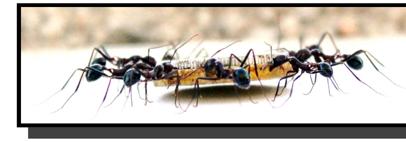
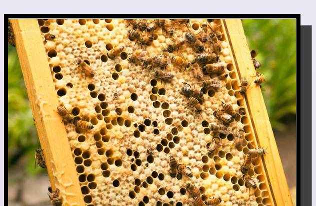


Kinetic modeling of collective behavior: When a good match goes bad

Dr. Theodore (Ted) P. Pavlic
tpavlic@asu.edu
www

Sunday, April 19, 2015



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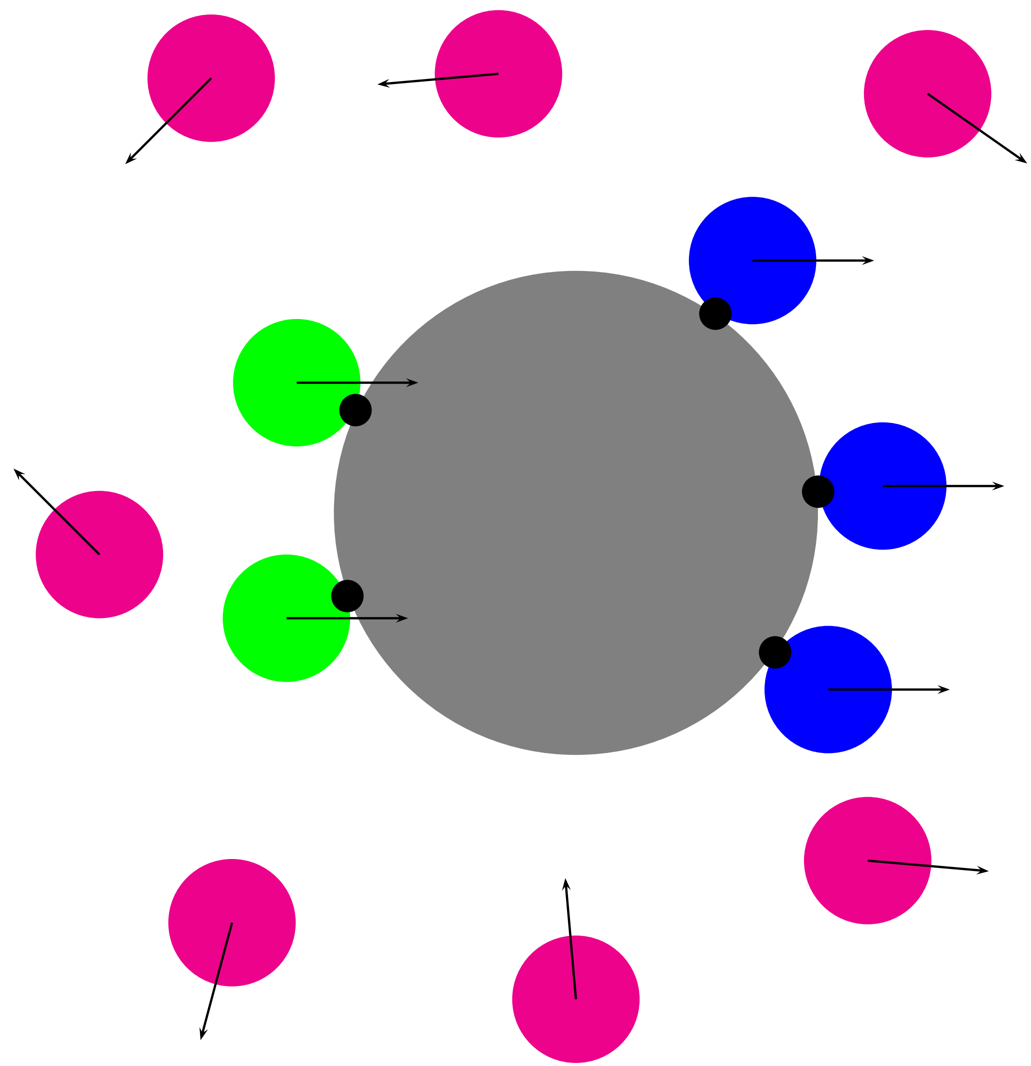

