Modeling microbial diversity

"Deciphering Biology: the Systems Perspective of Health and Disease"

HKBU May 11, 2021

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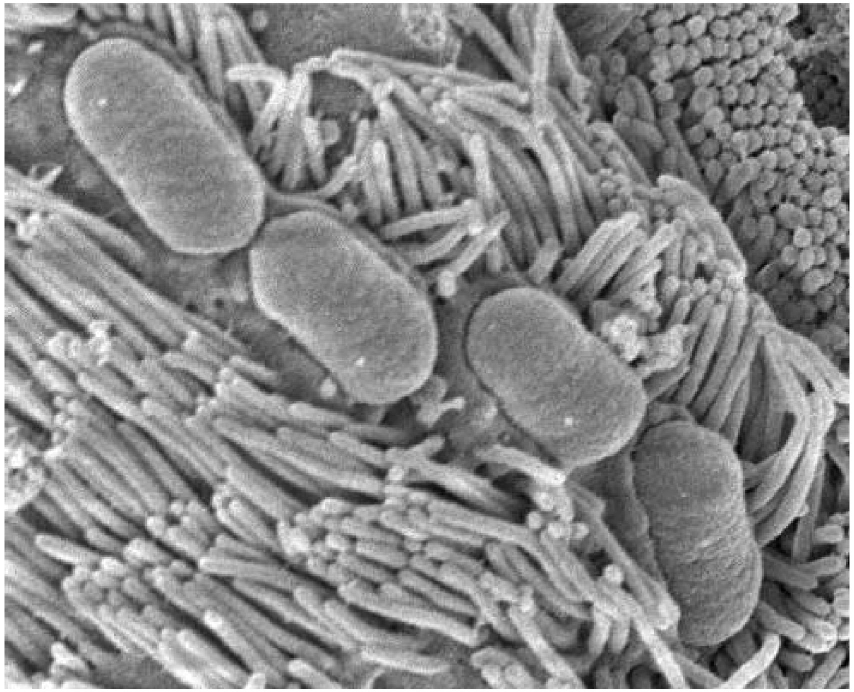
The Human Microbiome



Adult human: 10^{13} mammalian cells + 10^{13} microbial cells

>1000 bacterial phylotypes

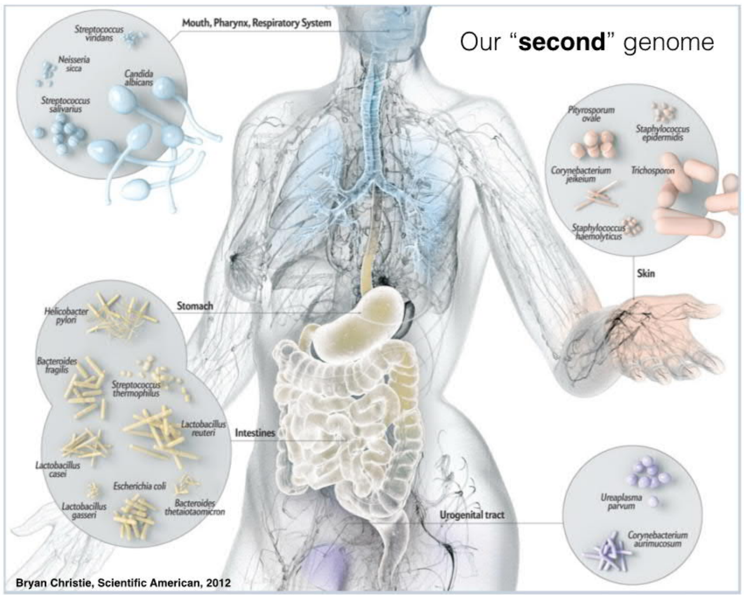
Human genome: ~ 20,000 genes
Human microbiome: ~ 100 X human genes (or more...)

What does our microbiome do?

Food digestion

Mood control

Immune system development & autoimmunity

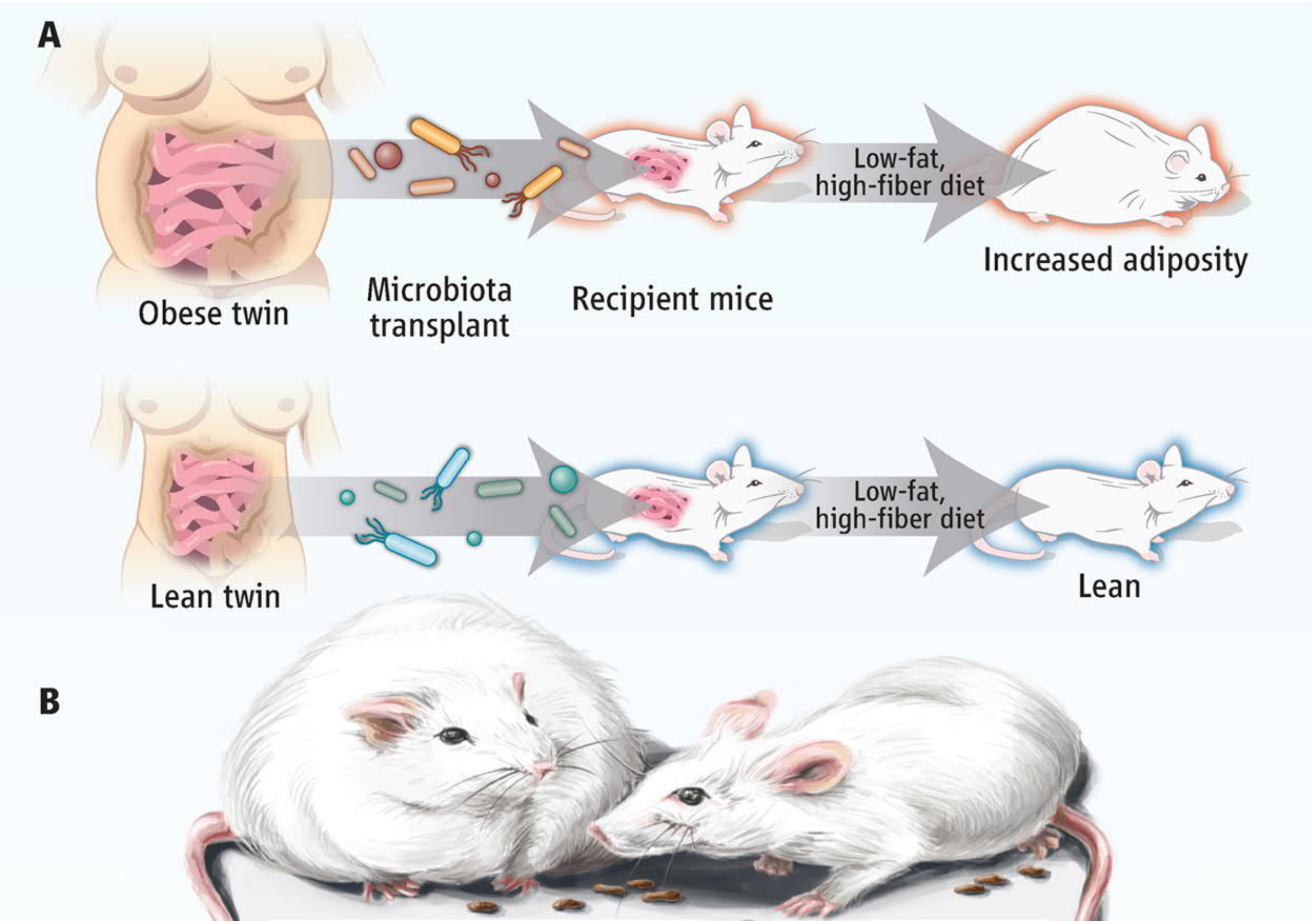


Fighting pathogens

Vitamin synthesis

Bowel function

Microbiome and Disease



Walker & Parkhill, Science (2013)

How can we understand microbiome diversity?

An astonishing characteristic of life is its great variety:

- In tropical rainforests more than 300 tree species may be found on a single hectare.
- In one gram of soil the number of distinct microbial genomes has been estimated at ~ 2000 -- 18,000.

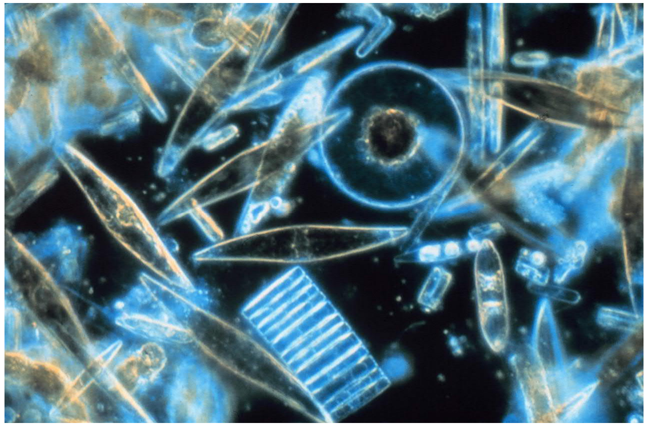
But...the competitive exclusion principle says:

- Two species that compete for the same limiting resource cannot stably coexist.
- In resource competition models, the number of species coexisting in equilibrium cannot exceed the number of resources.

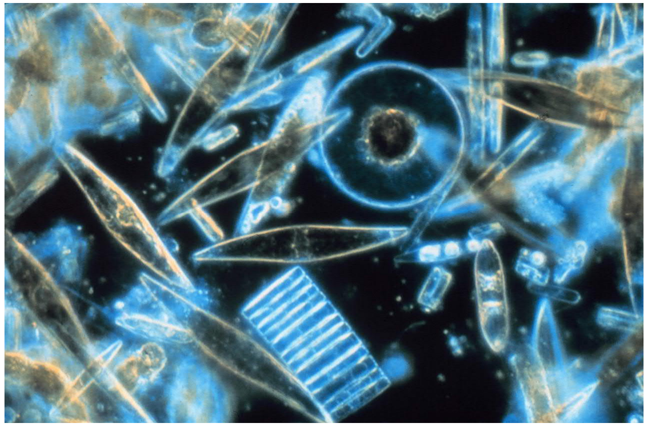
Paradox of the plankton

Originally described by G. E. Hutchinson in 1961:

"...a limited range of resources supports an unexpectedly wide range of plankton species, apparently flouting the competitive exclusion principle..."



Paradox of the plankton



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"…a limited range of resources supports an unexpectedly wide range of plankton species, apparently flouting the competitive exclusion principle…"

Possible solutions:

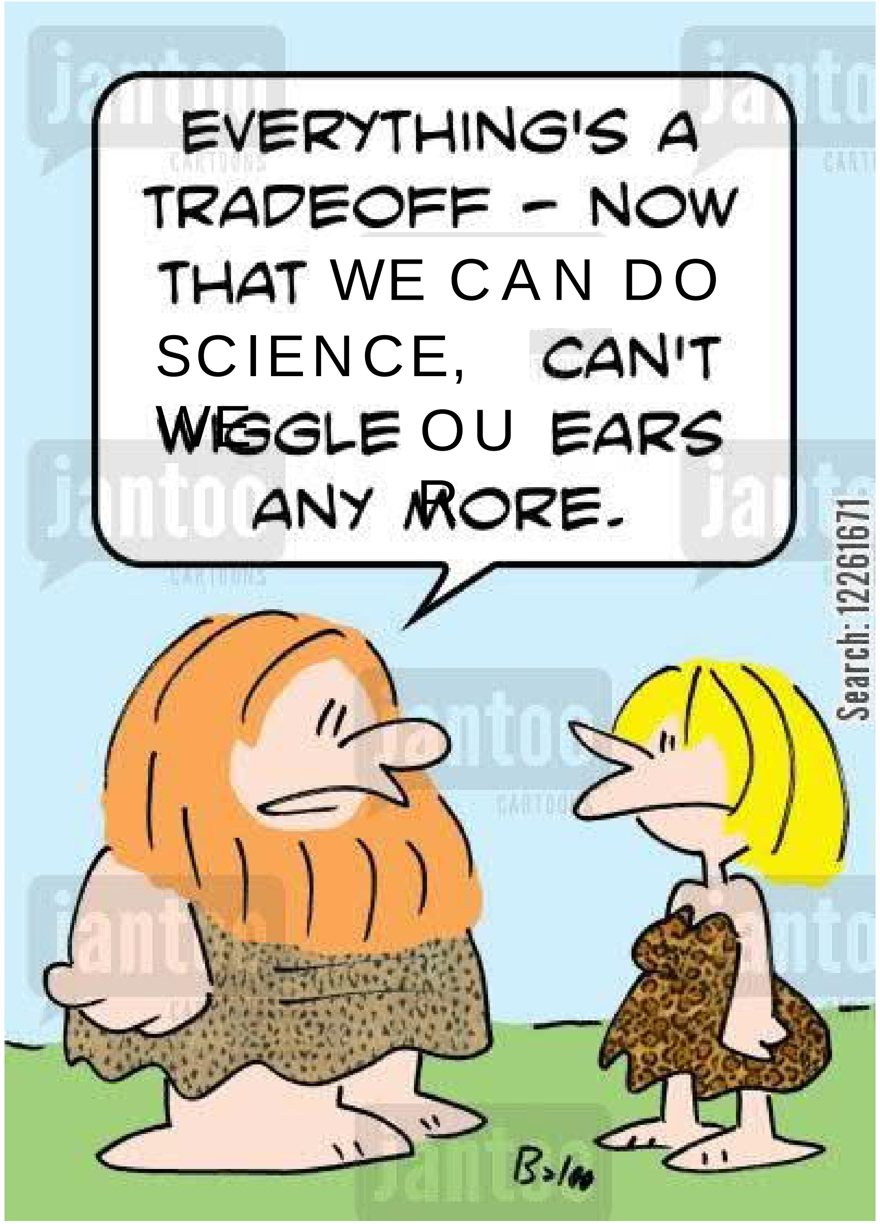
- Cross-feeding

- Oscillatory or chaotic population dynamics

- Temporal variation of environment,
  e.g. weather changes, seasonal cycles

- Spatial variation of environment,
  e.g. gradients such as temperature, salinity, exposure to light

