Evolution of RNA-like Replicators —Roles of Parasites—

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Individual-based and ecosystem-based solutions

(Prebiotic) Evolution of complexity in RNA-like replicator systems

Individual-based solution

Long genome

ecosystem-based solution

Coexistence of multiple replicator species

Individual-based and ecosystem-based solutions

(Prebiotic) Evolution of complexity in RNA-like replicator systems

Individual-based solution

Long genome $\Rightarrow$ Error threshold

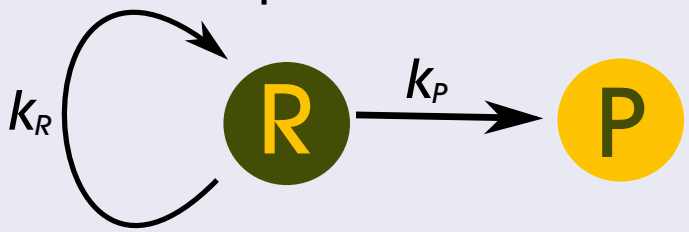
ecosystem-based solution

Coexistence of multiple replicator species $\Rightarrow$ parasites

Why do parasites pose a problem?

Let's consider simple replicator system

- System with 1 replicase & 1 parasite



- Well-mixed system with continuous population

$$\dot{R} = k_R R^2 \theta - dR$$
$$\dot{P} = k_P R P \theta - dP$$

- If $k_P > k_R$, parasites out-compete catalysts
- Parasites can drive replicator system to extinction

Problem seems even worse

Replication is instantaneous (simplification)

- No complex formation

$$2\mathrm{R} \xrightarrow{k_R\theta} 3\mathrm{R}$$
$$\mathrm{R} + \mathrm{P} \xrightarrow{k_P\theta} \mathrm{R} + 2\mathrm{P}$$

- If $k_R < k_P$, system goes extinct

Replication is not instantaneous (more realistic)

- Complex formation

$$2\mathrm{R} \underset{1-k_R}{\overset{k_R}{\rightleftharpoons}} \mathrm{C_R} \xrightarrow{\kappa\theta} 3\mathrm{R}$$
$$\mathrm{R} + \mathrm{P} \underset{1-k_P}{\overset{k_P}{\rightleftharpoons}} \mathrm{C_P} \xrightarrow{\kappa\theta} \mathrm{R} + 2\mathrm{P}$$

- Even if $k_R > k_P$, system can go extinct

To sum up

- To catalyze replication is disadvantageous
- Parasites have selective advantage over catalysts
- Catalysts tend to evolve toward becoming parasites

So,

- Parasites pose a problem to the evolution of replicator systems

Let's consider alternative model

Ordinary differential equation model

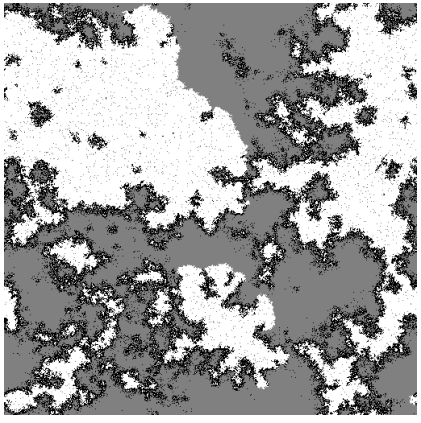
- Well-mixed
- Global interactions
- Infinite population (continuous population)
  $\rightarrow$ deterministic dynamics

Stochastic cellular automata model

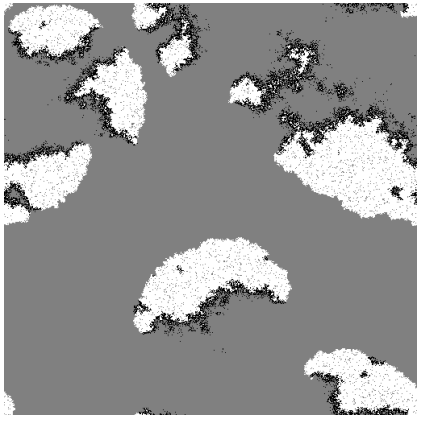
- Spatial extension
- Local interactions
- Locally finite population (discrete population)
  $\rightarrow$ stochastic dynamics