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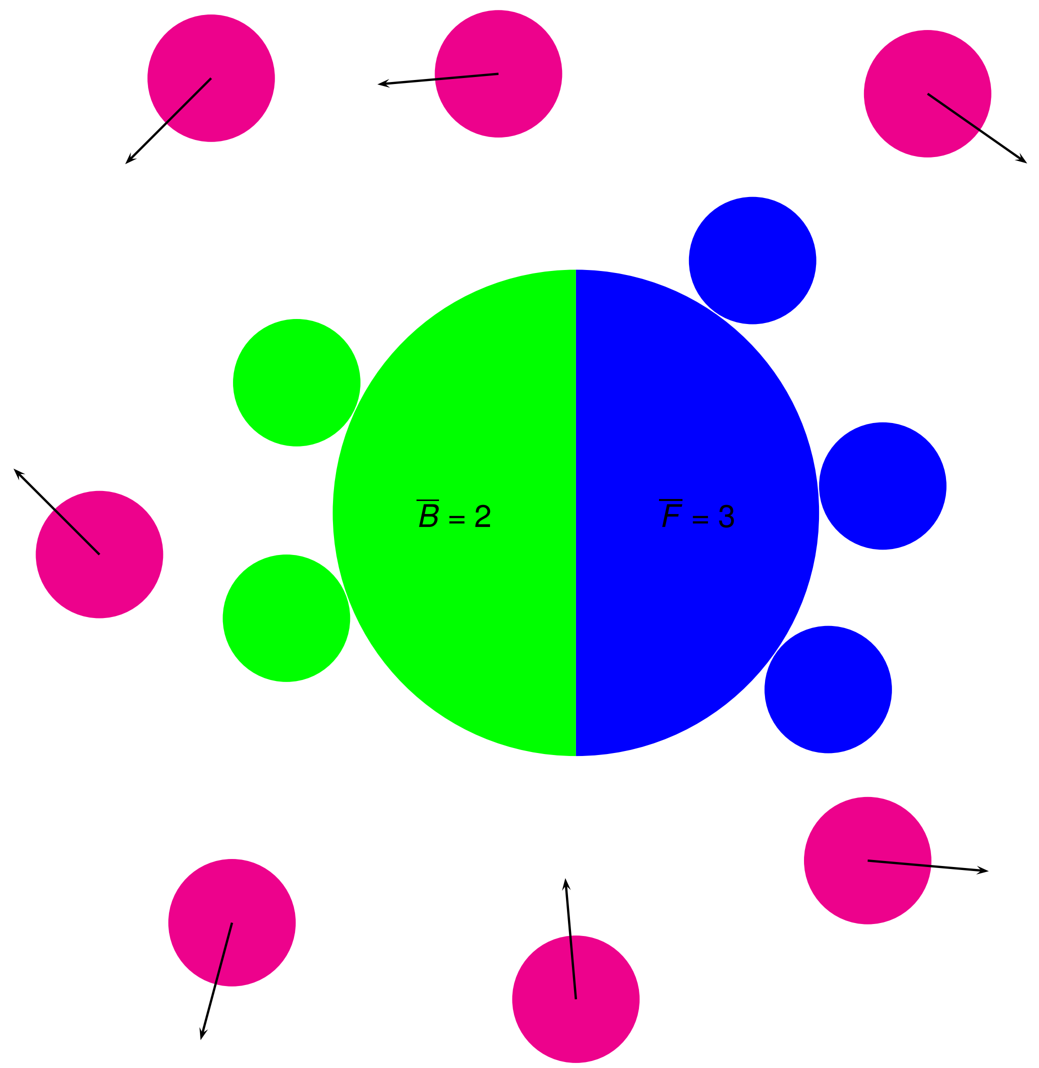