- Other limiting factors,
  e.g. predation


EVERYTHING'S A TRADEOFF - NOW THAT WE CAN DO SCIENCE, WE CAN'T WIGGLE OUR EARS ANY MORE.
Search: 12261671

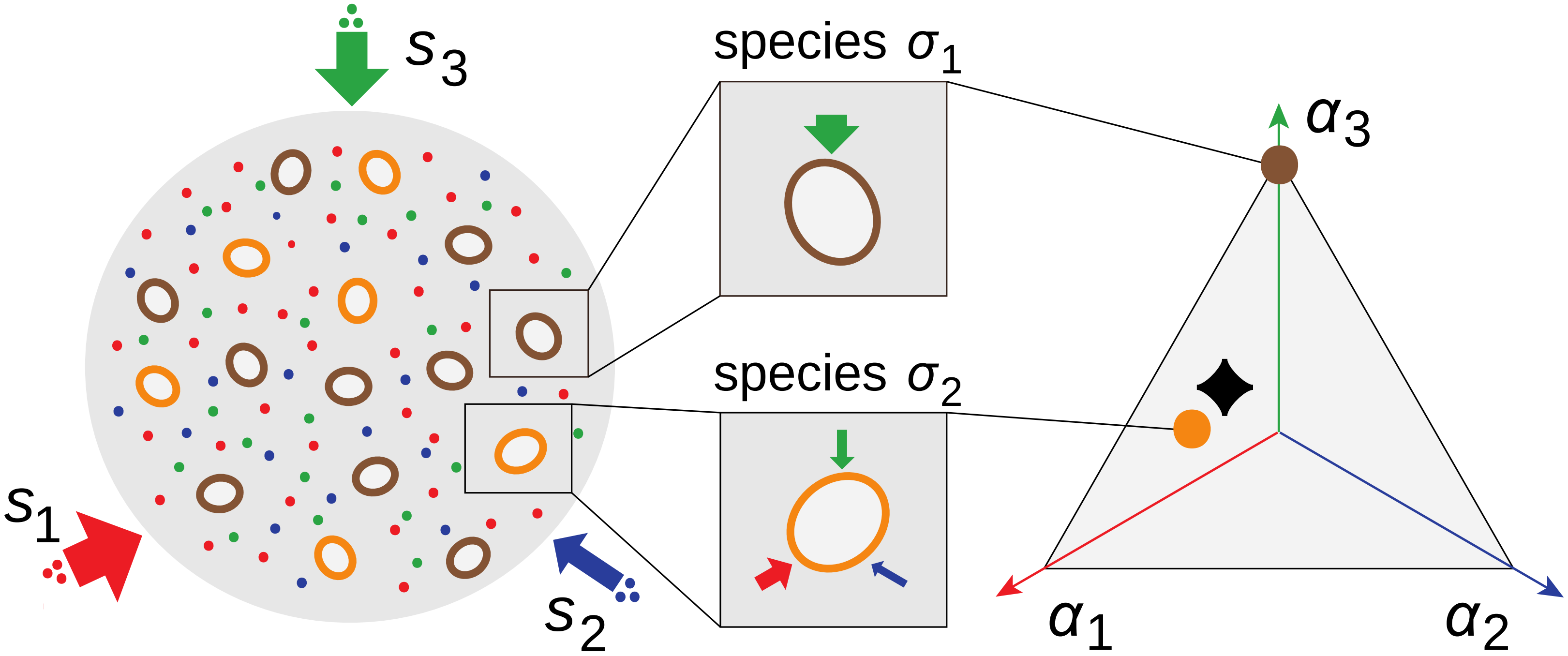
Resource-competition model with trade-offs

p resources

Species: $\vec{\alpha}_\sigma = (\alpha_{\sigma 1}, \ldots, \alpha_{\sigma p})$

Trade-offs in ability to utilize different resources:

$$\sum_{i=1}^{p} w_i \alpha_{\sigma i} = E$$



Q & A Break

Resource-competition model with trade-offs

Nutrient concentrations dynamics:

$$\dot{c}_i = s_i - \sum_\sigma n_\sigma \, \alpha_{\sigma i} \frac{c_i}{K_i + c_i} - \mu_i c_i$$

$$= \text{supply} \;-\; \text{consumption} \;-\; \text{loss}$$

Growth rate of species σ:

$$g_\sigma(\vec{c}) = \sum_{i=1}^{p} v_i \, \alpha_{\sigma i} \frac{c_i}{K_i + c_i}$$

Population dynamics:

$$\dot{n}_\sigma = (g_\sigma(\vec{c}) - \delta) \, n_\sigma$$

Simplified parameters:

- no nutrient loss: $\mu_i = 0$
- separation of time scales: $\dot{c}_i = 0$
- “symmetric” nutrients: $w_i = K_i = v_i = 1$

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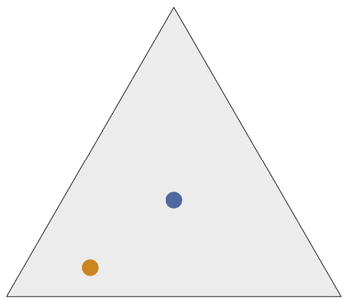
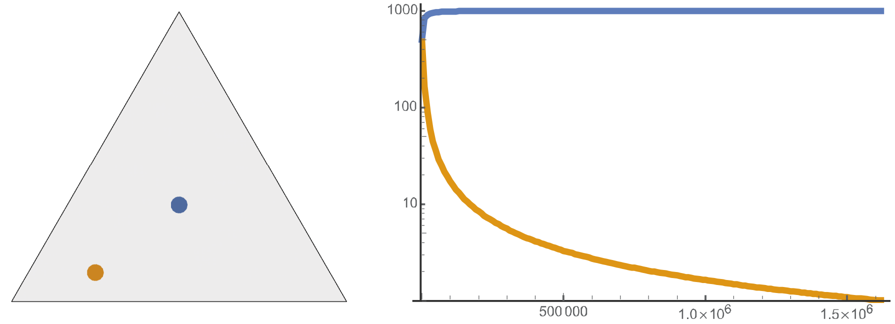
$$\dot{n}_\sigma = \left(\sum_{i=1}^{p} \alpha_{\sigma i} \frac{s_i}{\sum_\kappa \alpha_{\kappa i} n_\kappa} - \delta \right) n_\sigma, \qquad \sum_{i=1}^{p} \alpha_{\sigma i} = E$$

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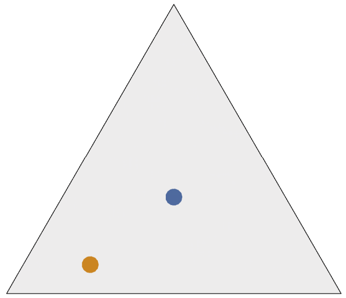

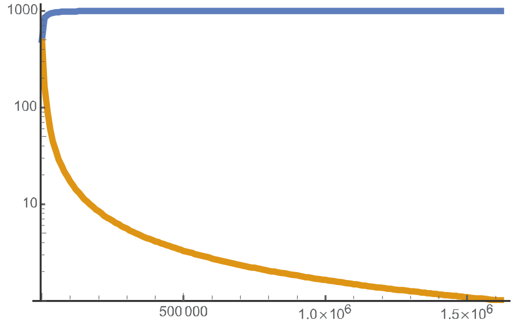
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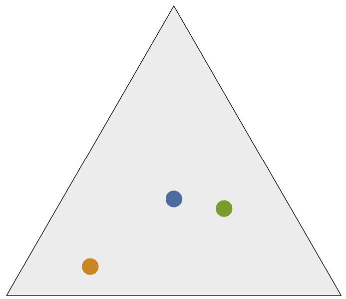