Spatial self-organization changes the picture

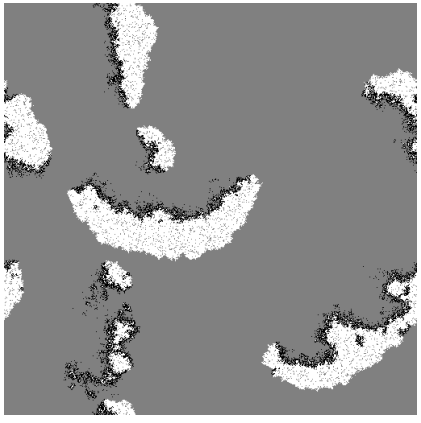
d=0.01
k_P/k_R=2.18



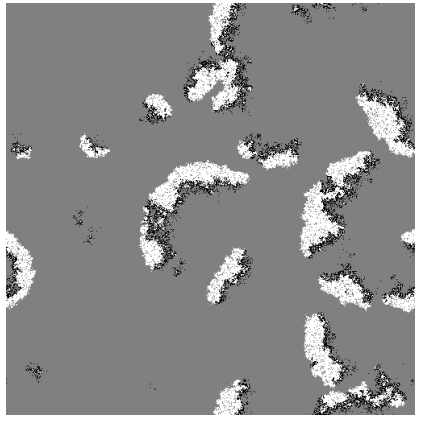
d=0.02
k_P/k_R=3.24



d=0.03
k_P/k_R=3.18



d=0.04
k_P/k_R=2.87



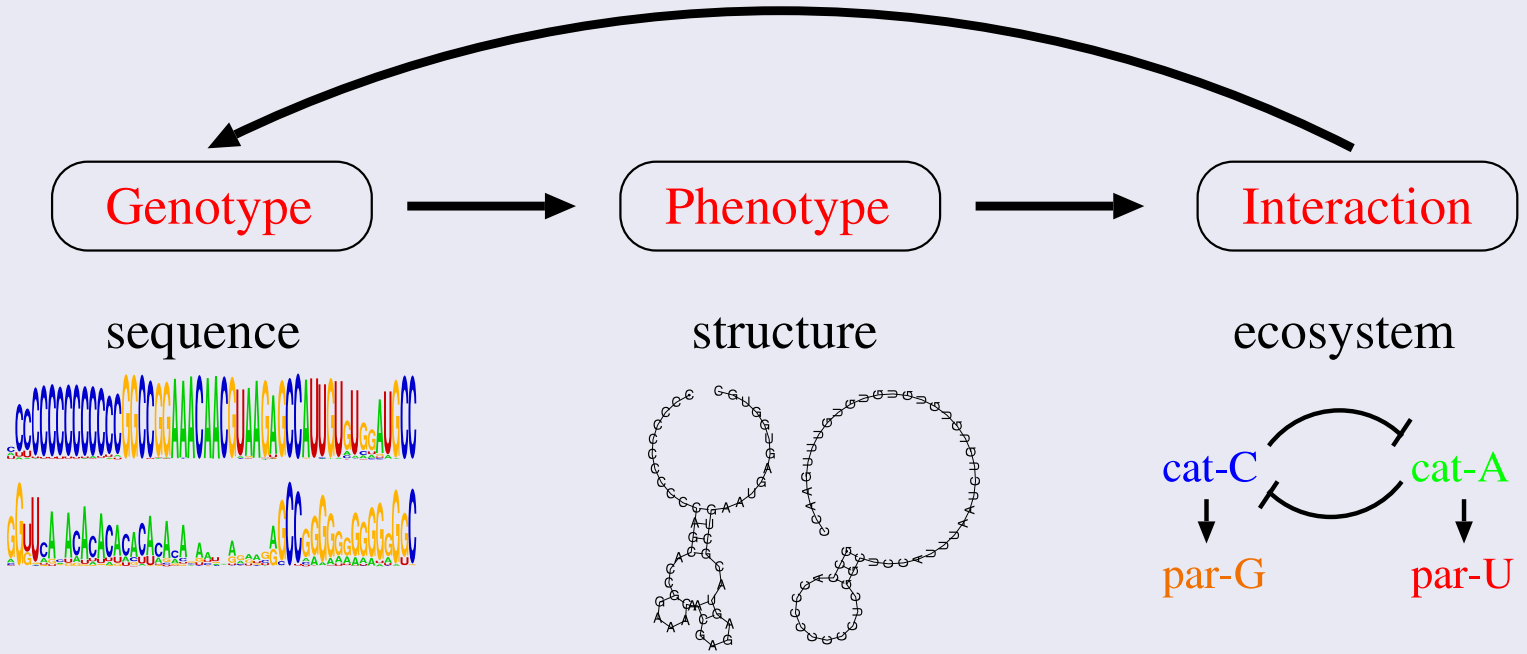
(Takeuchi & Hogeweg '07)

To sum up

- Parasites pose a problem, to which a replicator system responds by spatial self-organization

What sort of replicator system evolves?

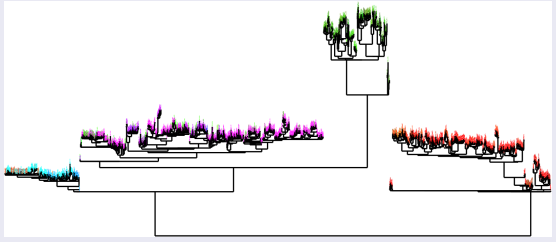
Genotype-phenotype-interaction map



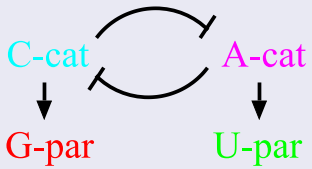
(Hogeweg & Takeuchi '08)

Pattern generation by evolution

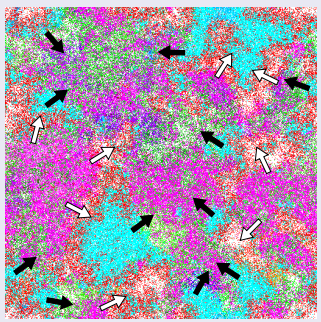
Phylogeny



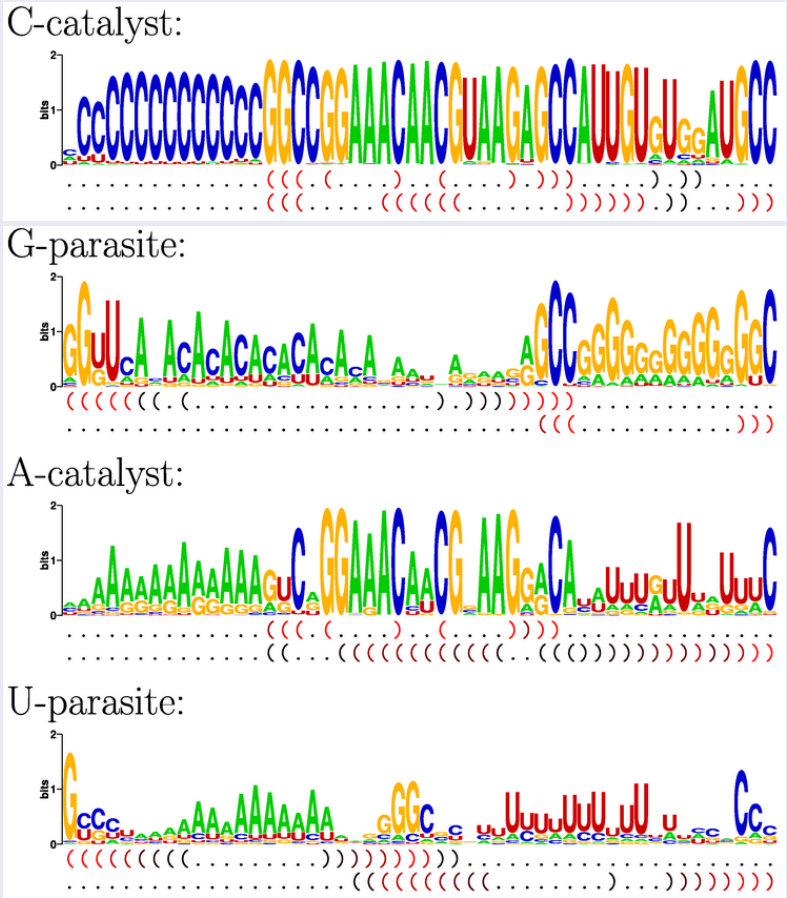
Interaction network



Spatial distribution



Genotypes & phenotypes



(Takeuchi & Hogeweg '08)

To sum up

- Parasites pose a problem, to which a replicator system responds by evolving complex ecosystem.

Why do parasites pose a problem, again?

To be a catalyst or to be a template

- Replication is not instantaneous

$$2\mathrm{R} \underset{1-k_R}{\overset{k_R}{\rightleftharpoons}} \mathrm{C_R} \xrightarrow{\kappa\theta} 3\mathrm{R}$$

- There is trade-off between serving as a catalyst and serving as a template

This trade-off lies at the core of RNA world hypothesis

RNA world

- Genetic information $\rightarrow$ RNA
- Chemical catalysis $\rightarrow$ RNA

Co-embodiment of template and catalyst in one molecule

DNA-protein world (RNA!)

- Genetic information $\rightarrow$ DNA
- Chemical catalysis $\rightarrow$ proteins (& RNA)

Division of labor between templates and catalysts

How would such division of labor evolve?

Proteins, dedicated catalysts (vs. RNA)

- Superior catalyst
- Inferior template

DNA, dedicated templates (vs. RNA)

- Superior templates?
  - → More stable to hydrolysis However, see (Forterre '05)
  - → But inferior in template-directed polymerization (Zhang et al. '12)
- Inferior catalyst??
  - → No experimental evidence (Silverman '08)

How could dedicated templates evolve in the RNA world?

