On the Origin of DNA Genomes in RNA World

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One of the fundamental properties of living systems

The division of labor between templates & catalysts

- DNA stores genetic information: template
- proteins implement genetic information: catalyst

In RNA World

- RNA is the template
- RNA is the catalyst

The division of labor between templates & catalysts evolved later through the evolution of DNA and proteins.

Proteins & DNA compared with RNA

Proteins (vs. RNA)

- Superior catalyst
- Inferior template

DNA (vs. RNA)

- Superior templates?
  - → Chemically more stable However, see (Forterre 2005)
- Inferior catalyst??
  - → No experimental evidence (Silverman 2008)

Unlike proteins, the function of DNA (i.e. dedicated information storage medium) does not seem to derive directly from the chemical properties of DNA alone.

Why did DNA evolve?

Question

Is there any advantage for an RNA-based evolving system to evolve an entity that lacks catalytic activity and is solely dedicated to the storage of genetic information, i.e. an entity functionally equivalent to DNA?

Answer

Yes, there is.

Minimal computational model of RNA-like replicator systems

RNA-like replicator system

The simplest form of the RNA world that can undergo evolution

$$R + T \rightleftharpoons C \xrightarrow{\emptyset} R + T + T'$$
$$R, T \rightarrow \emptyset$$

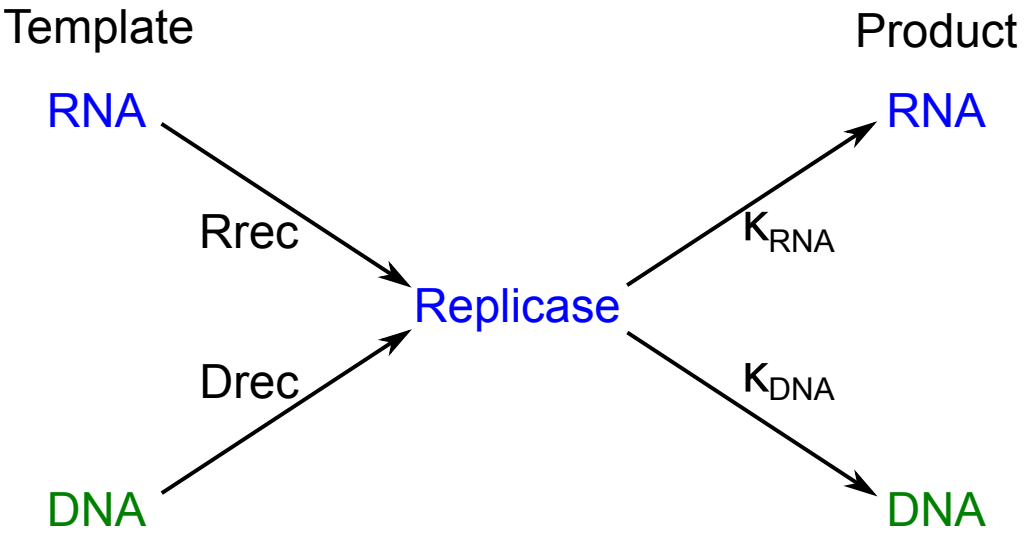
R: replicase, T: template, C: complex, $\emptyset$: substrate

Models consist 2 types of molecules

1. RNA-like molecules (RNA for short)
   - can be a template
   - can be a catalyst
2. DNA-like molecules (DNA for short)
   - can be a template
   - cannot be a catalyst

Schematic description of the model

- 4 types of replication reactions: RNA/DNA → RNA/DNA

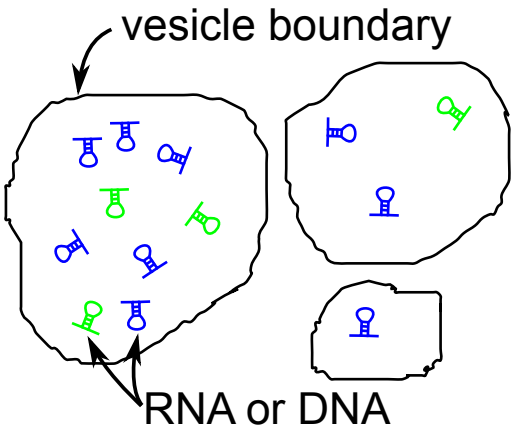


Boundary condition

$$Rrec, Drec \in [0, 1]$$

$$\kappa_{RNA} = 1 \text{ and } \kappa_{DNA} = 0$$
or
$$\kappa_{RNA} = 0 \text{ and } \kappa_{DNA} = 1$$