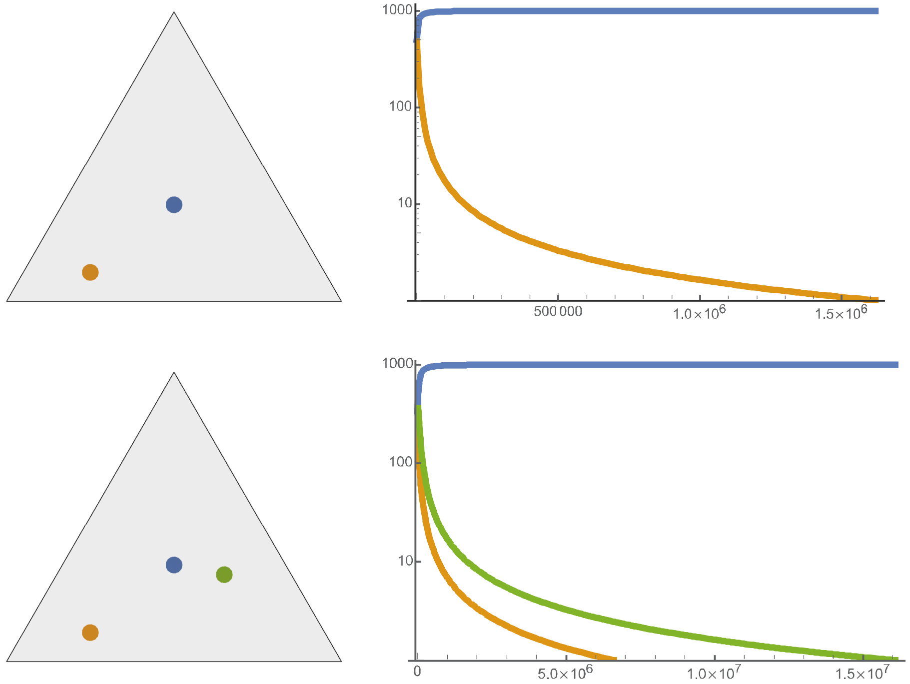

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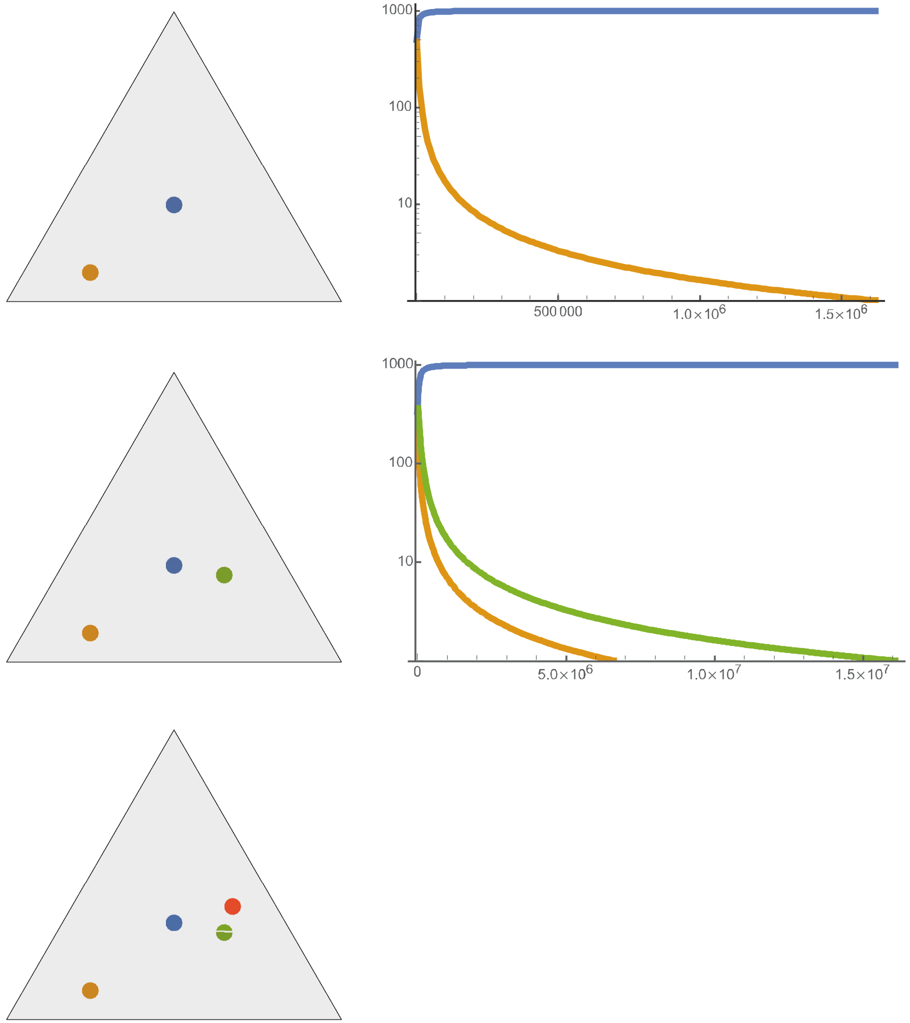

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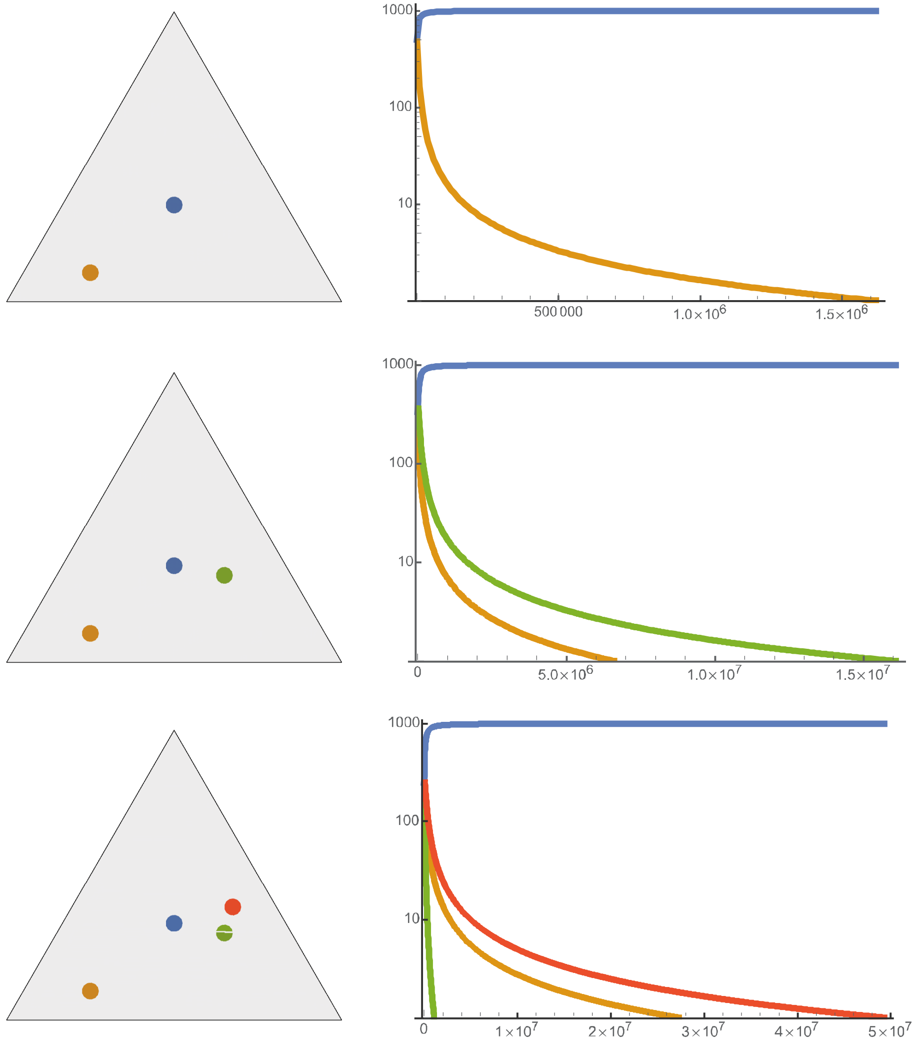
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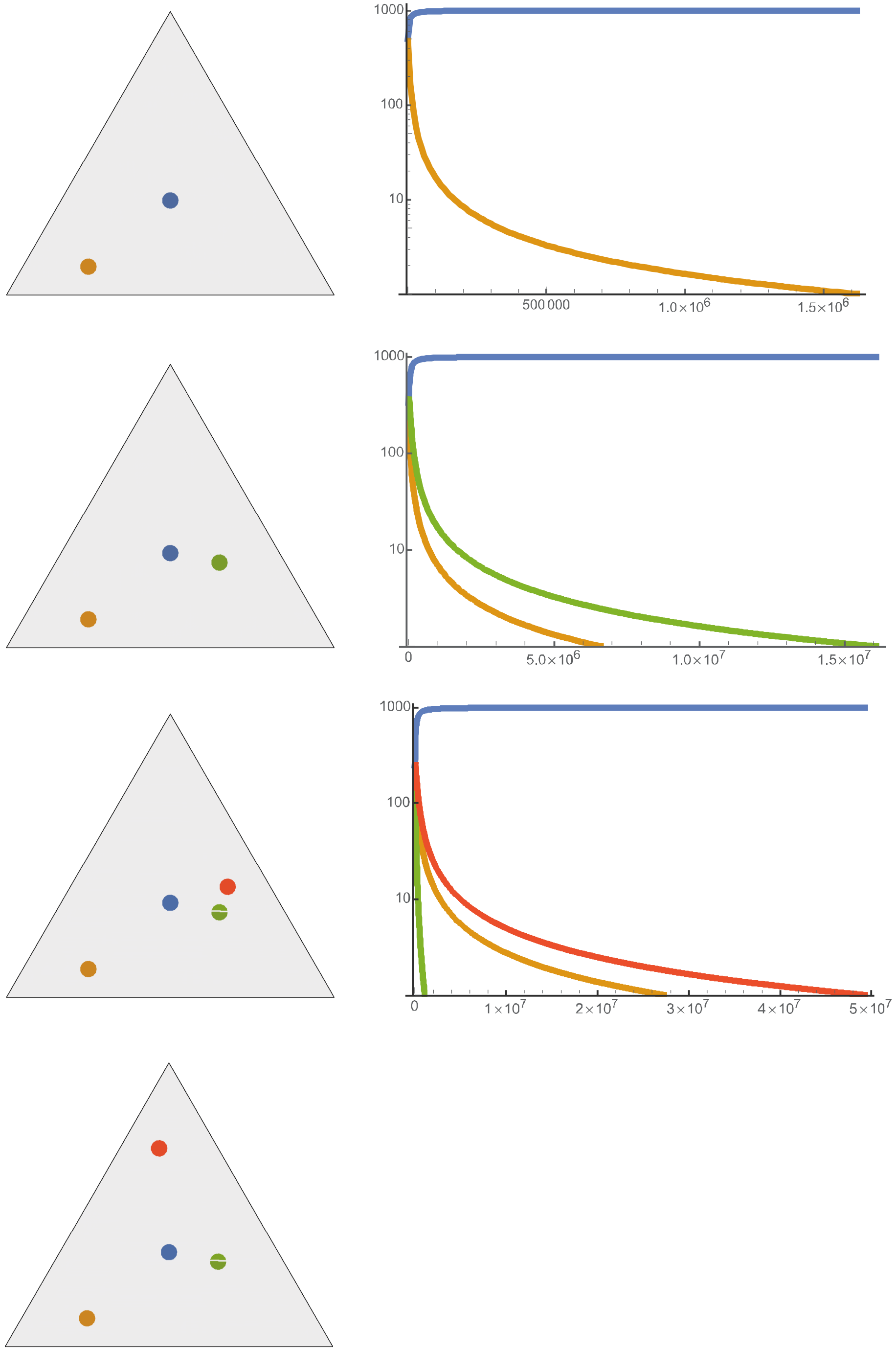

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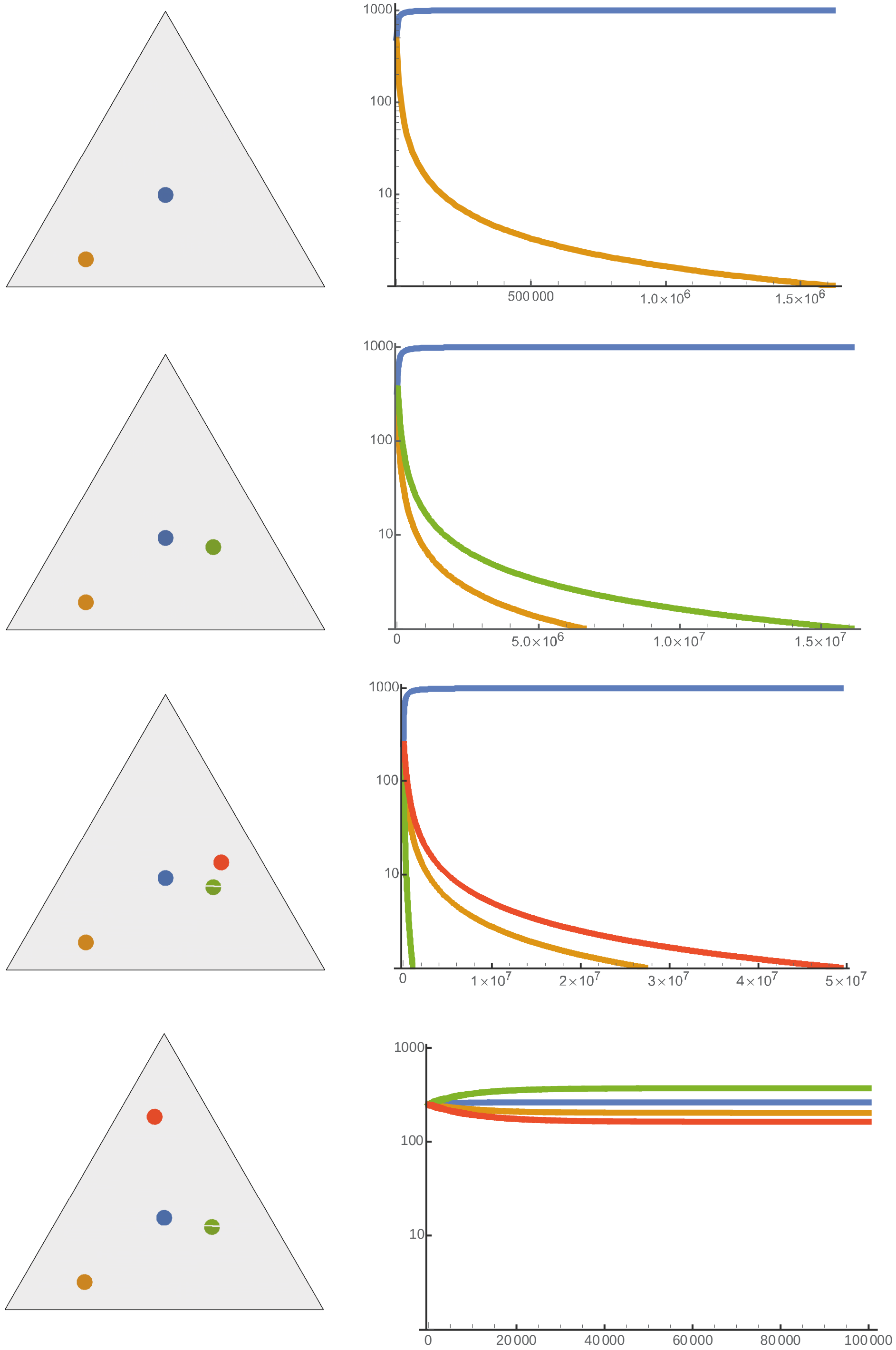