Model of replicator system with DNA

Replicator system

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

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

Models assumes 2 types of molecules

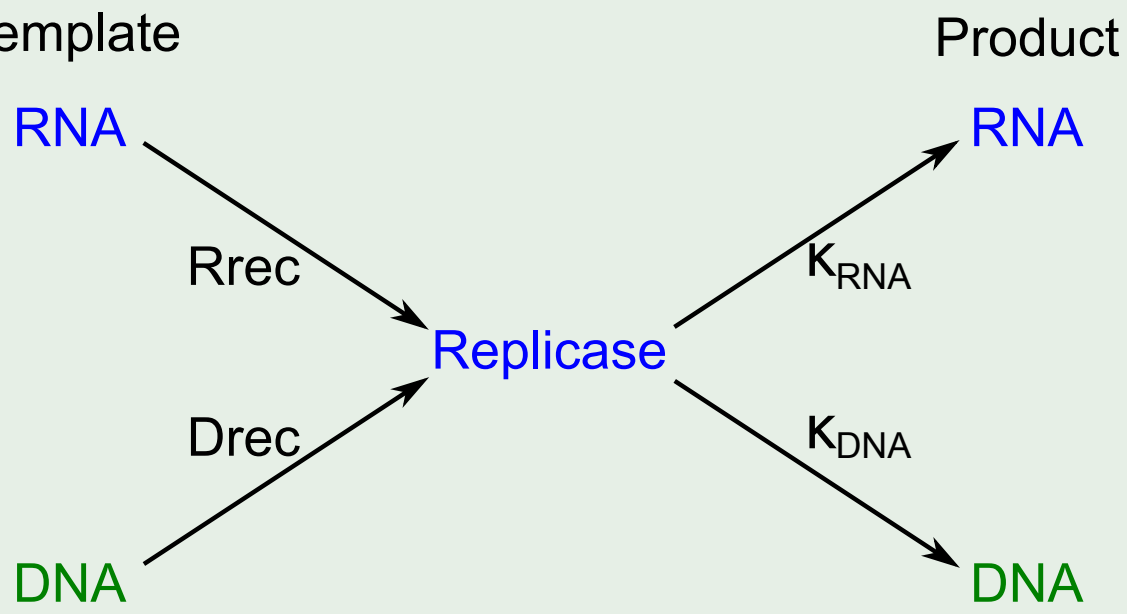
1. RNA-like molecules (RNA, for short)
   - can be a template
   - can be a catalyst
2. DNA-like molecules (DNA, for short)
   - can be a template
   - cannot be a catalyst

Model of replicator system with DNA

DNA and RNA provide for 4 types of replication

- RNA-dependent RNA polymerization (RNA replication)
- RNA-dependent DNA polymerization (reverse transcription)
- DNA-dependent RNA polymerization (transcription)
- DNA-dependent DNA polymerization (DNA replication)

Template and product specificity



All 4 parameters can mutate within the following boundary condition.

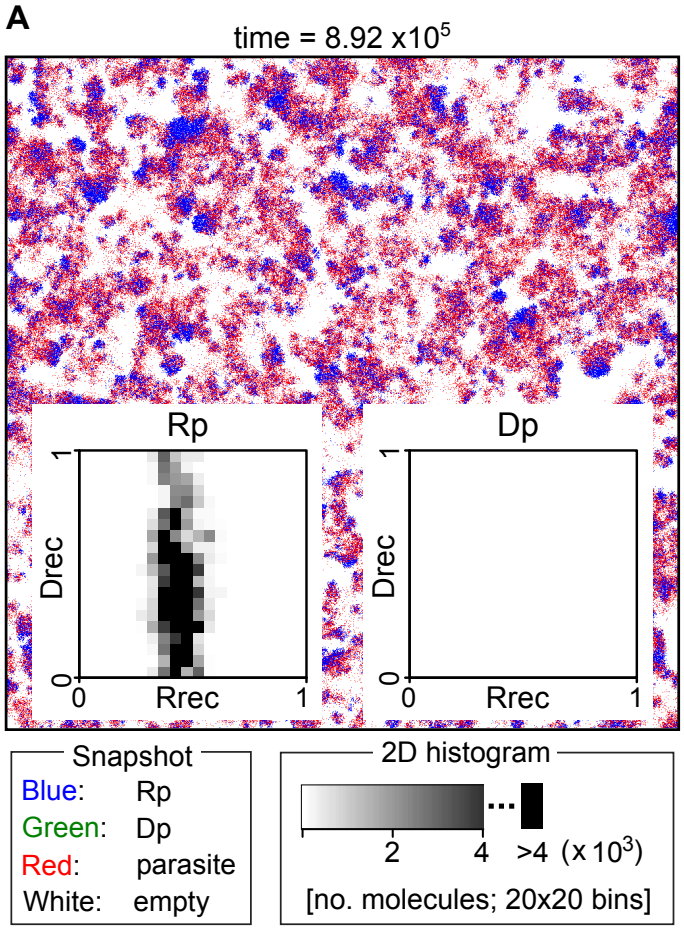
$$\text{Rrec, Drec} \in [0, 1]$$

$$\begin{cases} \kappa_{RNA} = 1 \ \& \ \kappa_{DNA} = 0 \\ \text{or} \\ \kappa_{RNA} = 0 \ \& \ \kappa_{DNA} = 1 \end{cases}$$

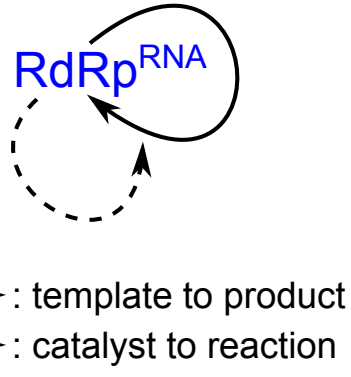
Additional notes

- DNA molecules cannot function as catalysts, but can contain information on catalysts
- The model also assumes parasites.