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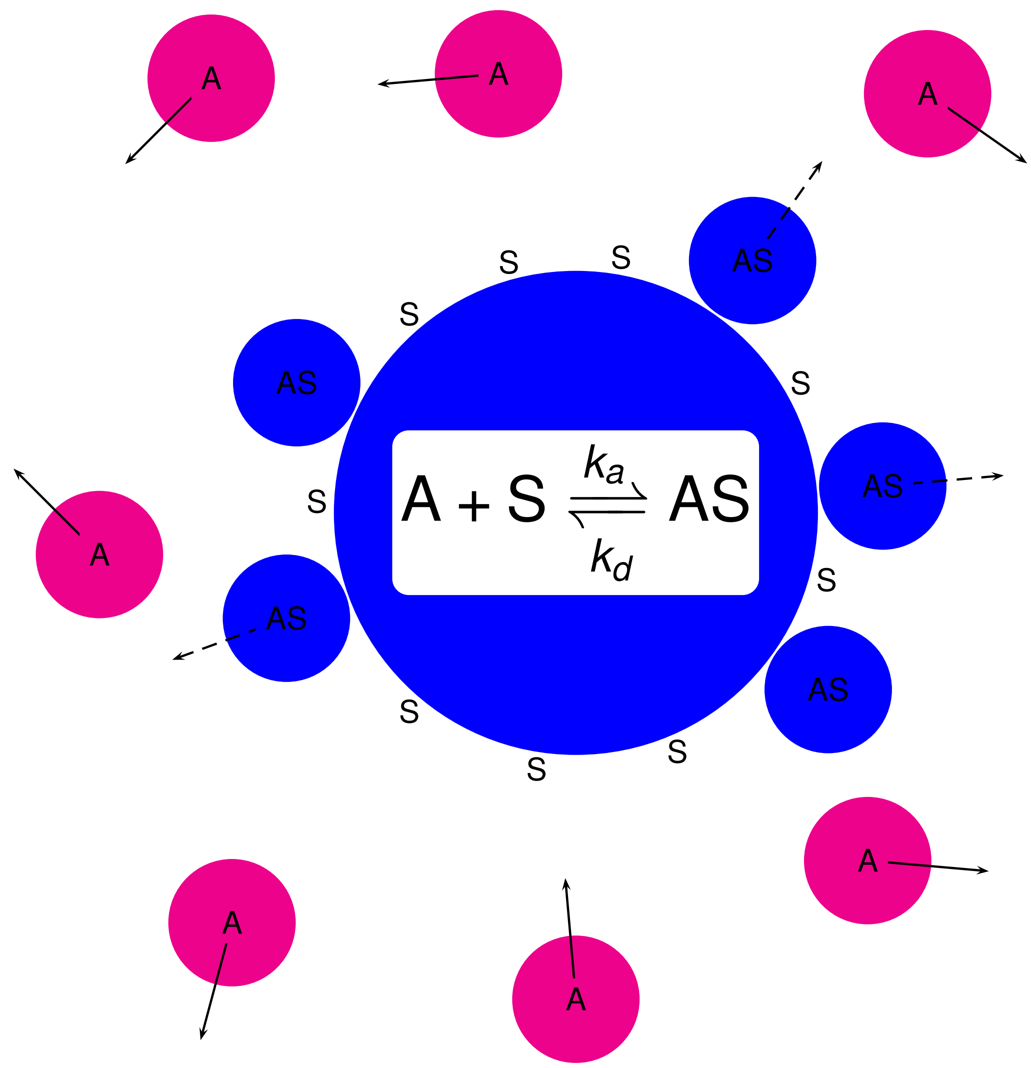