- Replicators are compartmentalized by vesicle

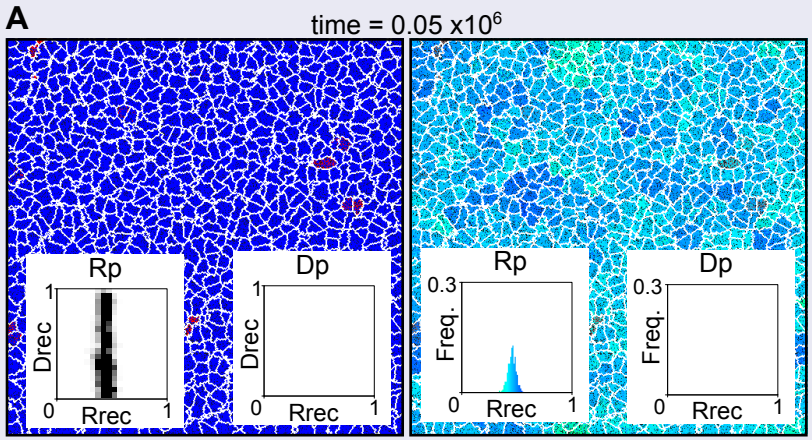


Coupling

compartment size $\propto$ no. replicators
compartment size $>$ threshold $\rightarrow$ division

Results of simulations

Initial state



Left panel

Snapshot

Blue: Rp
Green: Dp
Red: parasite
White: comp. bound.
Black: empty

2D histogram

0.5 1 >1 ($x10^3$)

[no. molecules; 20x20 bins]

Right panel

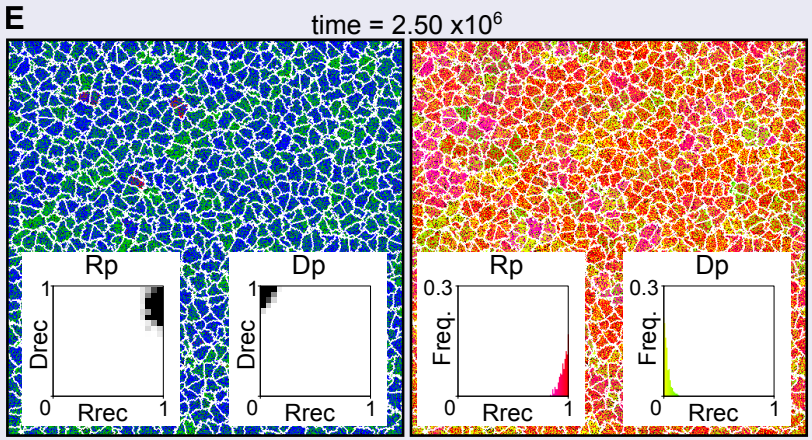
Snapshot

The color corresponds to the value of Rrec as indicated in the histogram. (Parasites are colored brown.)

1D histogram

It depicts the relative frequency of Rrec values. 100 bins.

End result



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1D histogram

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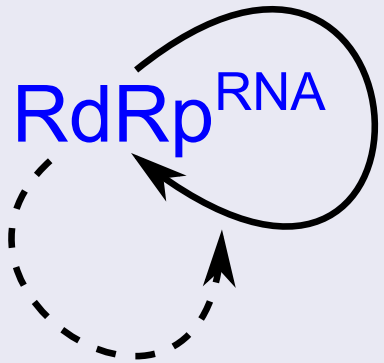
Schematic description of the result