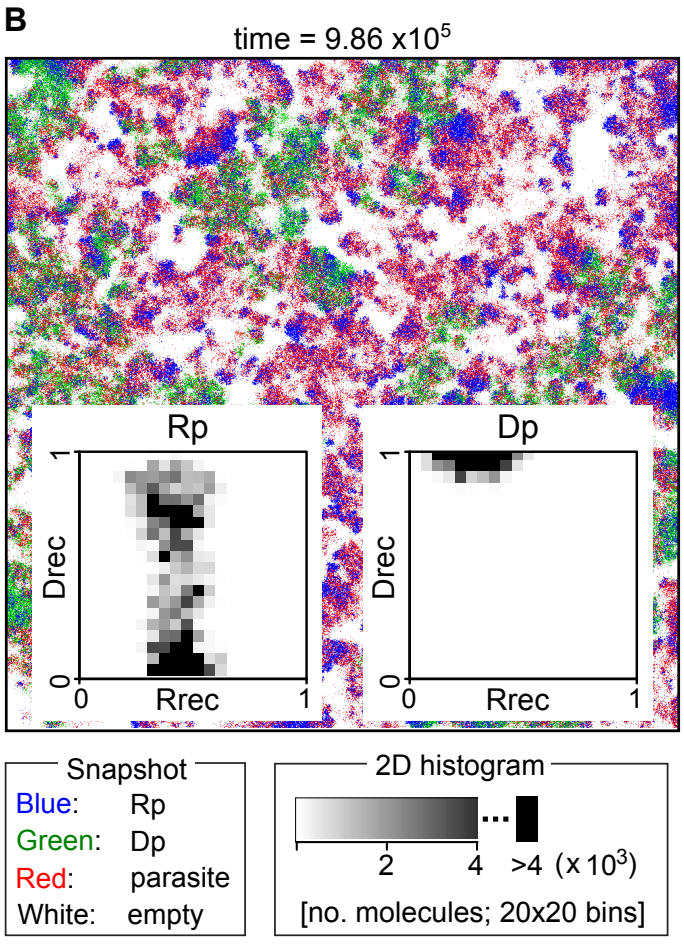
Initial condition

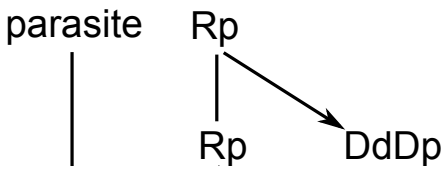


parasite Rp

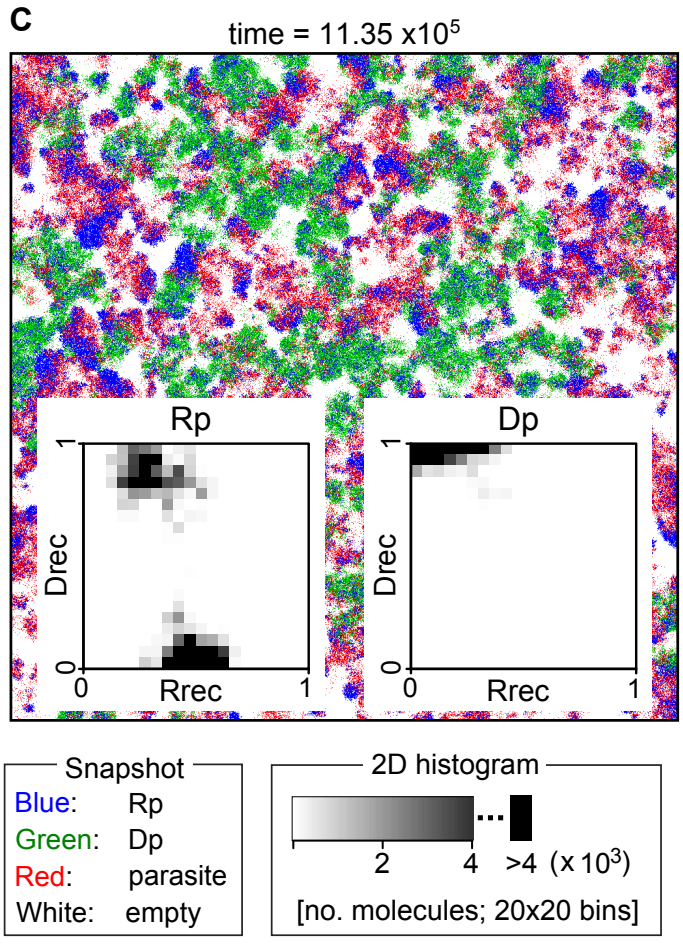


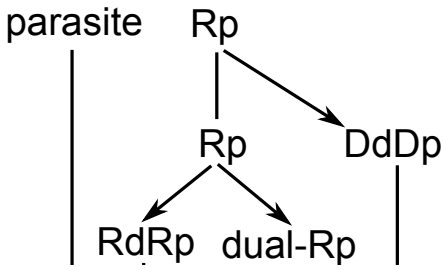
DNA polymerase invades



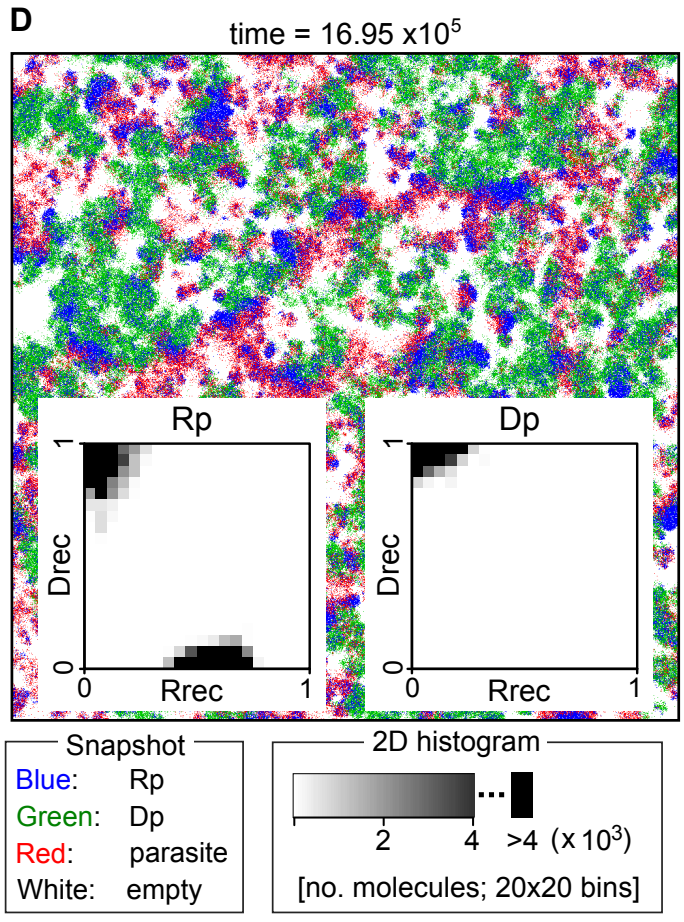


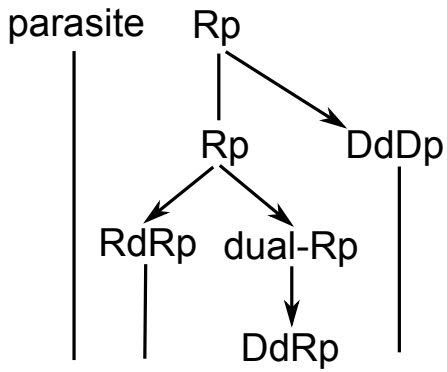
RNA polymerase speciates

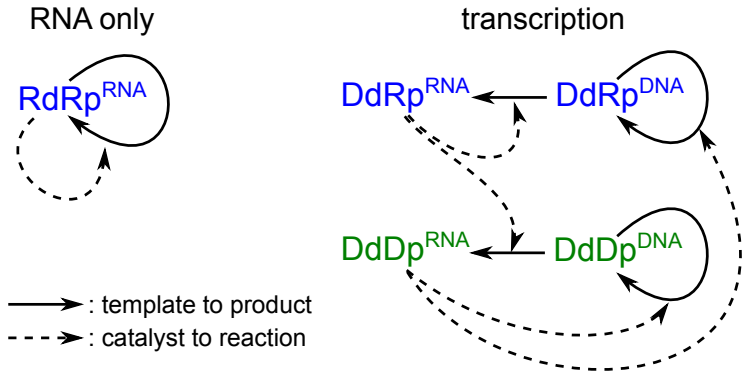