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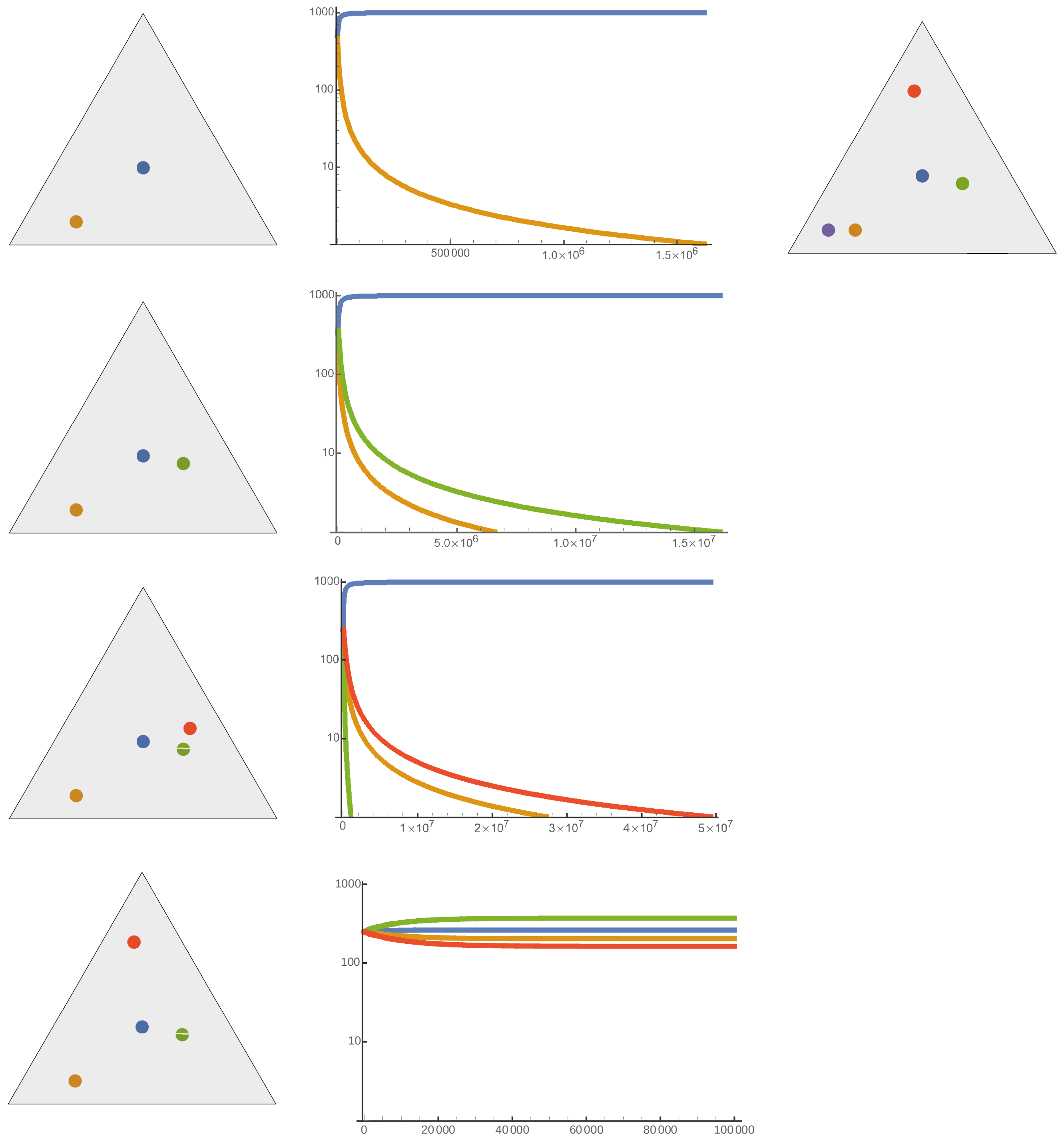
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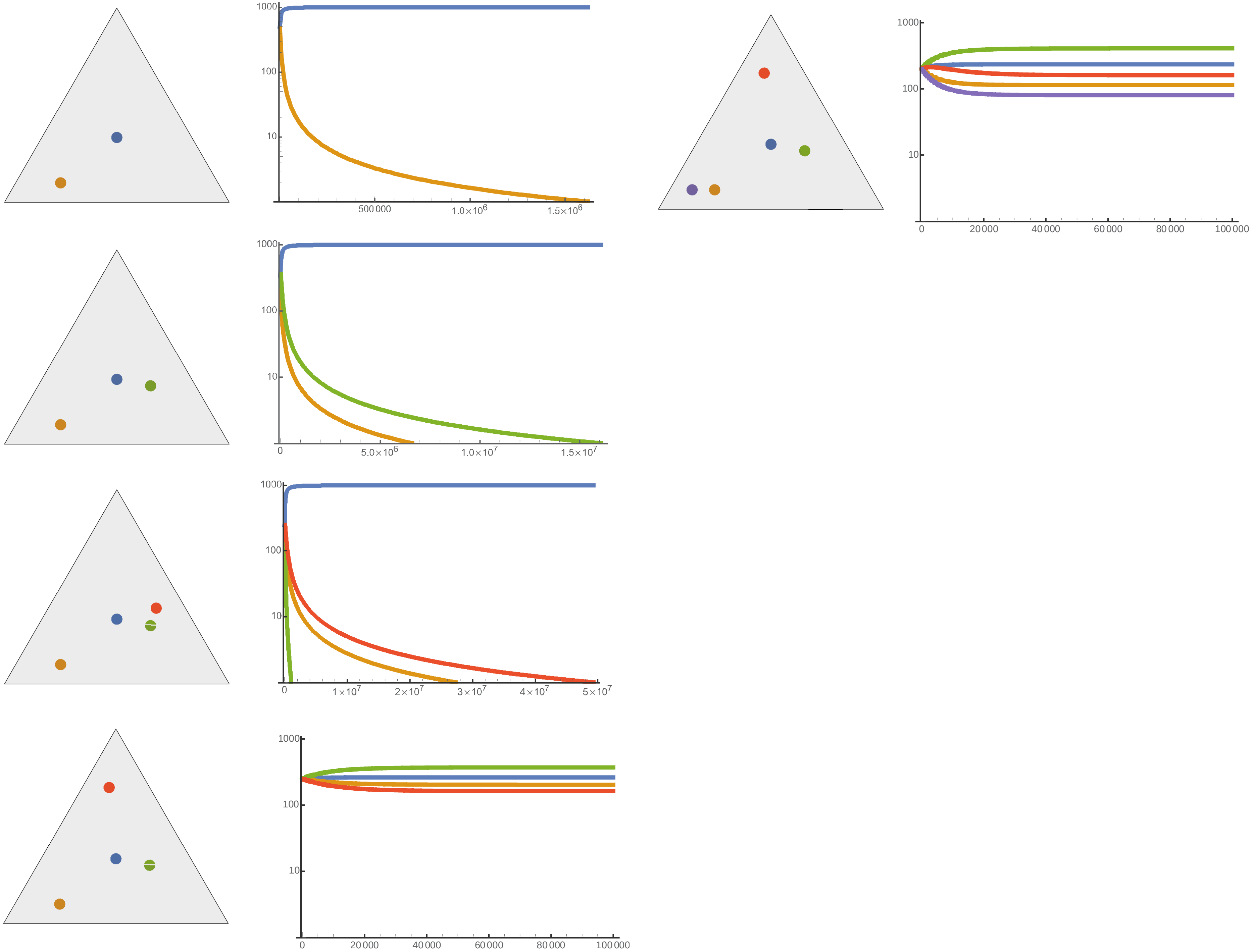
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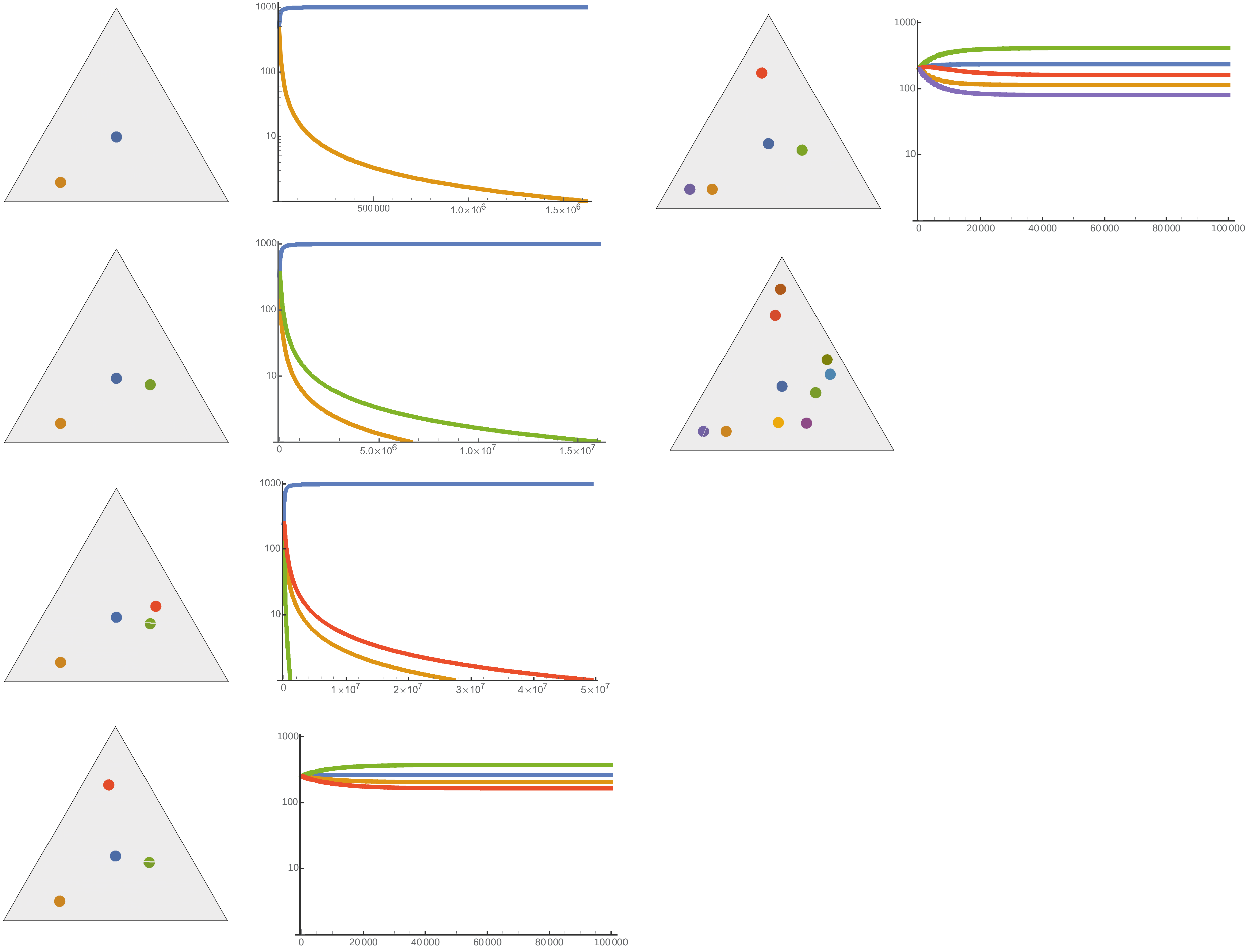
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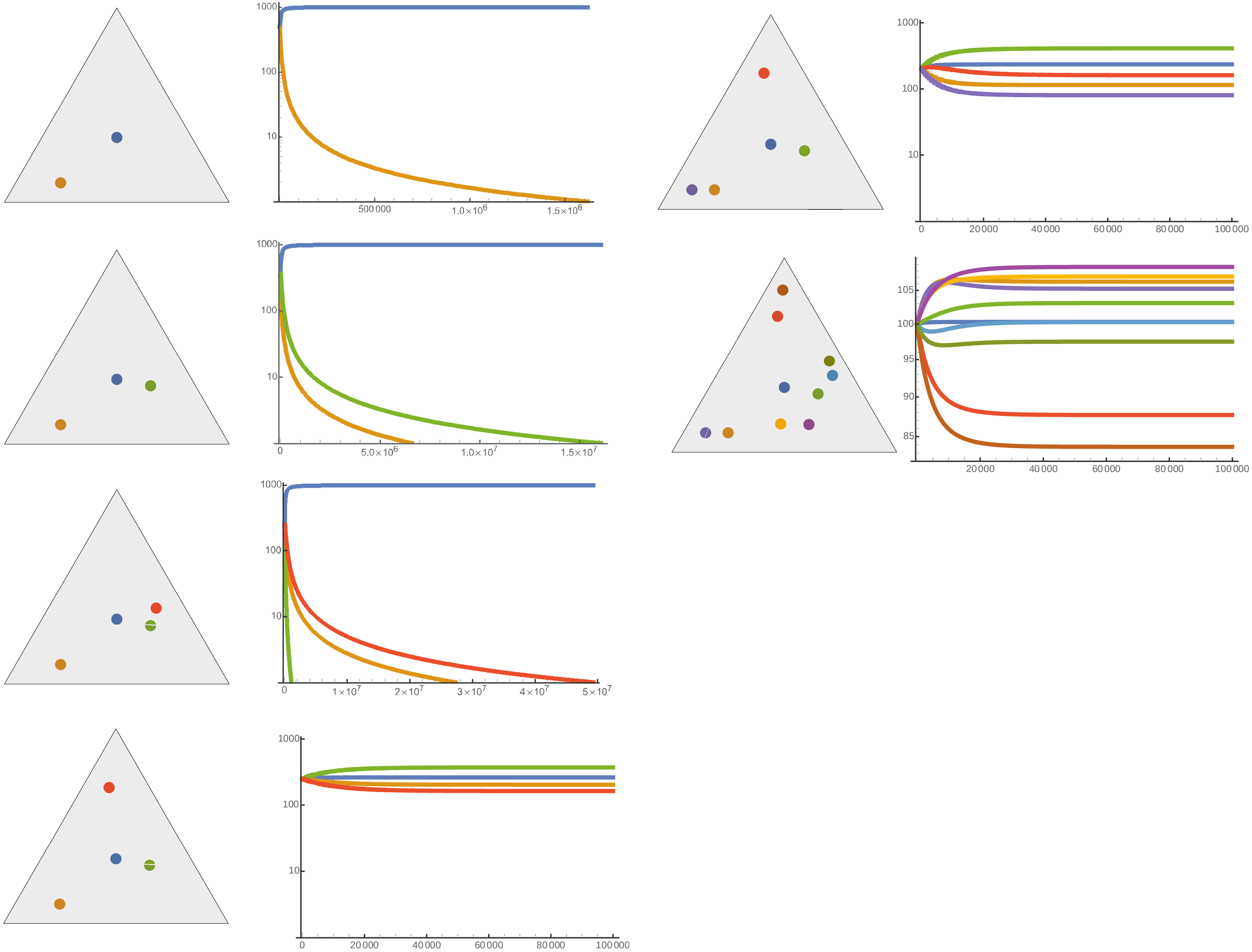