Initial state

- Self-replication system

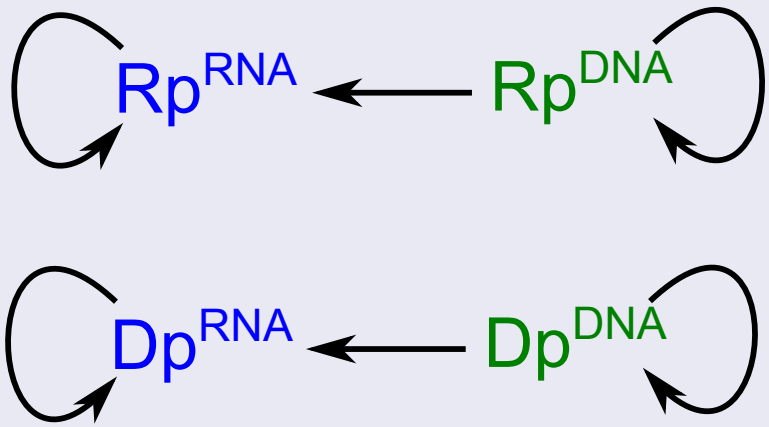


: template to product

: catalyst to reaction

End state

- Transcription-like system



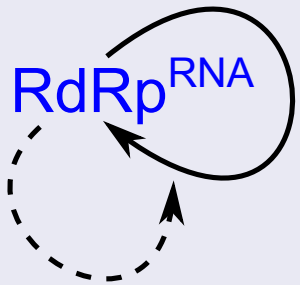
: template to product

Change of parameters: mutation rate & population size

Condition	RNA-only	Transcription-like
Higher μ_{rec}	Lose	Win
Lower μ_{rec}	Win	Lose
greater compartment size	Lose	Win
smaller compartment size	Win	Lose

Self-replication system (i.e. RNA-only system)

Self-replication system

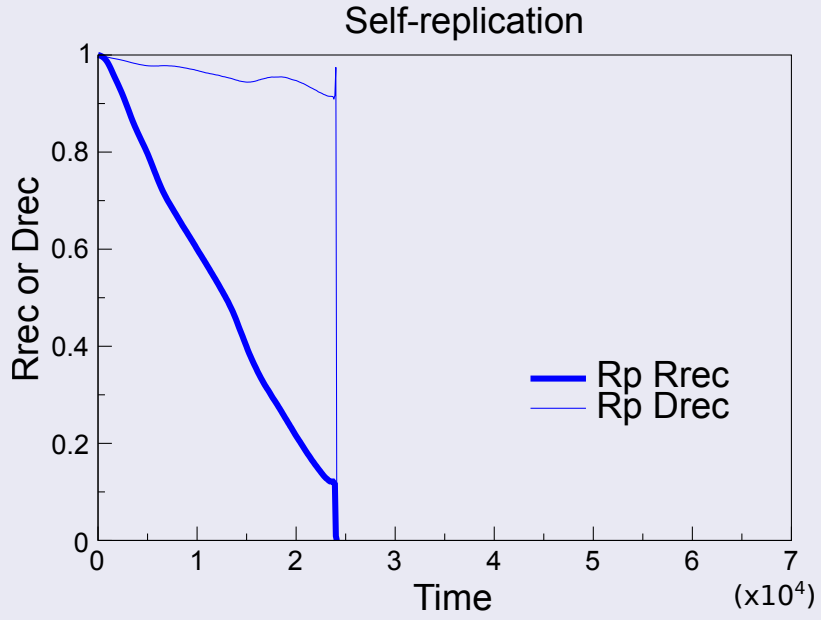


: template to product

: catalyst to reaction

- the trade-off between templates & catalysts
- has tendency toward evolving into pure templates (parasites)