$$A + S \underset{k_d}{\overset{k_a}{\rightleftharpoons}} AS$$

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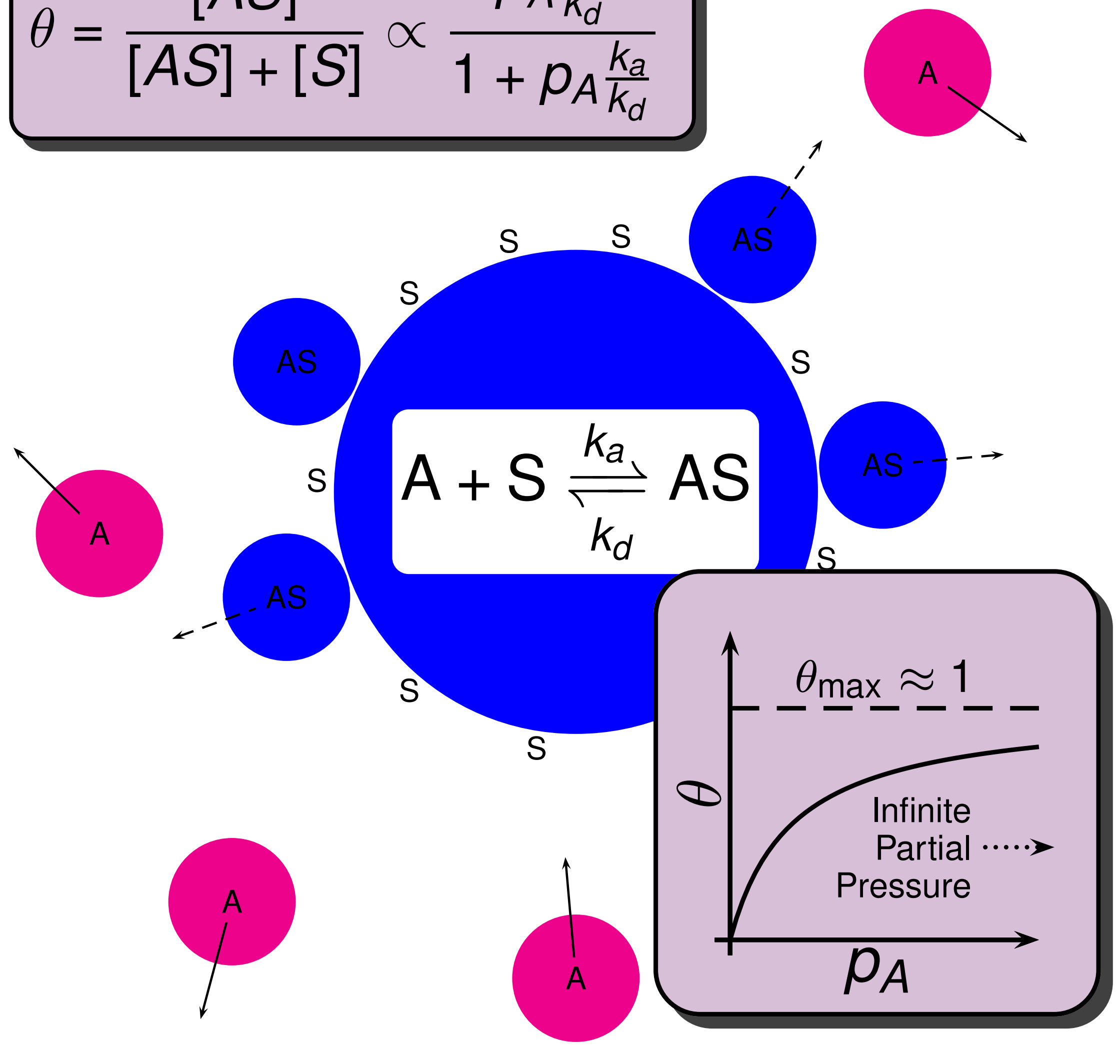
$$\theta = \frac{[AS]}{[AS]+[S]} \propto \frac{p_A \frac{k_a}{k_d}}{1 + p_A \frac{k_a}{k_d}}$$



Stochastic Boundary Coverage

Design of Robotic Adsorption

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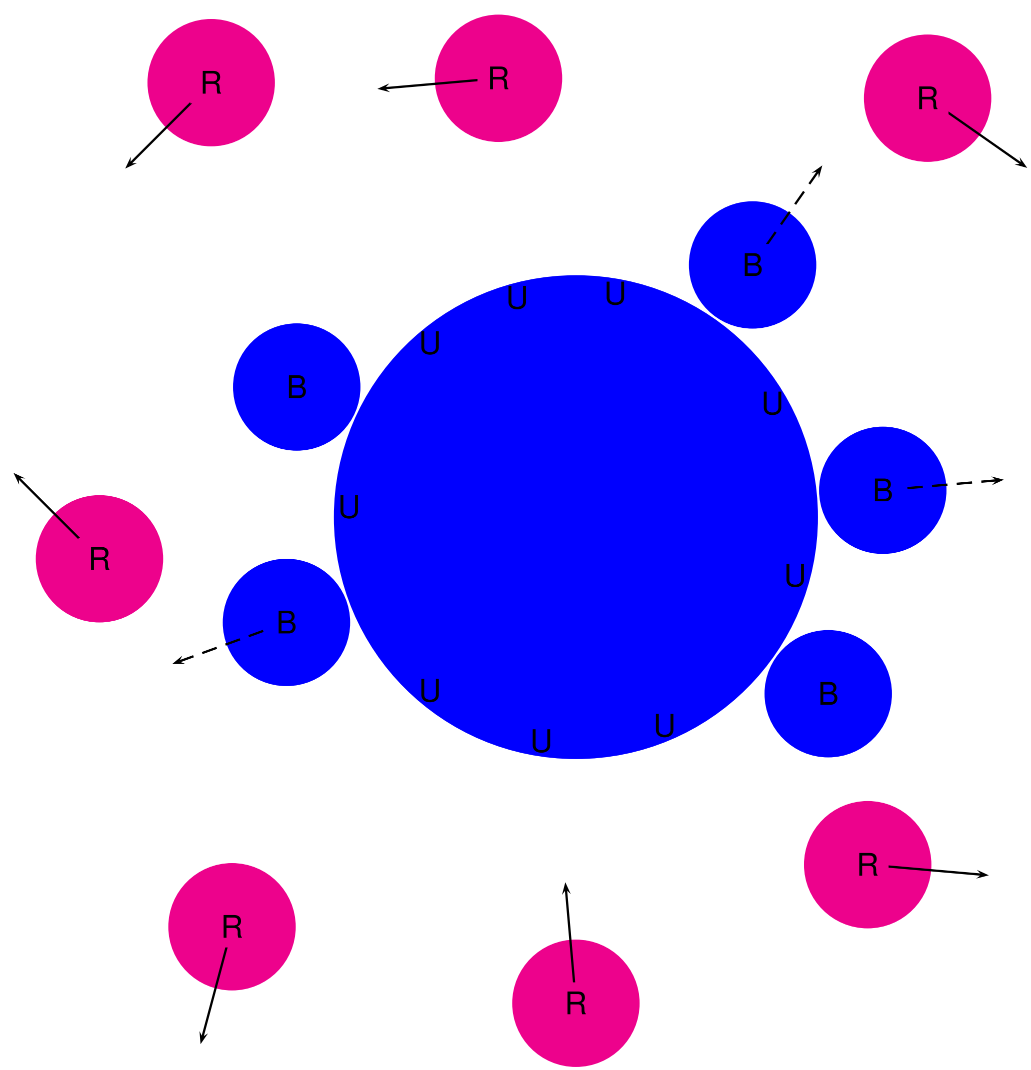