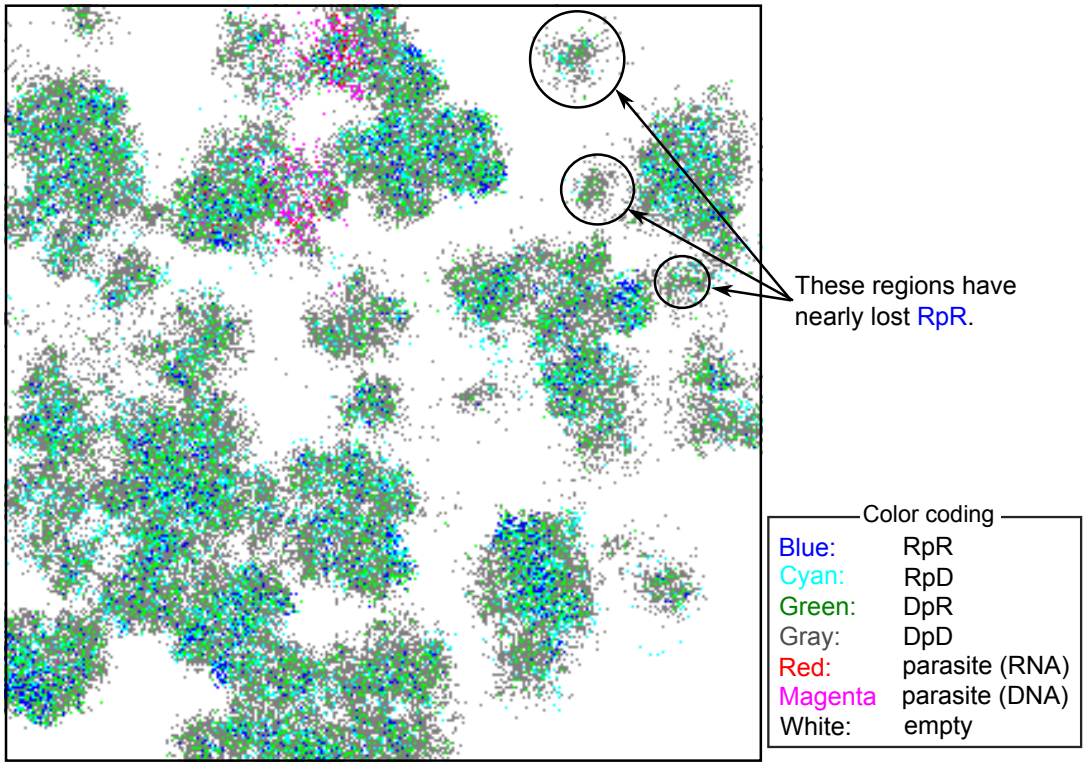
Transcriptase evolves

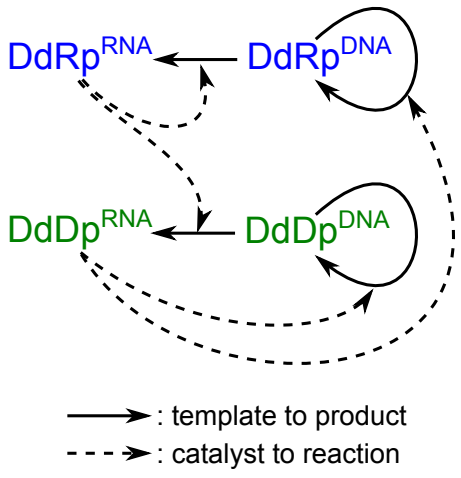






Dynamics of transcription system

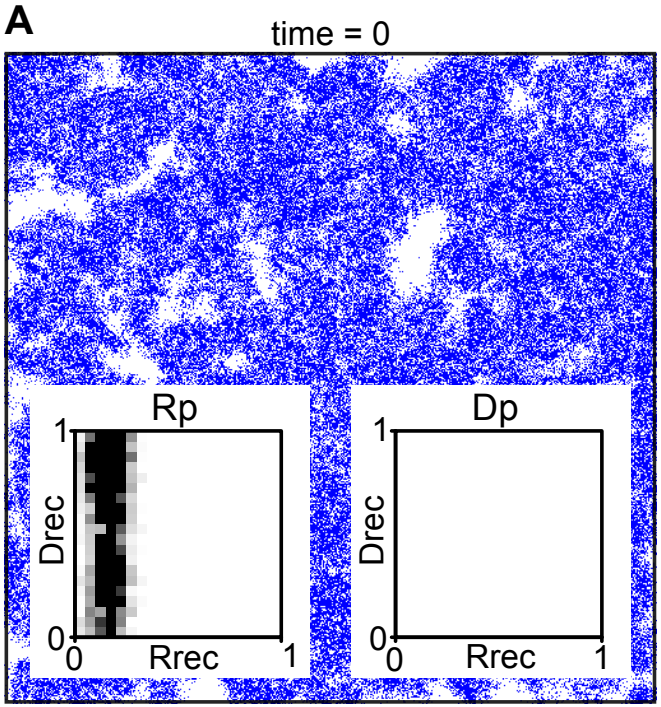




To sum up

- Parasites pose a problem, to which a replicator system responds by evolving the division of labor between templates and catalysts

Evolution without parasites?