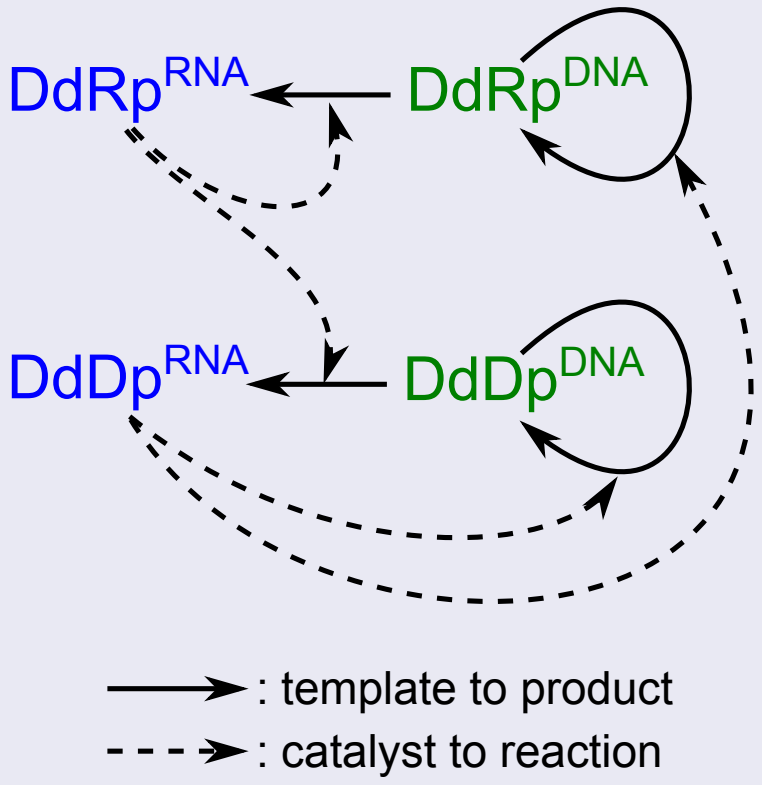
Under well-mixed condition



param.	tendency
greater μ_{rec}	stronger
larger pop. size	stronger

Effect of including DNA into a replication cycle

Transcription system



Pros and cons of DNA

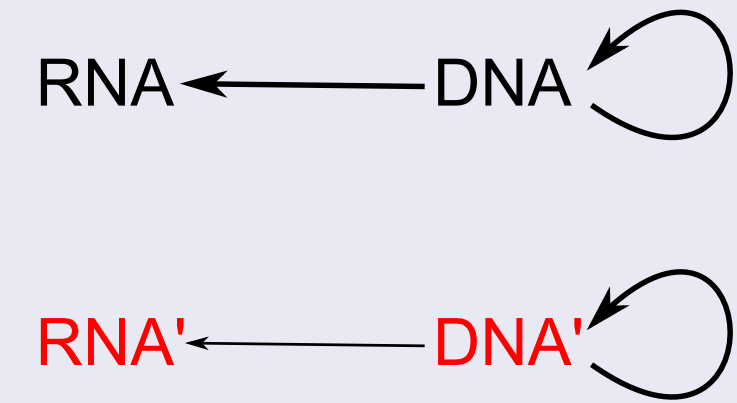
- Inefficient multiplication due to increased complexity
- Releases RNA from the tendency toward evolving into parasites

parameter	tendency to parasite	transc.-like system
greater μ_{rec}	stronger	evolves
greater comp. size	stronger	evolves

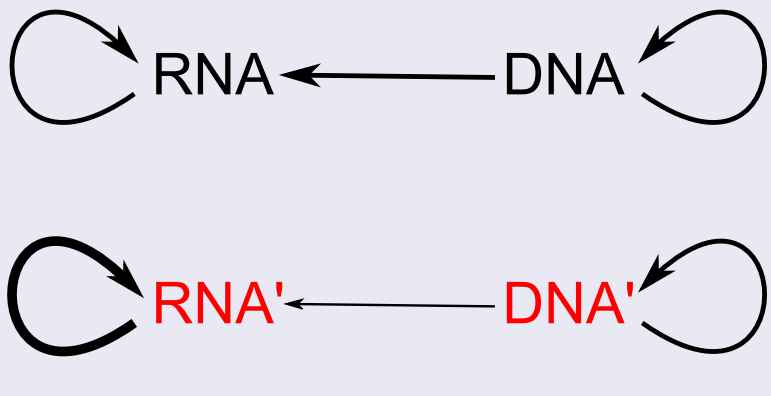
Can DNA prevent the evolution of RNA into parasites?

- $\rightarrow$ Can “parasitic” mutant invade?