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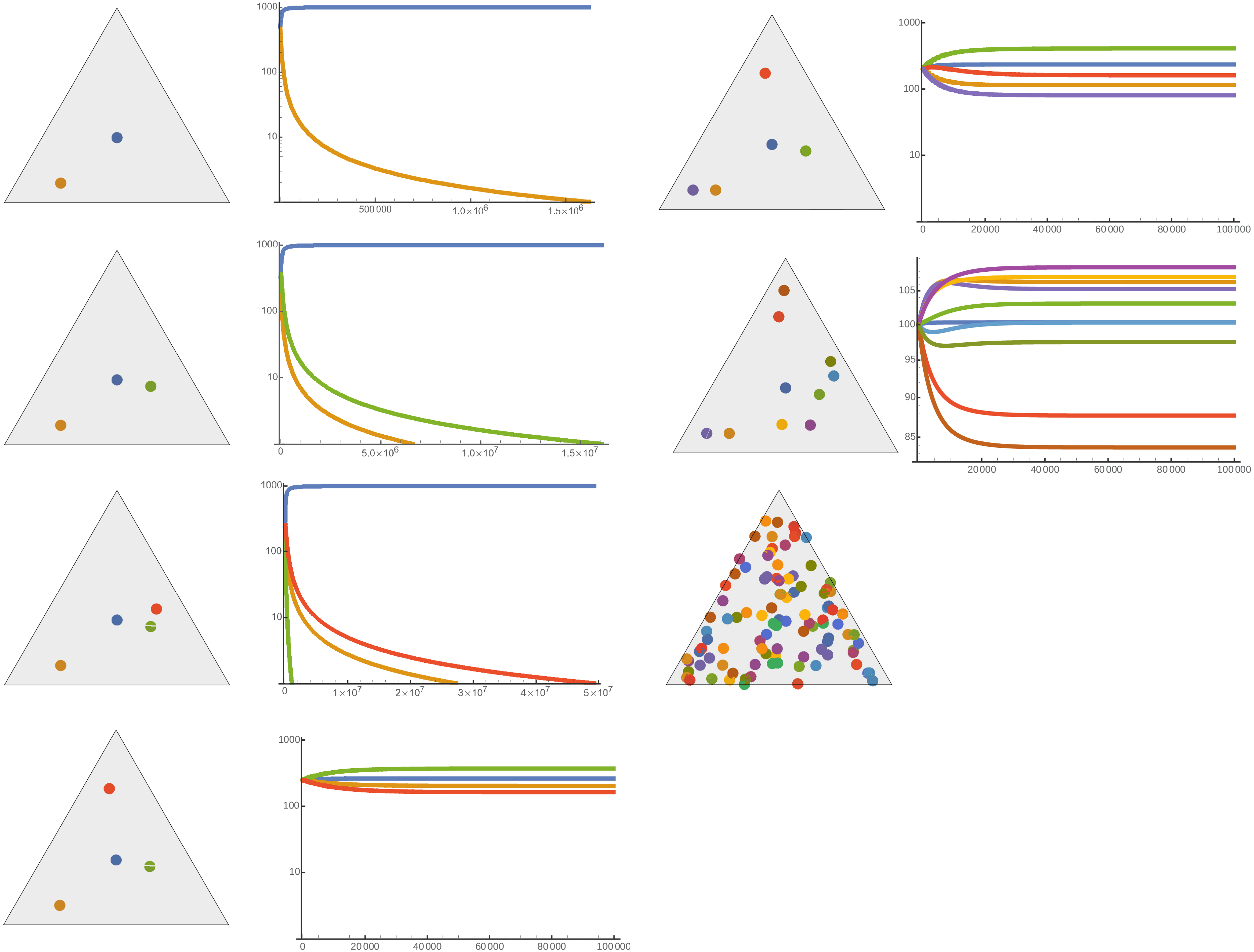

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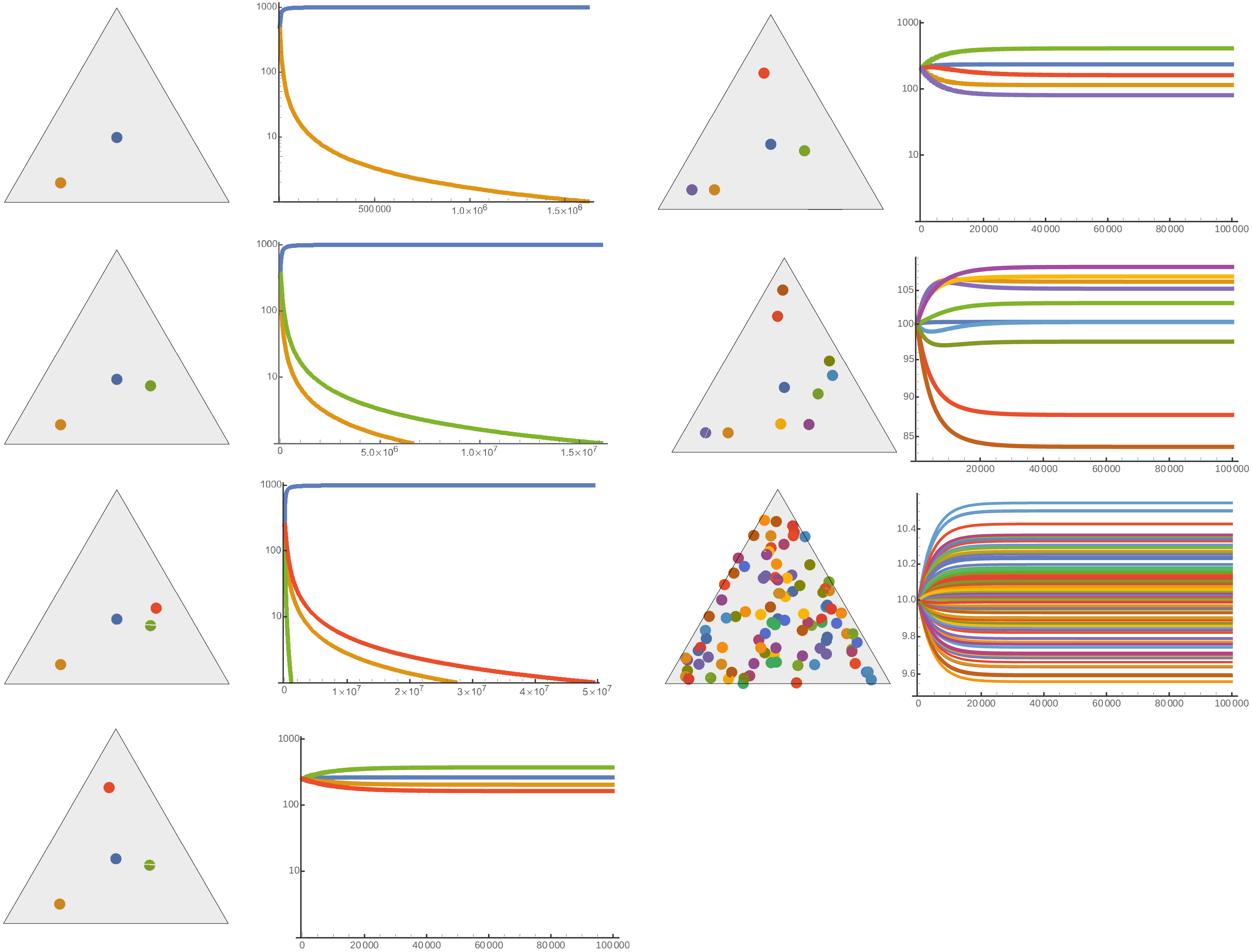

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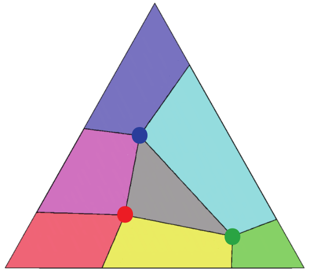
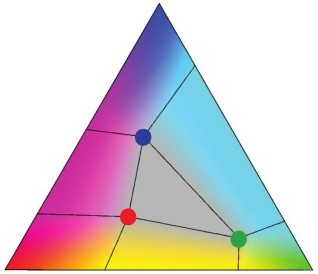
species = # resources:



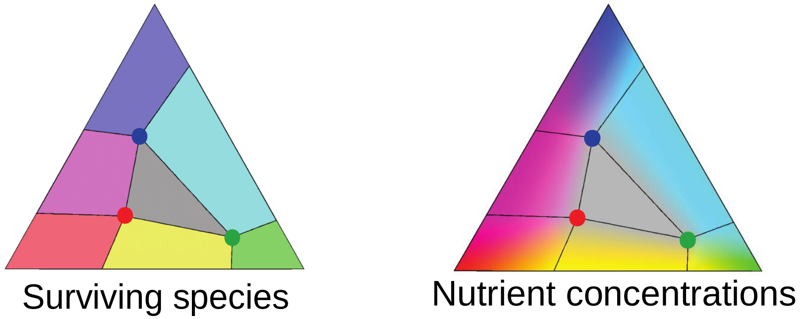
Surviving species



Nutrient concentrations

$$g_\sigma(\vec{c}) = \sum_i \alpha_{\sigma i} \frac{c_i}{1 + c_i}$$

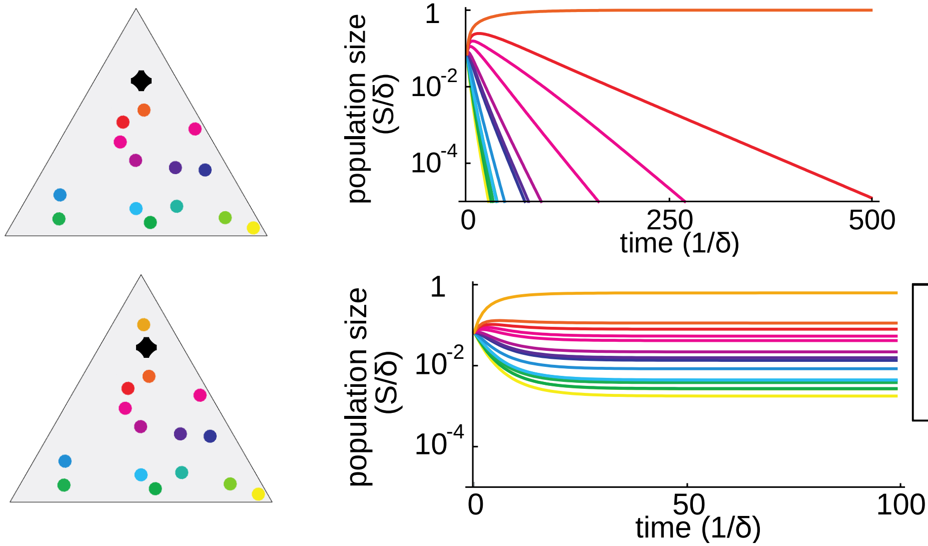
$\#$ species $=$ $\#$ resources:



$$g_\sigma(\vec{c}) = \sum_i \alpha_{\sigma i} \frac{c_i}{1+c_i}$$

$\#$ species $\geq$ $\#$ resources:

A collection of $\{\vec{\alpha}_\sigma\}$ species coexist in steady state $\Leftrightarrow$ the supply $\vec{s}$ lies within the convex hull of the species $\{\vec{\alpha}_\sigma\}$.



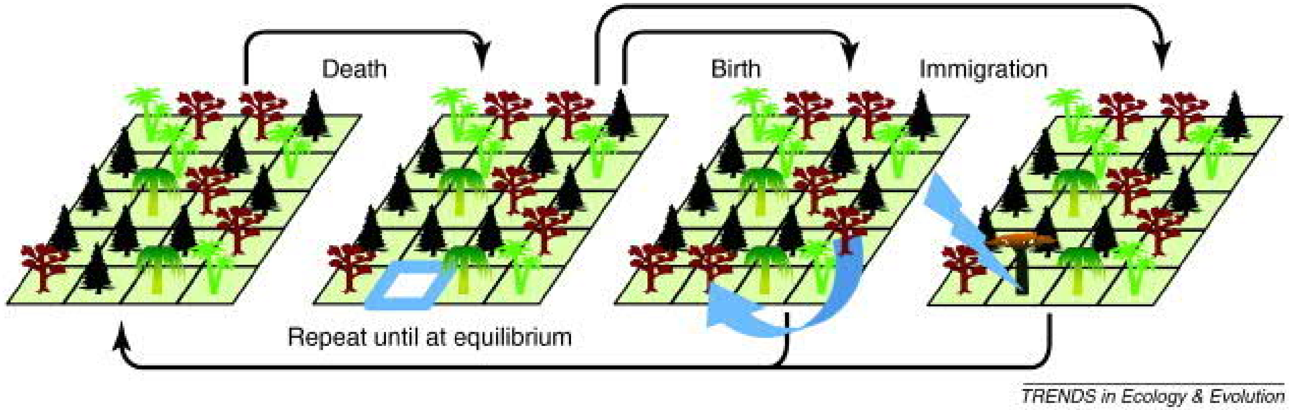
Gold species acts as “keystone species”.

Competition → nutrient concentrations too low for certain species to survive → at most #resources-1 species survive.
Neutrality → balanced nutrient concentrations → all species equally fit → all species survive!

Q & A Break

The neutral theory of biodiversity

Neutral theory: species are ecologically equivalent, and diversity emerges from ecological drift.



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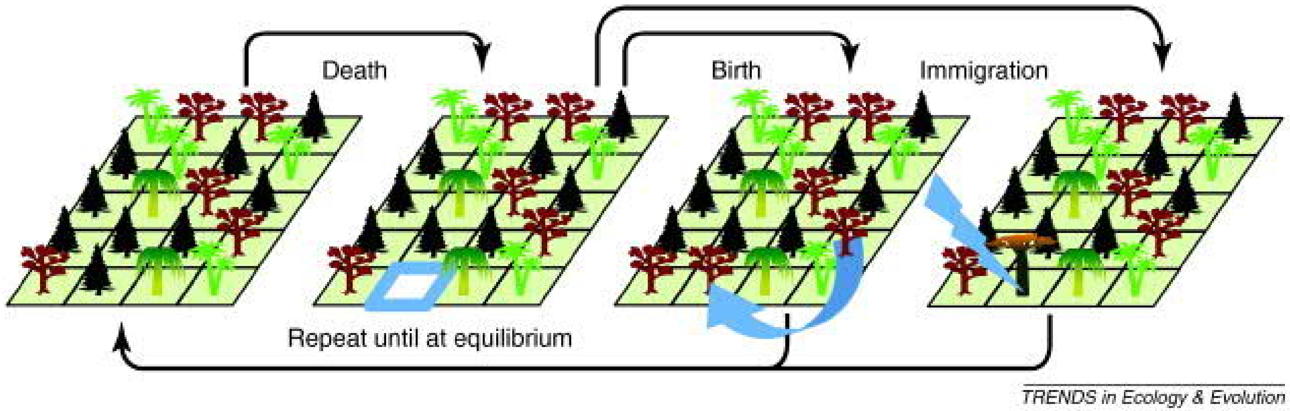
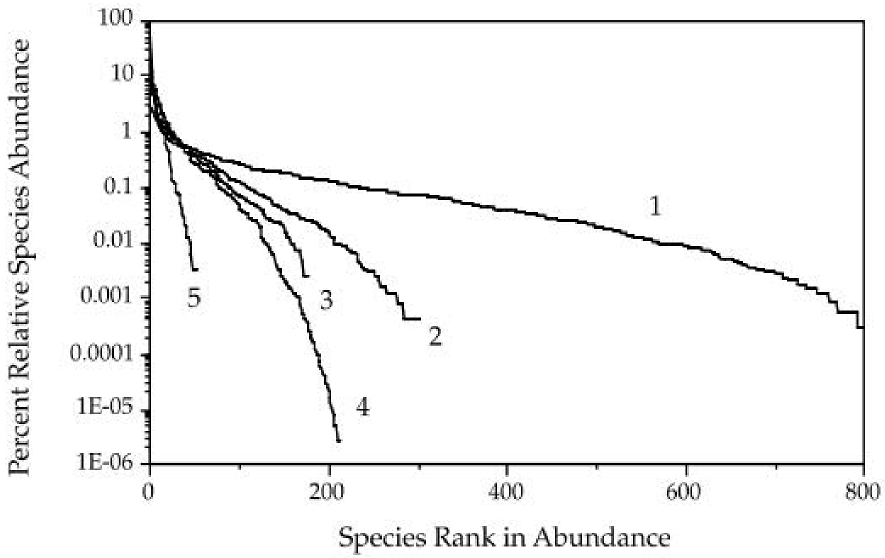




1. Tropical wet forest in Amazonia
2. Tropical dry deciduous forest in Costa Rica
3. Marine planktonic copepod community from the North Pacific gyre
4. Terrestrial breeding birds of Britain
5. Tropical bat community from Panama

S. Hubbell: The Unified Neutral Theory of Biodiversity and Biogeography

Connection to the neutral theory of biodiversity

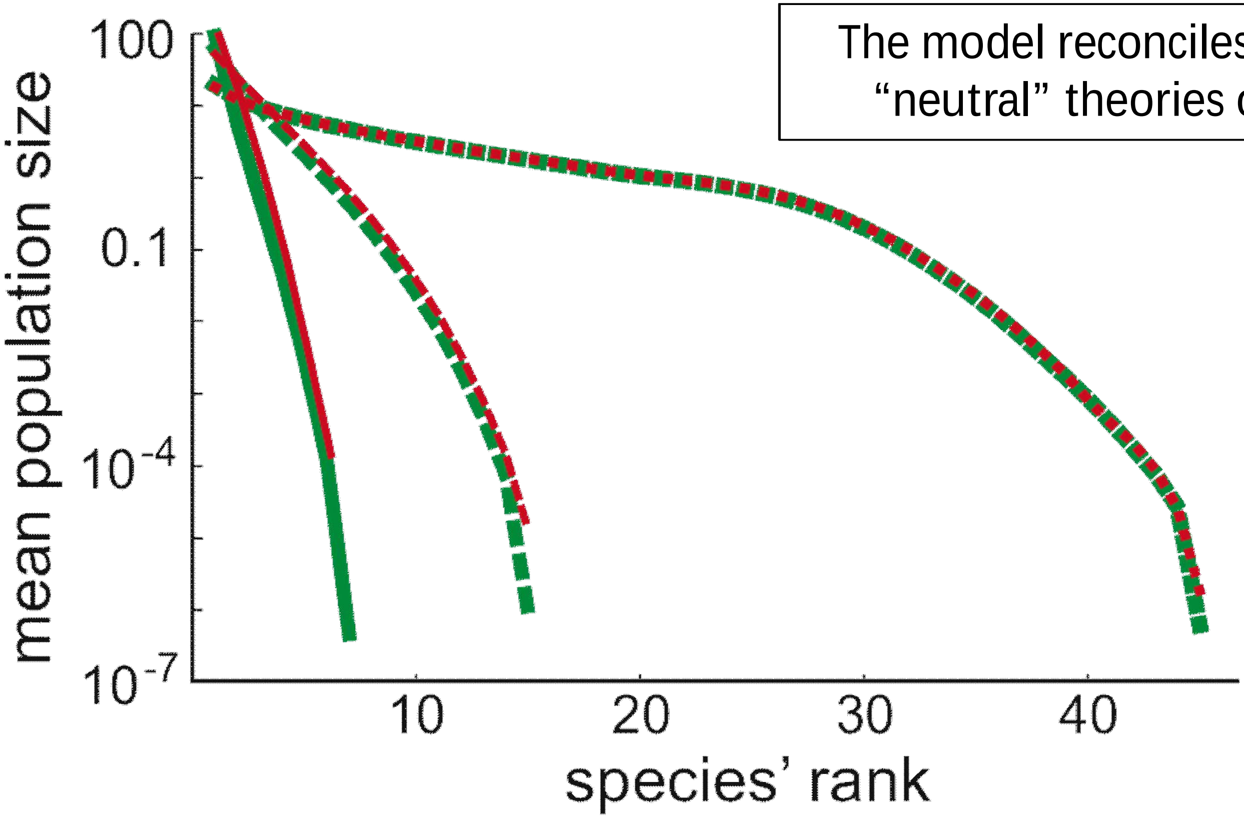
Rank-abundance curves

red – resource-competition model

green – neutral model

total population: $N_{\text{tot}} = 100$

immigration probabilities: $\nu = 0.001, 0.01, 0.1$



The model reconciles "niche" and "neutral" theories of diversity.

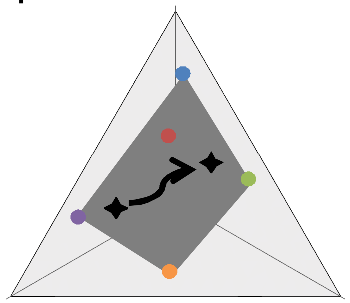
Robustness of coexistence

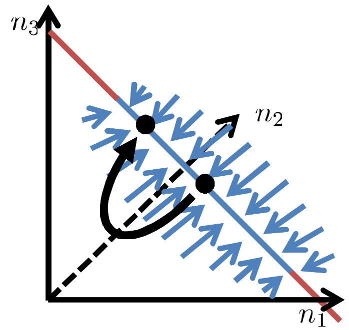
I. Against population disturbances
II. Against fluctuations in nutrient availability
III. Against variability in species' budgets and death rates

Robustness of coexistence

II. Against fluctuations in nutrient availability:

If nutrient supply changes, but remains in the convex hull of the species, the populations find a new equilibrium of coexistence.