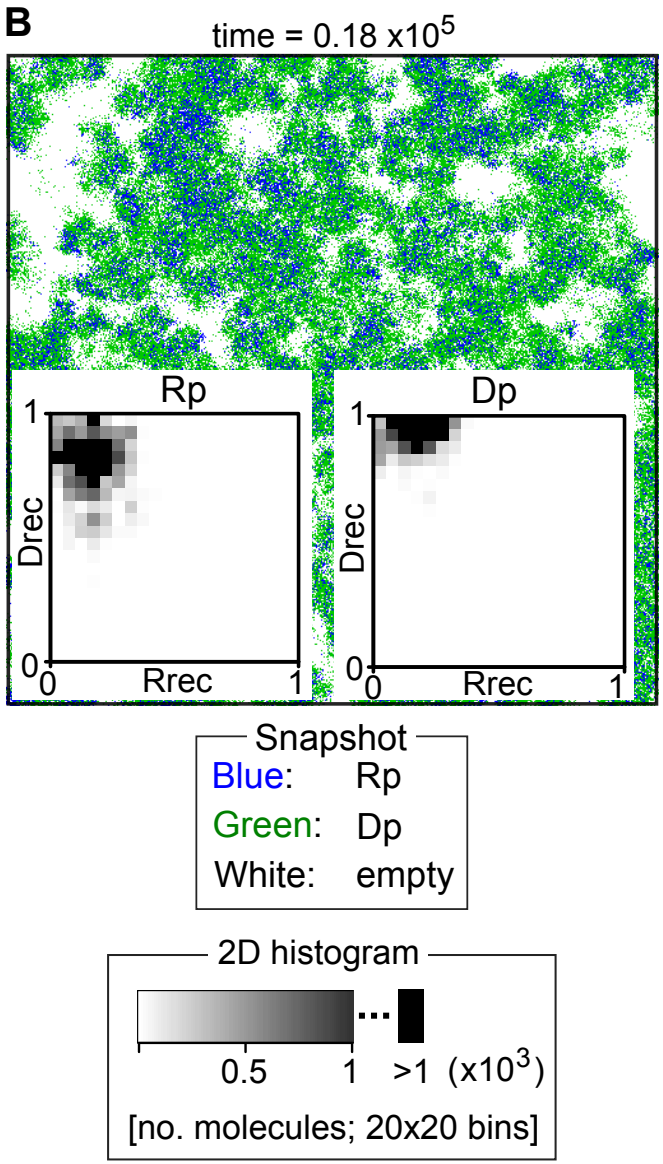


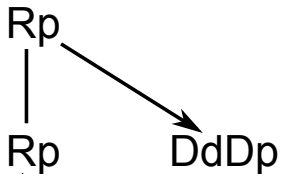
Snapshot
Blue: Rp
Green: Dp
White: empty

2D histogram
0.5 1 >1 (x10^3)
[no. molecules; 20x20 bins]

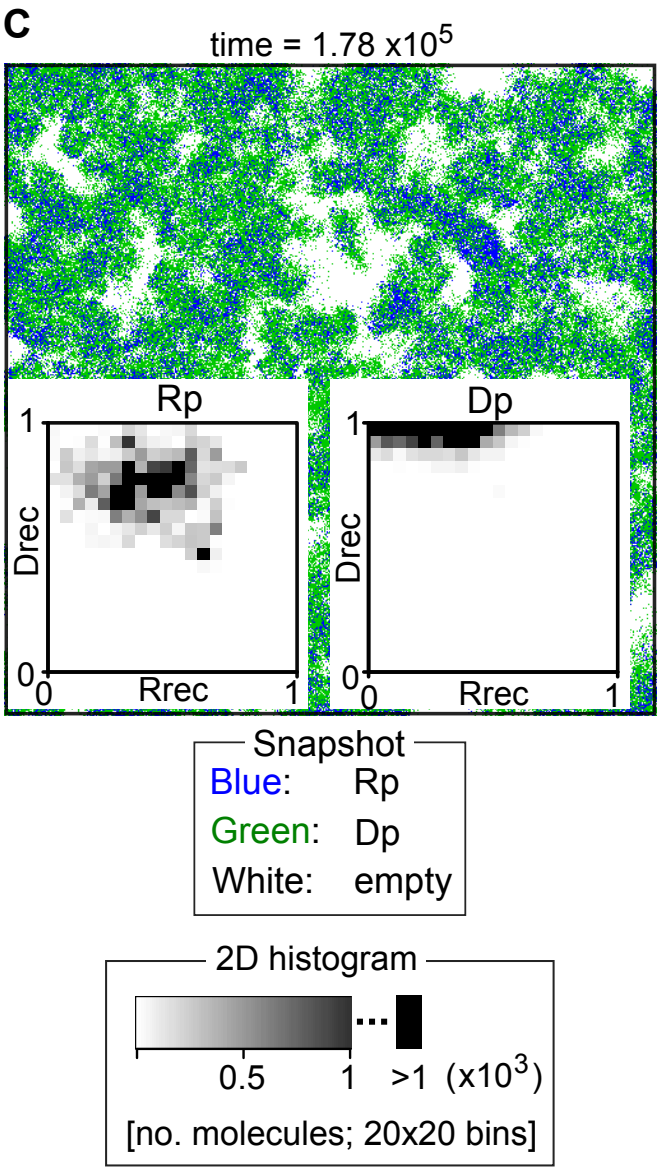
Rp

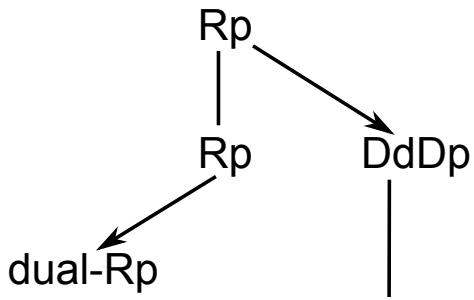
Evolution without parasites?



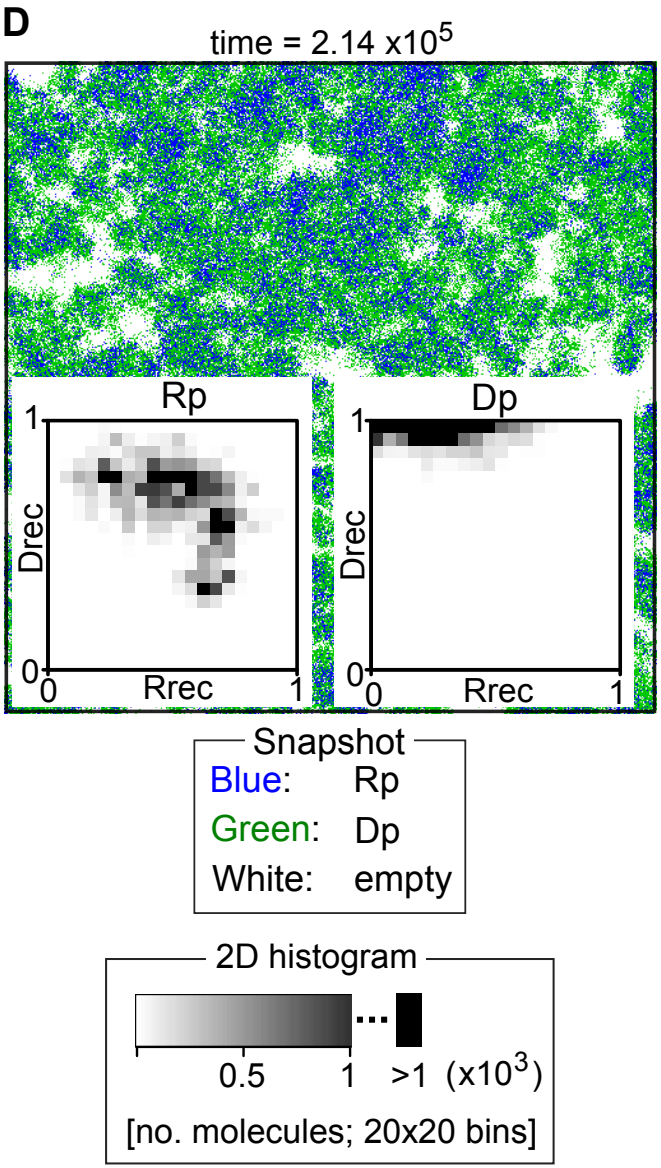


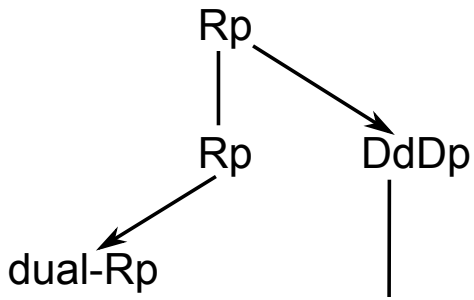
Evolution without parasites?





