SimSoup: Molecular Structures Designed For Network Memory And Evolution

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Background And Motivation

A key challenge for BioChemIT is the development of evolvable systems. This requires the implementation of a mechanism for inheritance using components that can be readily constructed and manipulated.

Contemporary life-forms use RNA and DNA and associated mechanisms. Origin Of Life research suggests that these mechanisms are too complex to be plausible in a prebiotic environment. The SimSoup project is seeking a simpler inheritance mechanism based on chemical networks. This search is relevant from a BioChemIT perspective, with its need for mechanisms that are sufficiently simple to be implementable.

This paper summarises *in silico* work on an inheritance mechanism using molecular structures designed to produce autocatalytic reaction networks (Gordon-Smith, 2011). The motivation is to highlight the potential of this approach for a practical evolutionary mechanism in a BioChemIT context. The paper concludes by identifying key requirements for a BioChemIT implementation of such a mechanism.

Conceptual Background

The SimSoup project takes inspiration from:

- Metabolic theories including those of Aleksandr Oparin (Oparin, 1957), Stuart Kauffman (Kauffman, 1993), Freeman Dyson (Dyson, 1999), and the Lipid World theory and GARD model of Doron Lancet's group (Segré et al., 2001)
- Tibor Gánti's work on the principles of life and chemoton theory (Gánti, 2003)
- Network theory, particularly the work of Sanjay Jain and Sandeep Krishna (Jain and Krishna, 1998)
- The Chemical Organisation Theory of Peter Dittrich and Pietro Speroni di Fenzio (Dittrich and di Fenizio, 2007)
- Günter Wächtershäuser's chemo-autotrophic Iron-Sulphur World (Wächtershäuser, 2006)
- Linus Pauling's chemical bond theory (Pauling, 1960).

Molecules Designed To Support Evolution

Evolution Without Template Molecules

Some theories of the Origin of Life propose that early organisms were metabolic systems that transmitted inherited information without the use of template replicating molecules such as DNA and RNA, and without the very complex mechanisms needed for their accurate replication.

It is envisaged that the systems were individuals capable of growth and reproduction; in some theories they are thought of as protocells or lipid enclosed droplets (vesicles) that could divide. Variations in the metabolisms of different individuals would have led to differences in fitness that would drive evolution.

For this to be workable, successful variations would have to be 'remembered' and passed on to offspring. In addition, for evolution to be effective it would need to be open-ended, with a large number of possible variations in metabolism.

A Chemical Network Memory Bank

An evolutionary system must have memory. The SimSoup design incorporates a chemical network with 'memory unit' sub-networks that are connected to form a 'memory bank'. Each of the memory units has two stable states; it can be either active or inactive. It can switch from the inactive state to the active state by the addition of 'perturbation' molecule(s) that trigger a set of self maintaining (autocatalytic) reactions.

SimSoup *In Silico* Molecular Structures To Implement The Memory Bank Network

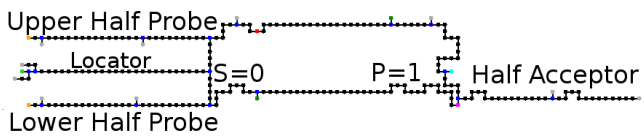

Figure 1: Monomer M_{01}

Figure 1 shows the structure of a monomer that forms part of a memory bank unit. The various recesses and protuberances provide the specificity required to support the auto-

catalytic properties of each memory unit, and to ensure that they do not interfere with one another.

Operation Of The Memory Units

The memory bank, the molecular structures, and their operation in memory units are described in detail elsewhere (Gordon-Smith, 2011). The core mechanism is as follows.

The memory bank uses a family of monomer species, each parameterised by an s,p value pair; M_{01} is the species with $s = 0$ and $p = 1$. The s, p parameters determine the positions of the recesses and protuberances.

The operation depends on a catalysed reaction in which two monomers of 'adjacent' species, M_{sp} and $M_{s,p-1}$, come together such that the Lower Half-Probe of one and the Upper Half-Probe of the other form a 'key' that is an exact match for a 'lock' formed by the two Half Acceptors of a 'Closed Dimer'. The Closed Dimer consists of two identical monomers in a 'back to back' configuration. Once the key is in place, the Closed Dimer is weakened. It splits to release more monomers, and this leads to the splitting of more Closed Dimers. This autocatalytic reaction set enables an activated memory unit to maintain its active state.

A memory unit is activated by a perturbation in which a small number[1] of monomers such as M_{01} in Figure 1 are introduced. These then combine with readily available M_{00} monomers to produce the key described above.

Each monomer in the family activates a different memory unit. The parameterised lock and key mechanism ensures that the memory units do not interfere with one-another.

Progress To Date And Future *In Silico* Work

A small memory bank has been implemented in the SimSoup artificial chemistry simulator[2]. Model runs so far have demonstrated a network that has four alternative stable states, with transition from one state to another being triggered by the addition of a single monomer to a reactor containing 60,000+ molecules.

Planned future work includes extending the memory bank to support a much larger number of states. The existing parameterised monomer family is designed to support up to 10^{10} states in a network including 100 monomers.

Future work will also improve the monomer design to support bidirectional switching between states[3].

Prospects For BioChemIT

With the advent of engineering at the molecular level, it may be possible to use the concepts outlined here as the basis of an evolutionary mechanism using actual (rather than *in silico*) molecules. A population of droplets / vesicles can be envisaged, each containing a memory bank chemical network in a particular state. The memory bank would influence other aspects of the reaction network such that it could support an evolutionary process in which 'desirable' behaviours of the network were selected.

Making the memory units switchable in both directions will make them suitable for purposes in addition to providing an evolutionary mechanism.

Regarding transferring the concepts described here to a BioChemIT context, it can be noted that the molecular structure of Figure 1 is a particular way of implementing the memory units; it is likely that there are many alternatives that are totally different in structure.

Key requirements for a BioChemIT implementation are that the memory bank reaction network has a connection structure that supports switching between multiple alternative stable states, and that these connections do not cross between memory units such that they interfere with one another. This requirement for modularisation of the network is the factor driving the need for molecular structures with lock and key mechanisms.

[1] Sometimes one is sufficient

[2] The open source code is available at the SimSoup website

[3] The evolutionary mechanism will work without this; an activation of a memory unit that is a 'mistake' in evolutionary terms will be reversed by fitness selection.

References

Dittrich, P. and di Fenizio, P. S. (2007). Chemical organisation theory. *Bull. Math. Biol.*, 69(4):1199–1231.

Dyson, F. (1999). *Origins Of Life*. Cambridge University Press.

Gánti, T. (2003). *Principles of Life*. Oxford University Press.

Gordon-Smith, C. (2011). Non-template molecules designed for open-ended evolution. In *Advances in Artificial Life, ECAL 2011 Proceedings of the Eleventh European Conference on the Synthesis and Simulation of Living Systems*.

Jain, S. and Krishna, S. (1998). Autocatalytic sets and the growth of complexity in an evolutionary model. *arXiv:adap-org/9809003v1*.

Kauffman, S. A. (1993). *The Origins Of Order*. Oxford University Press.

Oparin, A. (1957). *The Origin Of Life On The Earth*. Oliver And Boyd.

Pauling, L. (1960). *The Nature Of The Chemical Bond*. Cornell University Press.

Segré, D., Ben-Eli, D., Deamer, D. W., and Lancet, D. (2001). The lipid world. *Origins Life Evol. B.*, 31:119–145.

Wächtershäuser, G. (2006). From volcanic origins of chemoautotrophic life to bacteria, archaea and eukarya. *Philos Trans R Soc London [Biol]*, 361:1787–1808.