Transcription system

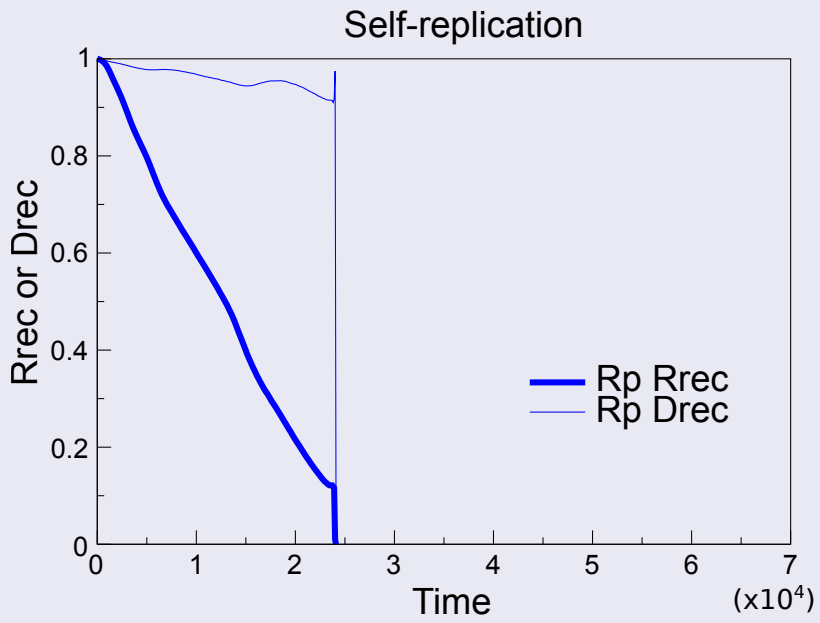


Transciption-like system

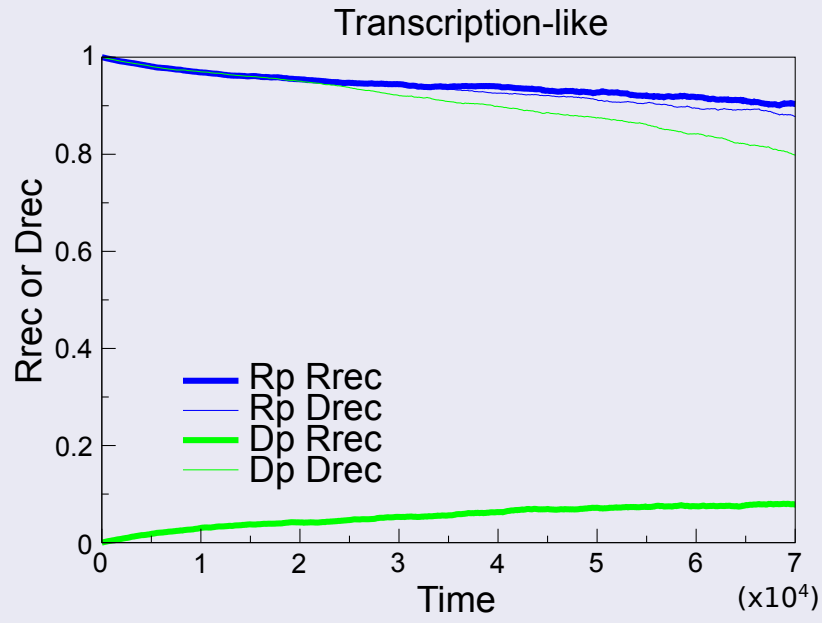


Effect of DNA-like molecules on evolution

Self-replication system

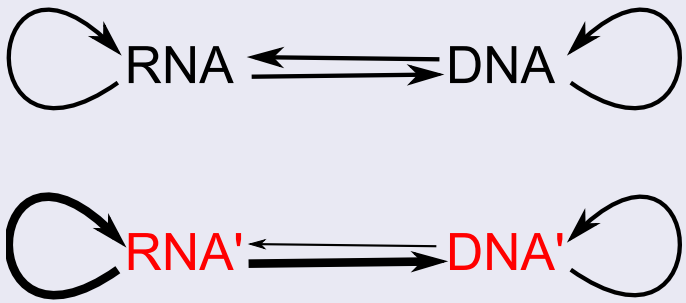


Transcription-like system

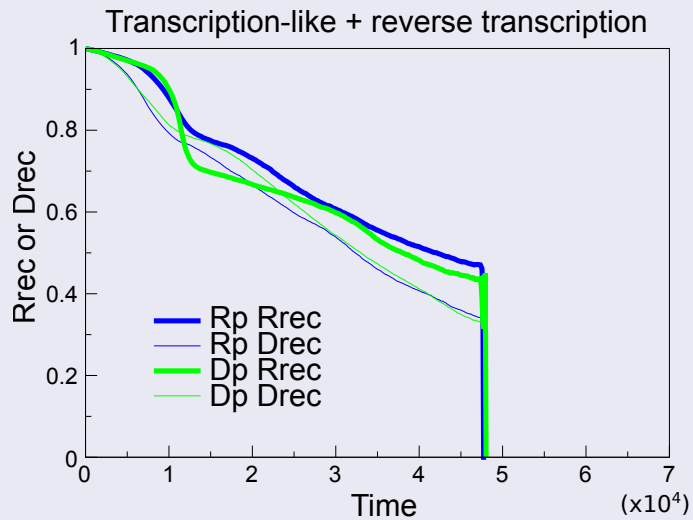


Effect of reverse transcription on evolution

Reverse transcription



Under well-mixed condition



Conclusion

Advantage of DNA

Releases RNA from the tendency toward evolving into parasite

- Transcriptional buffering
- Unidirectional flow of information (DNA $\rightarrow$ RNA)

Disadvantage of DNA

Slows down multiplication

- The increased complexity of replication cycle

- The lack of catalytic activity in DNA in itself can give rise to selection for the emergence of DNA.
- Given the widespread notion that DNA originated due to its greater chemical stability, this study provides a novel insight into the origin of DNA.

Ref. Takeuchi, Hogeweg & Koonin (2011) PLoS Comp Biol **7**:e1002024