The Origin Of Life: A Network Oriented View

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Origin of Life theories are in two main categories: 'template replication first' and 'metabolism first'. A network oriented viewpoint is presented, under which properties of metabolic networks played a key role in the origin of the first evolving systems. A mechanism for memory in chemical networks is illustrated. The simplicity of 'network memory', especially in comparison with template mechanisms, suggests its plausibility as a prebiotic phenomenon and as a fruitful area for Origin of Life research.

The view presented draws on a rich conceptual background, including Oparin (1957), Kauffman (1993), Dyson (1999), Cairns-Smith (1982), the Lipid World theory of Doron Lancet's group (Segré et al., 1998; 2001a;b), and Wächtershäuser (1990; 1997; 2006).

Network Memory

Evolution is essentially a process of trial and error. In order for it to gain a foothold, successful trials must be inherited; they must be remembered and transmitted to offspring. In contemporary life, inheritance is based primarily on DNA and the highly evolved enzymes that support accurate replication of this template molecule. These enzymes would not have been available to the first organisms, and so accurate template replication would not have been possible; this is the well known 'chicken and egg' problem.

The view presented here is that early organisms contained chemical networks that were capable of carrying information about successful variations and transmitting it to offspring.

An intuitive argument for this view is that there are many examples in which networks are known to carry information. The most striking is the brain.

Static And Dynamic Chemical Networks

Chemical networks are of two kinds: static and dynamic. A static chemical network is defined by the molecular species that are possible, the interactions between them that are possible, and the (temperature and pressure dependent) rate constants for these interactions. *The static network is determined for all time by the laws of physics.*

A dynamic chemical network is a set of actual molecules, the actual interactions taking place between them, and the rates of these interactions. It is useful to think of a dynamic chemical network as one of the possible configurations that can exist on the static chemical network.

Since there is no known upper limit to the size of a molecule, the number of possible species and the number of possible interactions between them is effectively infinite. In short, the size of the static network is effectively infinite.

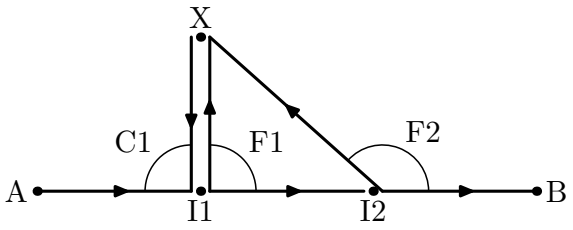

Figure 1: A simple (two state) chemical memory unit. C1 is a 'Construction' reaction, F1 and F2 are 'Fission' reactions, A is a maintained 'food' species. If a single molecule of X is introduced the network becomes active and remains active.

A Toy Model Mechanism For Memory In Chemical Networks

Figure 1 shows a simple (static) network for an artificial chemistry consisting of three elementary reactions C1, F1 and F2:

$$\begin{array}{ll} A + X \rightarrow I1 & (C1) \\ I1 \rightarrow I2 + X & (F1) \\ I2 \rightarrow B + X & (F2) \end{array}$$

A is abundantly available 'food'; initially no other molecules are present. In the absence of X molecules, reaction C1 cannot proceed and A remains the only species present. If a single molecule of X is introduced, a molecule of I1 is constructed (reaction C1). This subsequently splits (reaction F1) to release an X molecule and an I2 molecule. The I2 molecule then splits (reaction F2) to release another X molecule plus a B molecule. Overall, for each A molecule consumed, one X molecule becomes available in addition to the B molecule. As a result, the supply of X is maintained (even if there is some 'leakage').

The dynamic network has two states, one in which only A molecules are present and no reactions occur, and another in which the reactions proceed and a supply of X is maintained. The introduction of a single molecule of X is 'remembered' because it triggers a switch to a new persistent state.

The network therefore constitutes a simple memory unit with an information capacity of 1 bit.

The Dynamic Network Explores The Static Network

We now envisage in Figure 2 a static network in which two of the memory units in Figure 1 are connected in series.

If only A is available as 'food', there are three possible persistent states of the dynamic network: i) neither unit is active (only A is present), ii) only unit 1 is active, iii) both units are active.

In a more general situation where the static network is (effectively) infinite, we can consider a dynamic network to be 'exploring' the static network. A perturbation (such as the addition of a single X or Y molecule) can cause new parts of the network to become accessible.

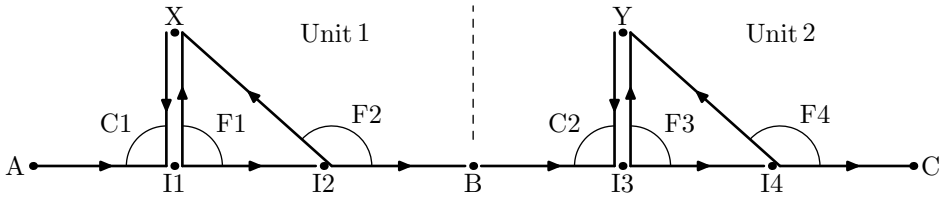

Figure 2: A two unit chemical memory network with three states; i) both units inactive, ii) unit 1 only active, iii) both units active

Individuality, Splitting, and Information Transfer

Metabolism first theories usually assume that:

- Early organisms had a level of individuality (e.g. by being enclosed within a lipid membrane or by being bonded to a surface)
- They could divide and produce offspring.

As illustrated by the toy model, the stability of a dynamic network is not dependent on the concentrations of the molecular species remaining within narrow bounds. Even if there is 'leakage', the network of Figure 1 will remain active as long as a single molecule of X is present. *Dynamic chemical networks are stable because they are attractors.*

Provided the molecular composition of each offspring is roughly similar to that of the parent, new sub-networks discovered by the parent will be retained by the offspring. *This is how inherited information can be transferred from parent to offspring without accurate replication.*

Conclusions and Open Questions

Chemical networks adopt dynamic configurations that are inherently stable. This opens the possibility that a new configuration arising from a perturbation can be 'remembered' and passed on to offspring, forming the basis of an inheritance mechanism in early organisms.

Open questions regarding the role of such mechanisms in the Origin of Life include:

- How many attractors existed in prebiotic chemical networks?
- Is network evolution 'limited'?
- Does network evolution require large molecules?
- How frequent are transitions between attractors in a chemical network?
- What causes them?
- What mechanisms could support individuality and splitting in non template replicating organisms ?
- How could the transition to template replicators be made? Genetic Takeover?

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