theory of life would yield an understanding of the energetic limits on life and life-like systems with implications for how common life is in our current energy rich universe. If life exists as a continuum between non-life and life, we may have to revise our notion of life and how common it is in the universe.
2) What fundamental principles explain the emergence of life? Information and thermodynamics maybe some of the key principles that explain the emergence of life. This paper suggests a framework that would enhance our understanding of how the interaction of information processing with thermodynamics can lead to life-like properties.

## CONCLUSION

Information processing is fundamental to life. A computational model of the origin of life would unify thermodynamics with information processing. Such a model would enhance our understanding of how the interaction of information processing with energy and thermodynamics may lead to life-like properties. This would also lead to an understanding of the energetic limits on information processing in life-like systems. We hypothesize that the key components of an information theory of life should include:

1) information processing (software),
2) information storage (memory),

3) the physical substrate (hardware) and the role of physical space,
4) information transfer (across both physical space and time),
5) persistence of information (selection and heredity), and
6) energy and thermodynamics (energetic limits on information processing and life).

Such a theory would give us an appreciation of why proteins and nucleotides evolved as the substrate of computation and information processing in living systems that we see on Earth. Are other computational substrates viable and energetically feasible? What forms of substrates capable of information processing could conceivably exist? Answers to questions like these may give us insights into non-carbon based forms of life that we could search for outside Earth.

This could also conceivably give us an understanding of the viability of information processing on exoplanets outside the habitable zone and the kinds of "biospheres" that might be able to sustain such life or life-like systems. We note that our approach is complementary to a non-von Neumann computing paradigm that has been investigated in the context of artificial life and biologically inspired computing [21].

Based on our co-existence and co-evolution on Earth for millions of years we have been conditioned to believe that life should be similar to what we observe on this planet. Mathematical principles coupled with a mathematical definition of life, rather than observational evidence based on what we see on Earth, would better prepare us for life or life-like forms that may exist elsewhere in the Universe.

Life as we know it is based on the computational substrate of chemical bonds, e.g. protein interaction networks are based on the principle of shape recognition and chemical bonds: proteins bind to the surface of other proteins based on shape complementarity and thereby setup complex information cascades. Arthur C. Clarke wrote imaginatively about complex intelligent life arising from electrical currents in superconductors on a cold seemingly lifeless planet [22]. He imagined the electrical currents as being only slowly attenuated (due to superconductivity) and ultimately leading to neuron-like networks capable of intelligence. He proposed a completely different computational substrate: electrical currents in superconductors. The story challenges our imagination and although unlikely to be feasible,challenges the very notions of life.

Our ultimate aim is to develop a framework for an information theoretic definition of life that is independent of the subjective definitions of only carbon-based life. What life forms could conceivably arise in our known universe subject to the known laws of physics? We hypothesize that carbon-based life forms are only one amongst a continuum of life-like systems in the universe.

Life may exist as a continuum between non-life and life and we may have to revise our notion of life and how common it is in the universe. Looking at life or near-life through the lens of information theory may yield a broader view of the origin of life that the general public may find of interest.

## ACKNOWLEDGEMENTS

This work was inspired by the short-story "Crusade" written by Arthur C. Clarke. The author is also deeply indebted to Dr. Mark Tanaka for discussions that inspired this paper.

## REFERENCES

[1] Banerjee, S. and Moses, M.: *Scale Invariance of Immune System Response Rates and Times: Perspectives on Immune System Architecture and Implications for Artificial Immune Systems*. Swarm Intelligence **4**(4), 301-318, 2010, http://dx.doi.org/10.1007/s11721-010-0048-2,