Evolution without parasites?





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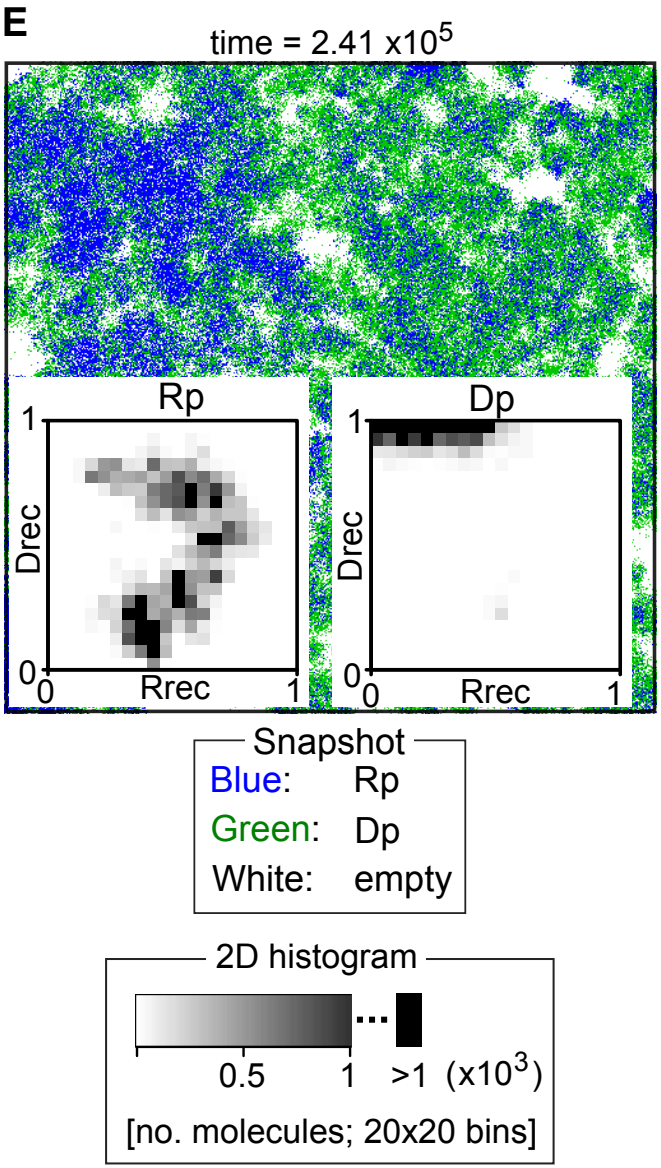

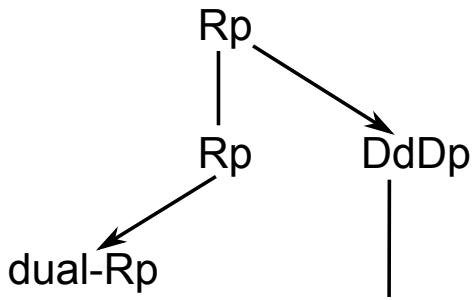

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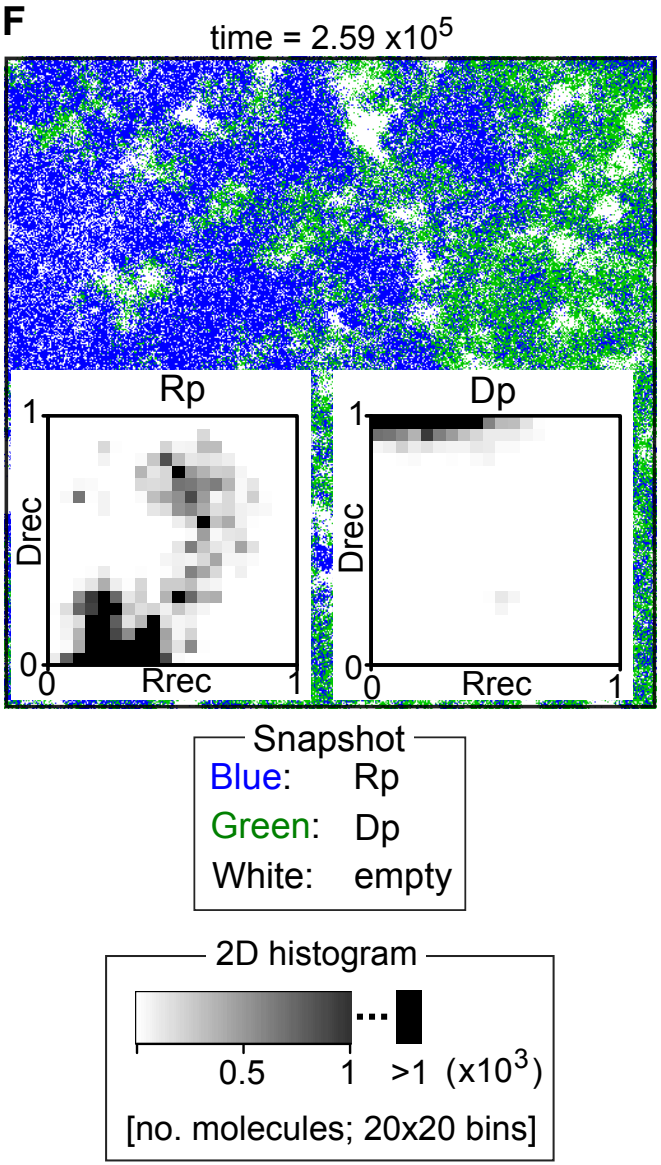
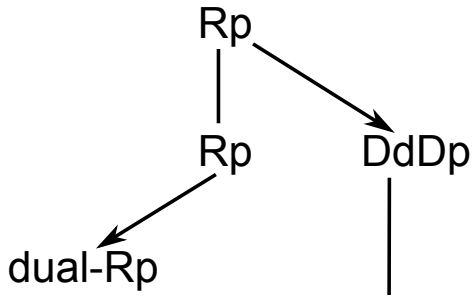
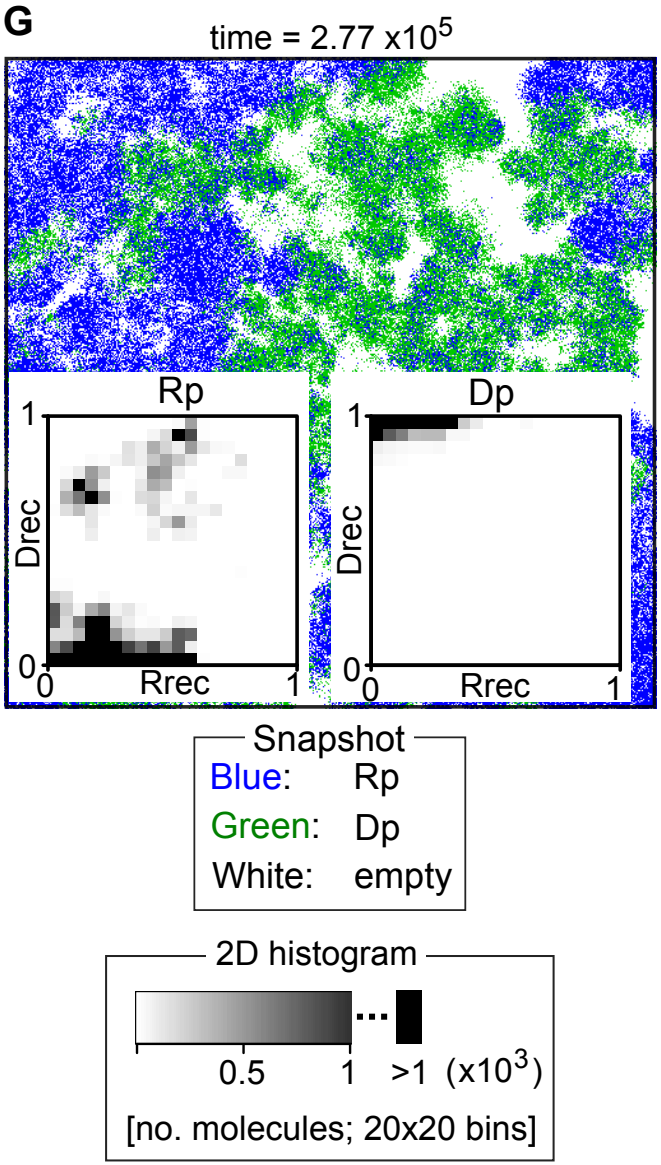
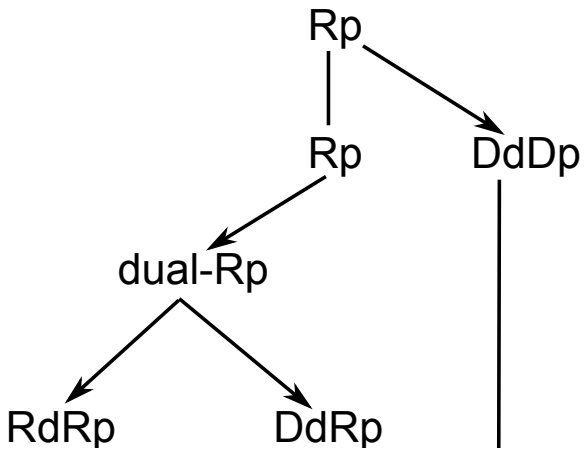