Robustness of coexistence

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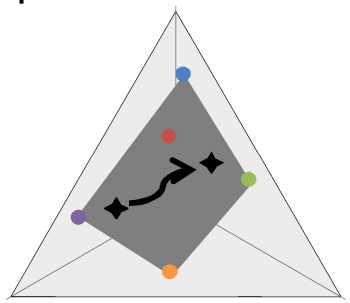
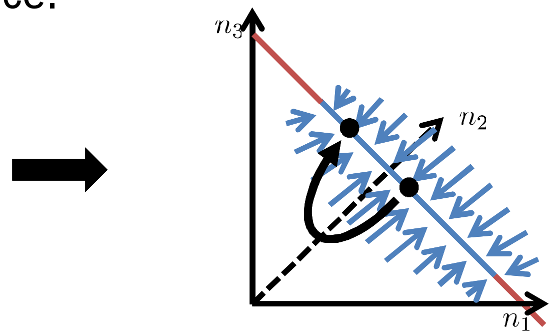
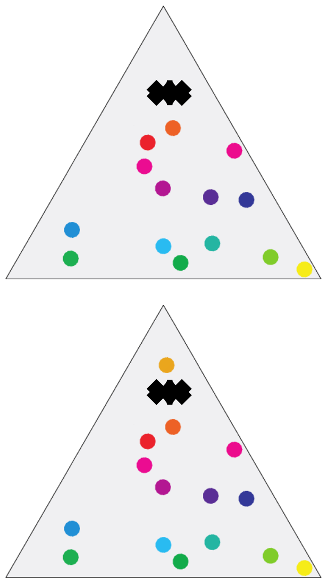
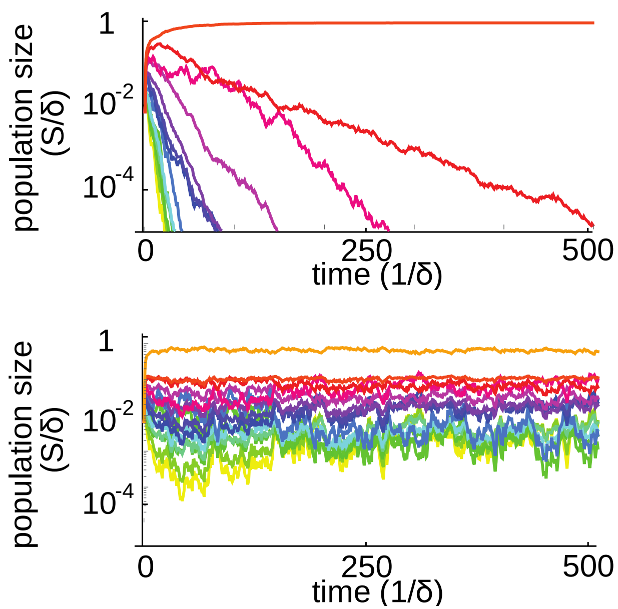




Time-dependent nutrient supply: The supply regularly changes, at a fixed time interval T, to a new randomly selected supply, while the total supply is fixed:





Mean supply hypothesis: A collection of species $\{\vec{\alpha}_\sigma\}$ coexist.

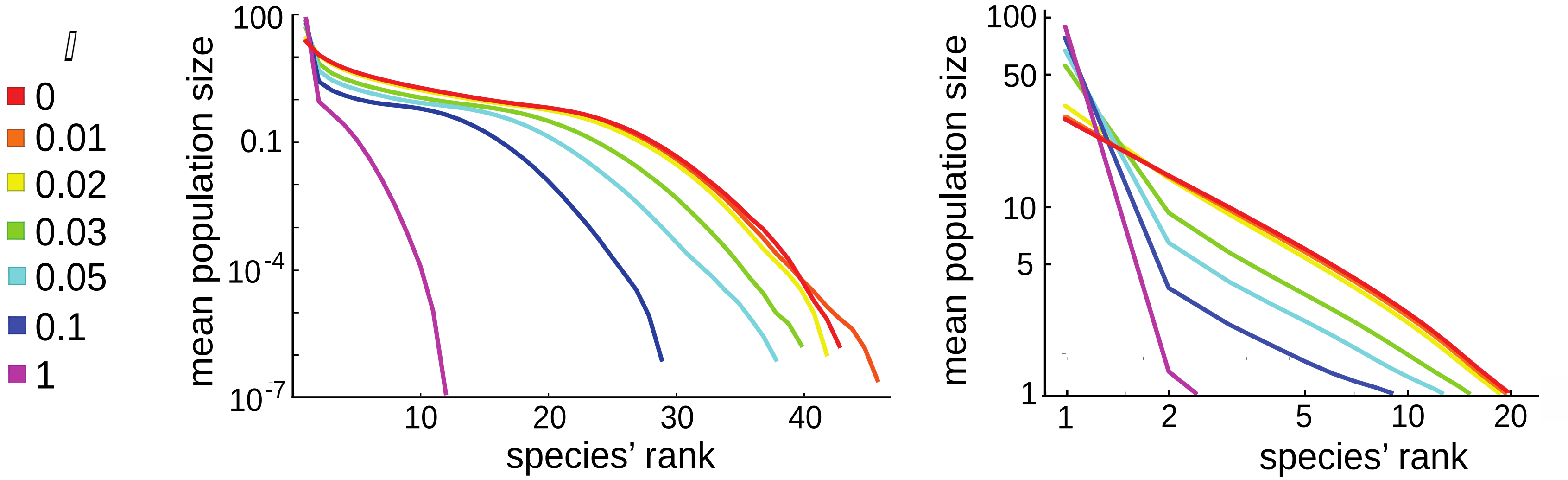
⇕

The mean supply $\langle \vec{s} \rangle$ lies within the convex hull of the species $\{\vec{\alpha}_\sigma\}$.

Robustness of coexistence

III. Against variability in species' budgets and death rates:

In the deterministic version of the model, diversity is lost. However, in the stochastic version, diversity can be maintained:



$\Sigma \leq 0.02$ ⇨ High diversity

$\Sigma \geq 0.03$ ⇨ Low diversity

Conclusions

- Features of model that allow for coexistence:
  - Organisms take part in shaping their environment.
  - All species are subject to the same trade-offs.

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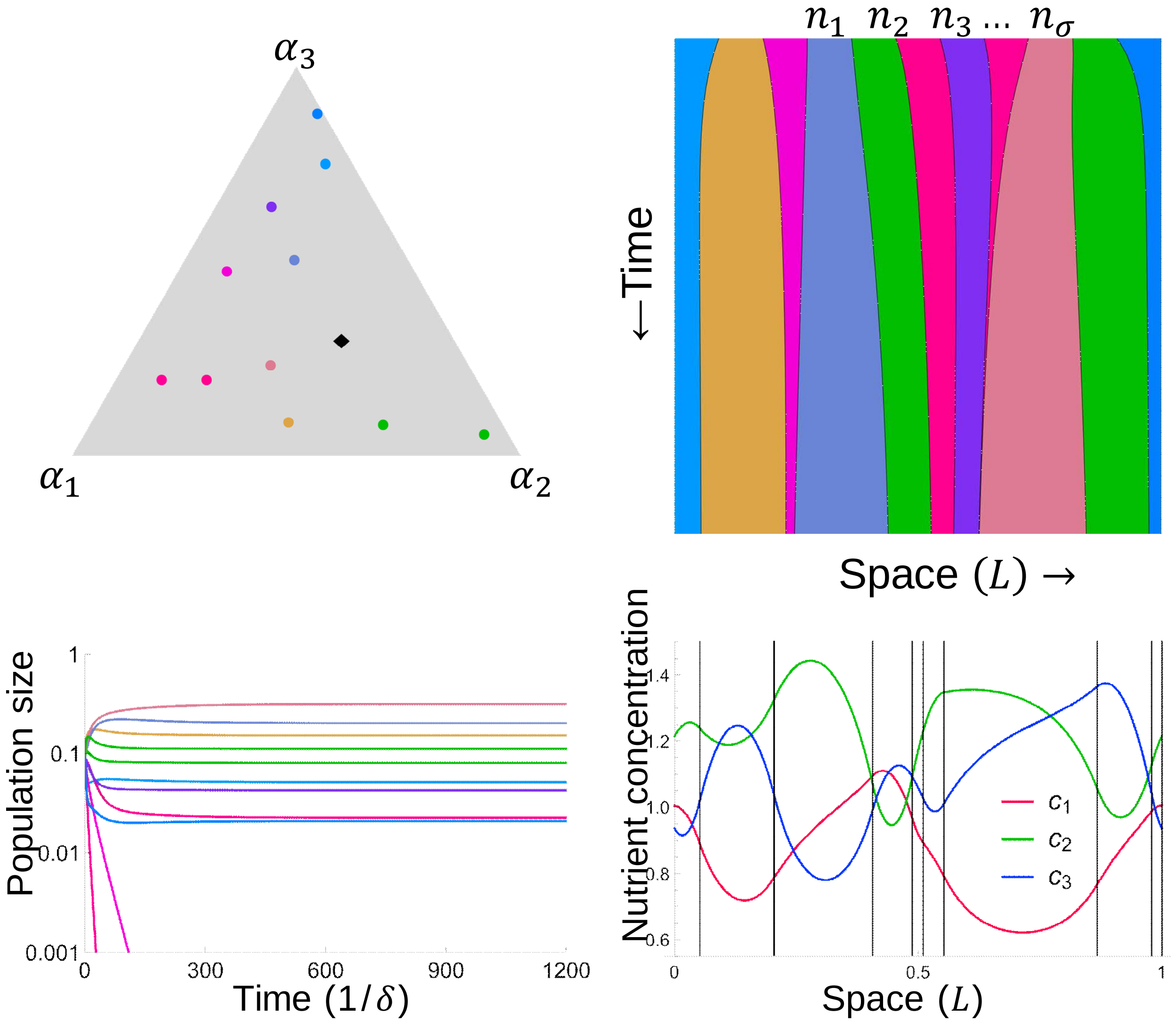
- Beyond the chemostat:
  - Spatial structure

Spatial structure



Weiner, Posfai, & NSW, PNAS (2019)

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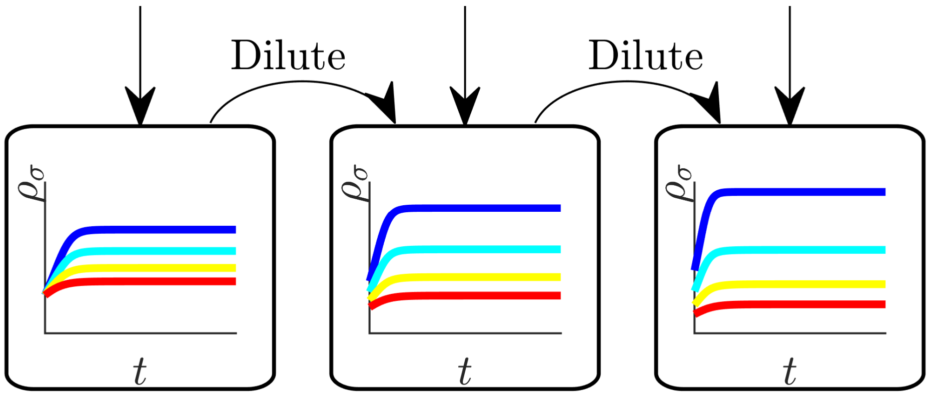
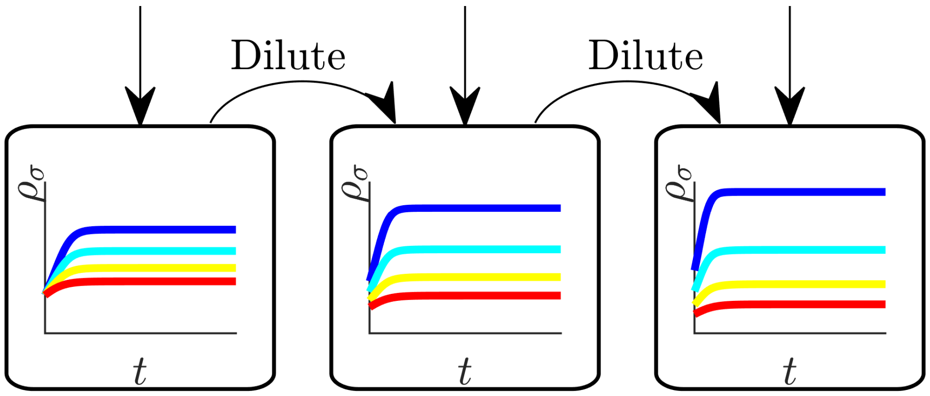
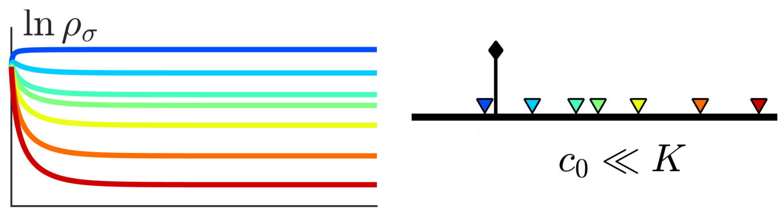
  - "Seasonal" ecosystem