[2] Banerjee S.; Levin D.; Moses, M.; Koster F. and Forrest, S.: *The Value of Inflammatory Signals in Adaptive Immune Responses*.
Proceedings of the 10th International Conference on Artificial Immune Systems, Springers, 2011,
[3] Moses, M.; and Banerjee, S.: *Biologically Inspired Design Principles for Scalable, Robust, Adaptive, Decentralized Search and Automated Response (RADAR).*
Proceedings of the 2011 IEEE Conference on Artificial Life, 2010,
http://dx.doi.org/10.1109/ALIFE.2011.5954663,
[4] Banerjee, S.; *Scaling in the Immune System*. Ph.D. Thesis.
University of New Mexico, Albuquerque, 2013,
[5] Adami, C.: *Information-theoretic considerations concerning the origin of life.*
Origins of Life and Evolution of the Bioshperes **45**, 309-317, 2015,
http://dx.doi.org/10.1007/s11084-015-9439-0,
[6] Imari Walker, S. and Davies, P.C.W.: *The algorithmic origins of life*.
Journal of the Royal Society Interface **10**(79), 2013,
http://dx.doi.org/10.1098/rsif.2012.0869,
[7] McGregor, S. and Virgo, N.: *Life and its close relatives.*
Advances in Artificial Life **5778**, 230-237, 2011,
[8] Froese, T.; Virgo, N. and Ikegami, T.: *Motility at the origin of life: Its characterization and a model.*
Artificial Life **20**(1), 55-76, 2014,
http://dx.doi.org/0.1162/ARTL_a_00096,
[9] Gutierrez, J.M.P.; Hinkley, T.; Taylor, J.W.; Yanev, K. and Cronin, L.: *Evolution of oil droplets in a chemorobotic platform*.
Nature Communications **5**, **No.** 5571, 2014,
http://dx.doi.org/10.1038/ncomms6571,
[10] Hanczyc, M. *Droplets: Unconventional Protocell Model with Life-Like Dynamics and Room to Grow.*
Life **4**(4), 1038-1049, 2014,
http://dx.doi.org/10.3390/life4041038,
[11] Banno, T. and Toyota, T.: *Molecular System for the Division of Self-Propelled Oil Droplets by Component Feeding*.
Langmuir **31**(25), 6943-6947, 2015,
http://dx.doi.org/10.1021/acs.langmuir.5b00904,
[12] Bricard, A.; Caussin, J.B.; Desreumaux, N.; Dauchot, O. and Bartolo, D.: *Emergence of macroscopic directed motion in populations of motile colloids*.
Nature **503**, 95-98, 2013,
http://dx.doi.org/10.1038/nature12673,
[13] Palacci, J.; Sacanna, S.; Steinberg, A.P.; Pine, D.J. and Chaikin, P.M.: *Living crystals of light-activated colloidal surfers.*
Science **339**(6122), 936-940, 2013,
http://dx.doi.org/10.1126/science.1230020,
[14] Adamatzky, A. and De Lacy C.B.: *Experimental logical gates in a reaction-diffusion medium: The XOR gate and beyond.*
Physical Review E **66**(4), No. 04612, 2002,
http://dx.doi.org/10.1103/PhysRevE.66.046112,
[15] Adamatzky, A.; De Lacy Costello, B. and Ratcliffe, N.M.: *Experimental reaction–diffusion pre-processor for shape recognition.*
Physics Letters **297**(5-6), 344-352, 2002,
http://dx.doi.org/10.1016/S0375-9601(02)00289-X,
[16] Paul, D.: *The Quantum Life*.
Physics World **22**(7), 24-28, 2009,
[17] Wilensky, U.: *NetLogo*.
Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, 1999,
http://ccl.northwestern.edu/netlogo,

[18] Wilensky, U.: *NetLogo B-Z Reaction model.*
Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, 2003,
http://ccl.northwestern.edu/netlogo/models/B-ZReaction,
[19] Pearson, J.: *Complex patterns in a simple system*.
Science **261**(5118), 189-192, 1993,
http://dx.doi.org/10.1126/science.261.5118.189,
[20] England, J.: *Statistical physics of self-replication*.
Journal of Chemical Physics **139**, No. 121923, 2013,
http://dx.doi.org/10.1063/1.4818538,
[21] Ackley, D.H. and Small Trent, T.R.: *Indefinitely Scalable Computing = Artificial Life Engineering*.
Proceedings of the Fourteenth International Conference on the Synthesis and Simulation of Living Systems, The MIT Press, 2014,
http://dx.doi.org/10.7551/978-0-262-32621-6-ch098,
[22] Clarke, A.: *Crusade, The wind from the Sun*.
Vista, 1996.