On the roles of parasites in RNA world

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Introduction

RNA + evolution → **life?**

The origin of life is **not** the same as the origin of evolution. For example, think of **Spiegelman**'s experiment: Replicating molecules became shorter and shorter through evolution (i.e., became simpler and simpler).

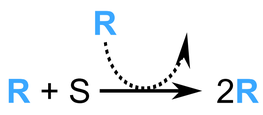

Sol Spiegelman at lab bench with pipette
(National Library of Medicine, USA)

How can replicating molecules evolve into something as complex as life? Here, I will show that "**parasites**" play a key role for this, using mathematical modeling and computer simulations.

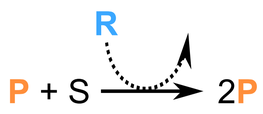
➪ Go to **Part 1** for what parasites are
➪ Go to **Part 2** for what parasites can do

Part 1. What parasites are

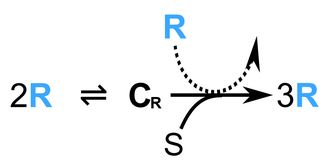
Let us suppose there are molecules (R) that can catalyze their own replication (☞).

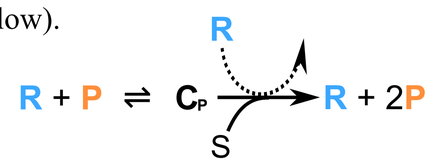


Mutations can happen during replication, turnnig R into a non-catalytic molecule (P). If P can still serve as template (☞), P is a parasite of R.

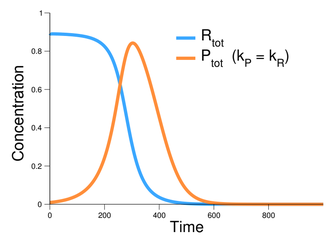


Replication is not instantaneous. Let us take this into account by assuming complex formation (☞). The consequence is devastating (see below).





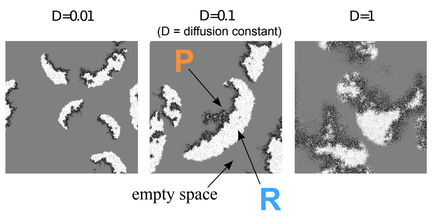
While R is replicating another molecule (i.e., forming a complex), it cannot serve as a template. So, its fitness is reduced. By contrast, P can always serves as a template—its replication is more efficient. Consequently, P out-competes R, driving the system into extinction (☞). So, does this mean:



Population dynamics of R and P in a well-mixed system. The plot was obtained by numerical integration of the reaction rate equations describing replication and decay (hydrolysis).

RNA + evolution → **death?**

Extinction, however, can be avoided if the system is spatially extended, and distributions of R and P self-organize into traveling wave patterns (☞). And this holds even if mutations continually turn R into P. So, does this mean:



Snapshot of a computer simulation showing spatial distributions of R and P. The data were generated by a stochastic cellular automata model simulating replication, decay, and diffusion of R and P.

RNA + evolution + pattern formation → **life?**

Conclusion

Parasites can lead to the evolution of the division of labor between template (DNA) and catalyst (RNA).

RNA + evolution + pattern formation → RNA / DNA

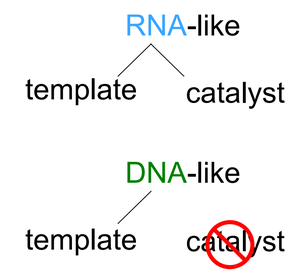
Part 2. What parasites can do

In a nutshell, the RNA world hypothesis posits that RNA served both as templates and catalysts in the first replicating systems. According to this hypothesis, DNA and proteins came later as specialized components: DNA is dedicated to information storage; proteins, to chemical catalysis (☞). How would such division of labor between templates and catalysts emerge through Darwinian evolution?

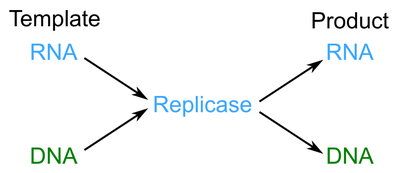
RNA world	
template	catalyst
RNA	RNA

Now	
template	catalyst
DNA	proteins

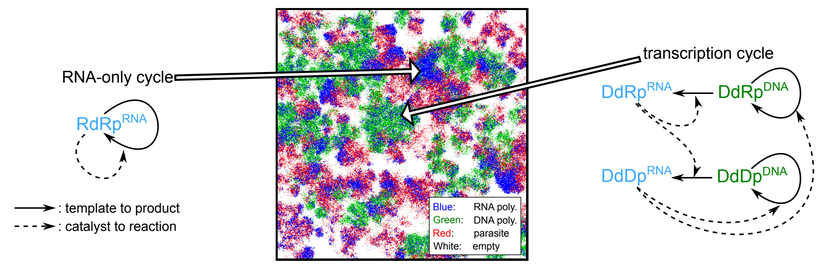
Let us suppose that there are two types of molecules: RNA-like and DNA-ilke molecules (RNA and DNA, for short). The only difference between them is the presence or absence of the catalytic capacity (☞).



RNA and DNA allow for four types of replication reaction (☞). Combinations of these reactions allow various replication cycles. What type of replication cycles would emerge through evolution if the system starts only with RNA?



A mathematical model incorporating the above assumptions shows the evolution of the replication cycle shown in the figure displayed below (see the network on the right). In this cycle, RNA molecules are dedicated to providing catalysis and do not serve as templates—the latter role is delegated to DNA molecules. So, the division of labor between template and catalyst emerged. But, why? (see the next paragraph)



Snapshot of a computer simulation (middle) and schematic diagrams of replication cycles that emerge during the simulation (left and right). The data were generated with a stochastic cellular automata model simulating replication (w/ mutation), decay, and diffusion of RNA and DNA molecules. In the network diagram, RdRp stands for RNA-dependent RNA polymerase; DdRp stands for DNA-dependent RNA polymerase; DdDp stands for DNA-dependent DNA polymerase. The superscripts indicate whether molecules are RNA or DNA.

As described in Part 1, the problem of parasites is that they have advantage over catalysts: a parasite spends its entire lifetime being templates, whereas a catalyst has to "waste" a part of its lifetime replicating other templates. This problem, however, no more exists in the transcription cycle where RNA (catalyst) are not replicated, but are "transcribed" from DNA (template). So, this cycle has an advantage over the RNA-only cycle.

Acknowledgement

NT is a Research Fellow of JSPS

References

Part 1: Takeuchi & Hogeweg (2012) Physics of Life Reviews 9:219-63
Part 2: Takeuchi et al. (2011) PLoS Computational Biology 7:e1002024