“Seasonal” ecosystem (serial dilution)

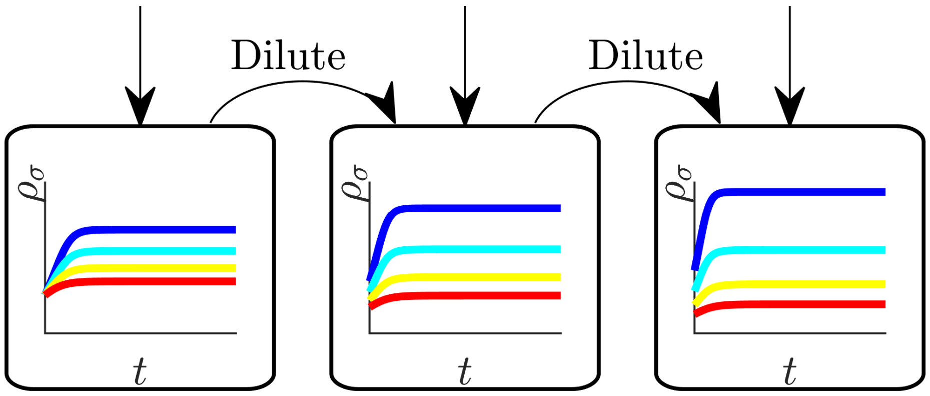


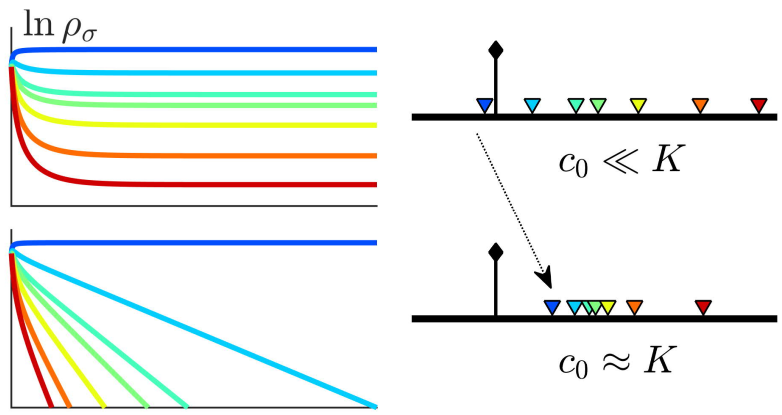
“Seasonal” ecosystem (serial dilution)



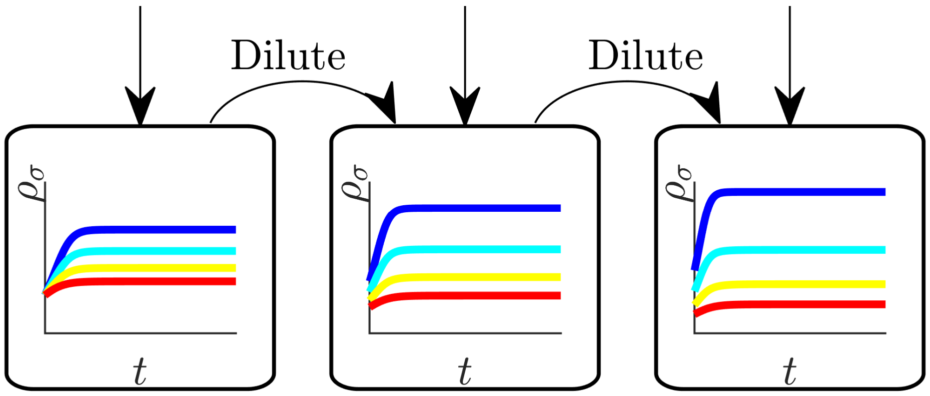


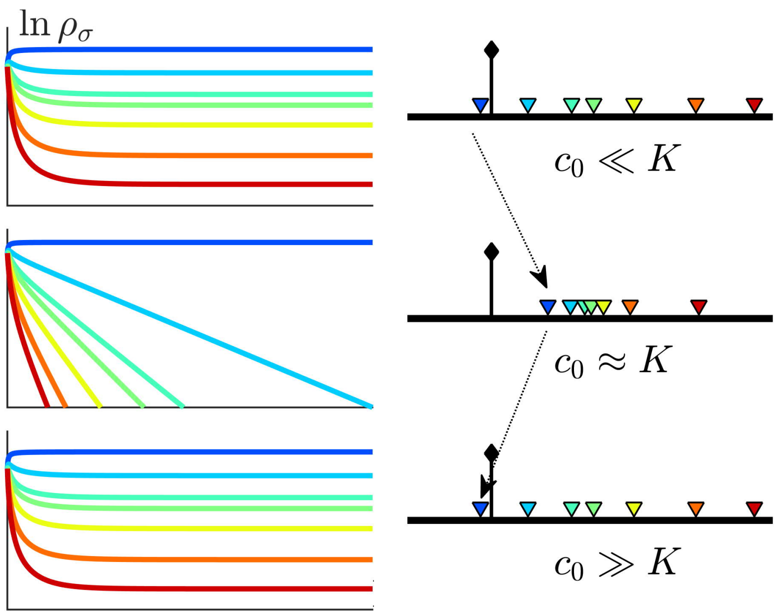
“Seasonal” ecosystem (serial dilution)



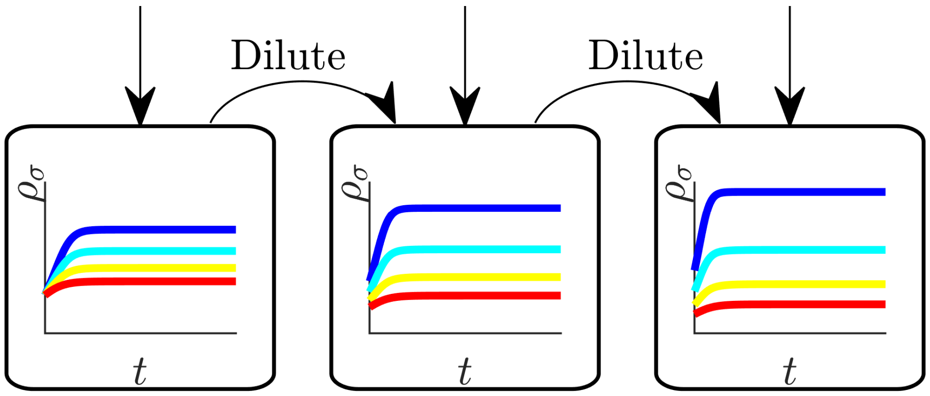


"Seasonal" ecosystem (serial dilution)

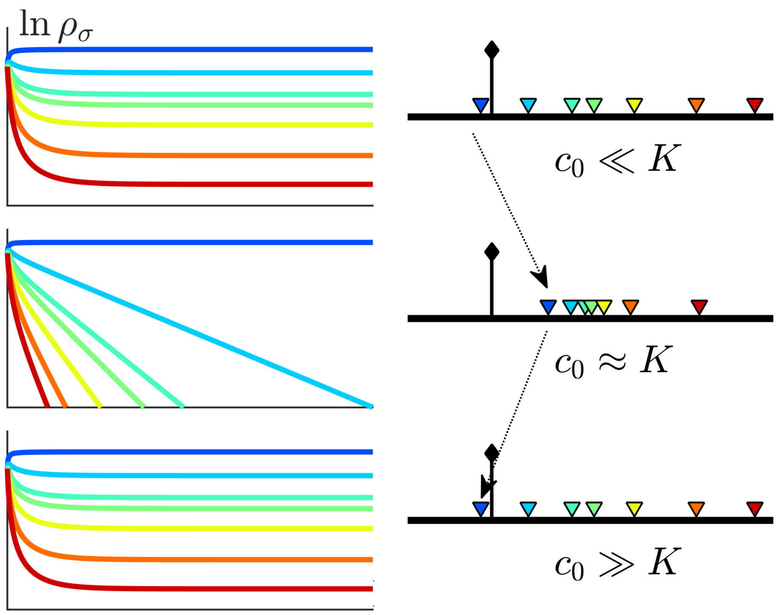




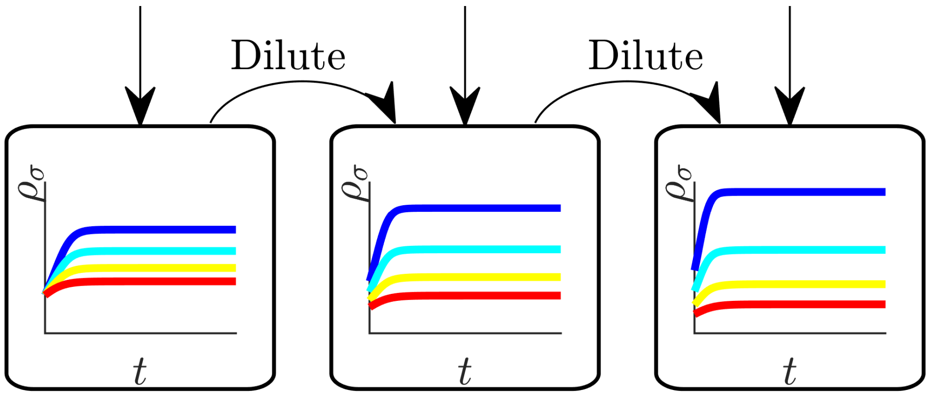
“Seasonal” ecosystem (serial dilution)



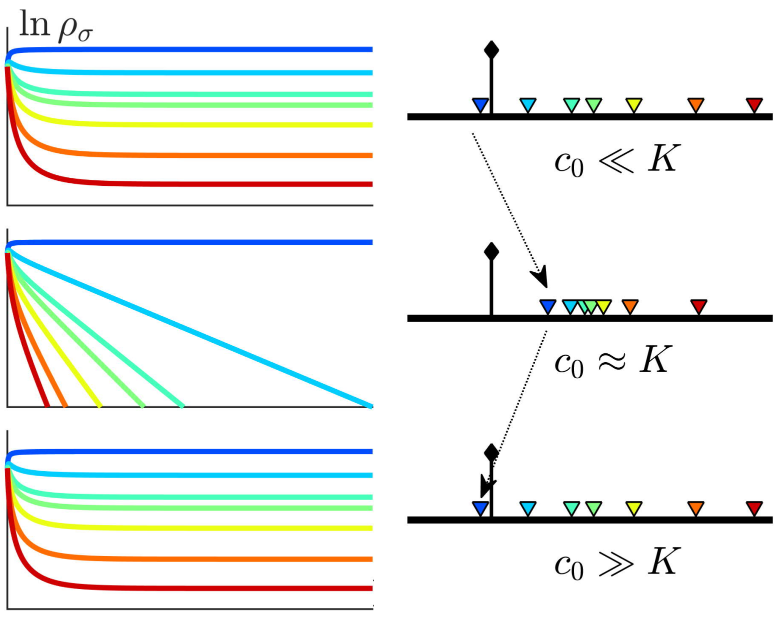
“Early-bird” effect



“Seasonal” ecosystem (serial dilution)



“Early-bird” effect



Erez, Lopez, Weiner, Meir, & NSW, eLife (2020)

Summary

- Features of model that allow for coexistence:
  - Organisms take part in shaping their environment.
  - All species are subject to the same trade-offs.

- Similarities with natural ecosystems:
  - Keystone species
  - Species' abundance patterns replicate neutral theory

- Beyond the chemostat:
  - Spatial structure
  - "Seasonal" ecosystem

Thank you!

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Posfai, Taillefumier, & NSW, Phys Rev Lett (2017)
Weiner, Posfai, & NSW, PNAS (2019)
Erez, Lopez, Weiner, Meir, & NSW, eLife (2020)