Evolution without parasites?





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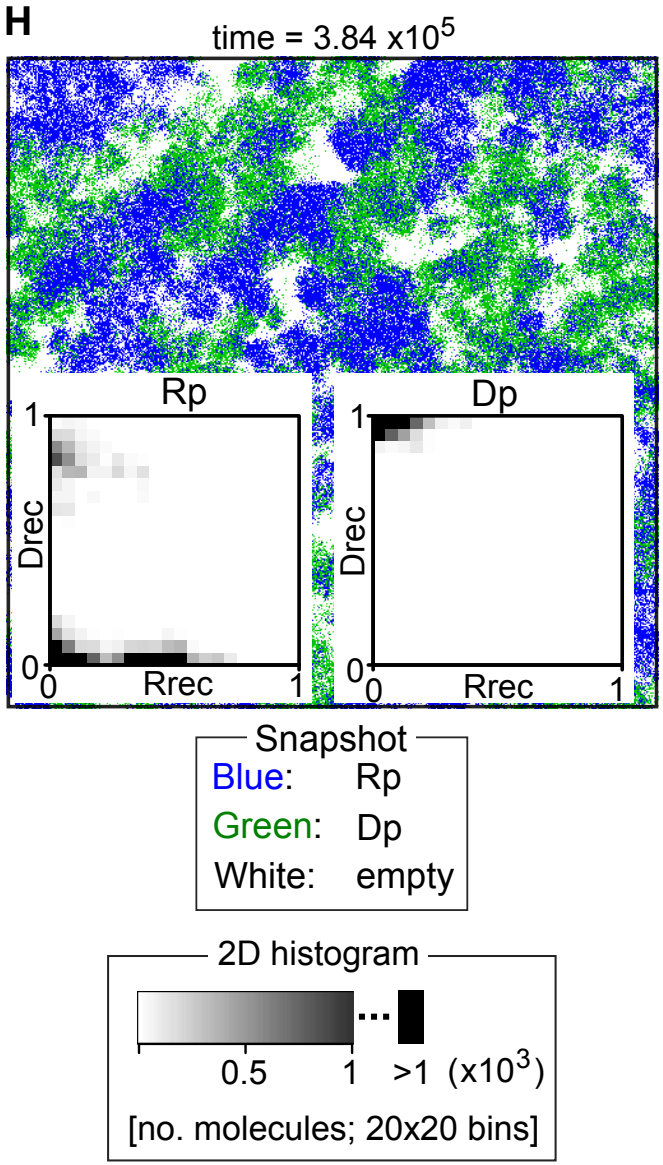

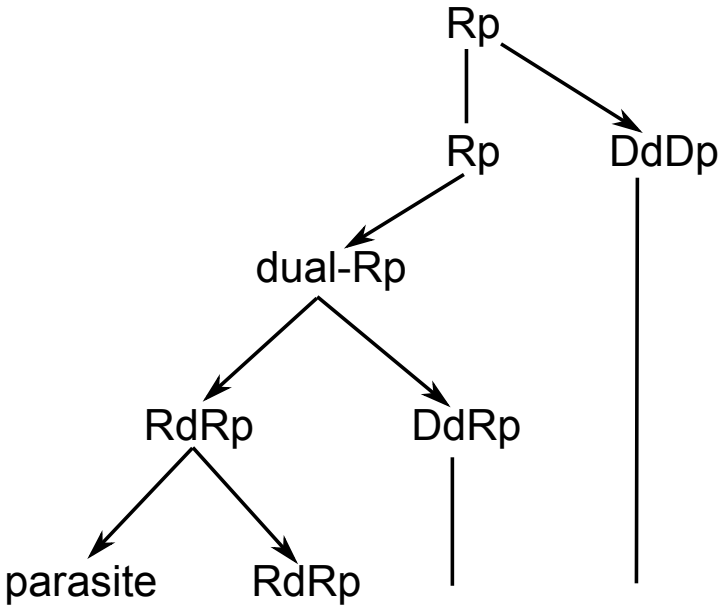

Conclusion

- Parasites pose a problem to the evolution of preconceived complexity (such as hypercycles), to which a replicator system responds by actually evolving complexity.