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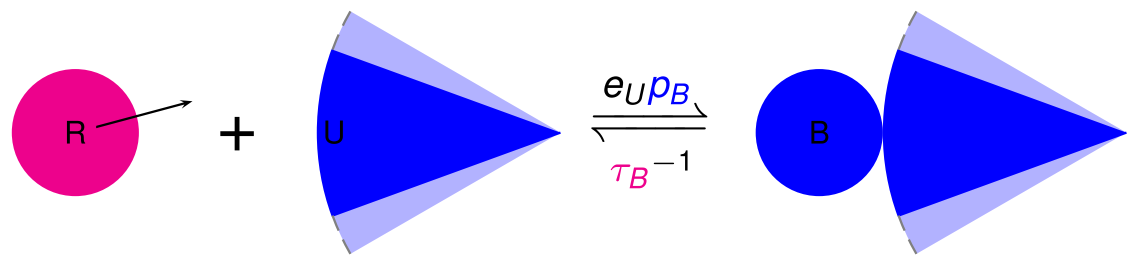

$$\frac{[B]}{[U]} = R_0 \frac{e_U p_B}{\tau_B{}^{-1}}$$

R_0: free-robot concentration
e_U: robot–load-site encounter rate
p_B: probability of binding
τ_B: mean time before unbinding

- **Control strategy:** Choose probability p_B and time τ_B for desired allocation.

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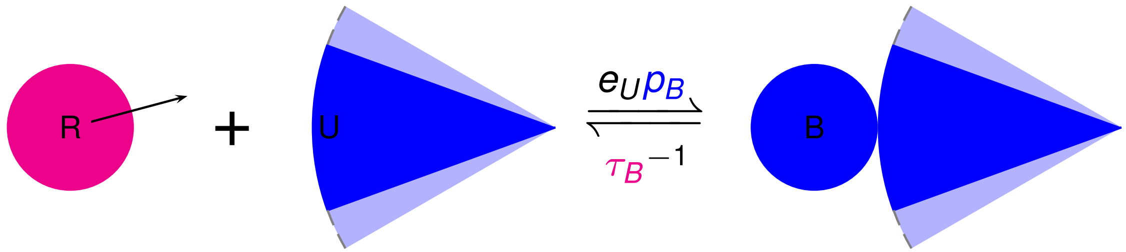

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- Choices depend on R_0. Not scalable.

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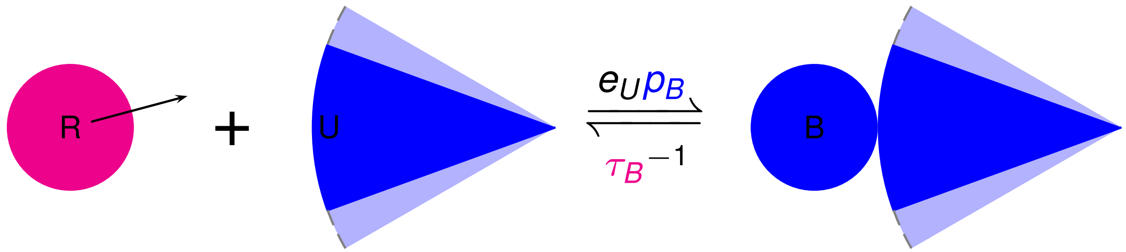

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- Choices depend on R_0. Not scalable.
- Choices depend on e_U. **How to model e_U *ab initio*?**

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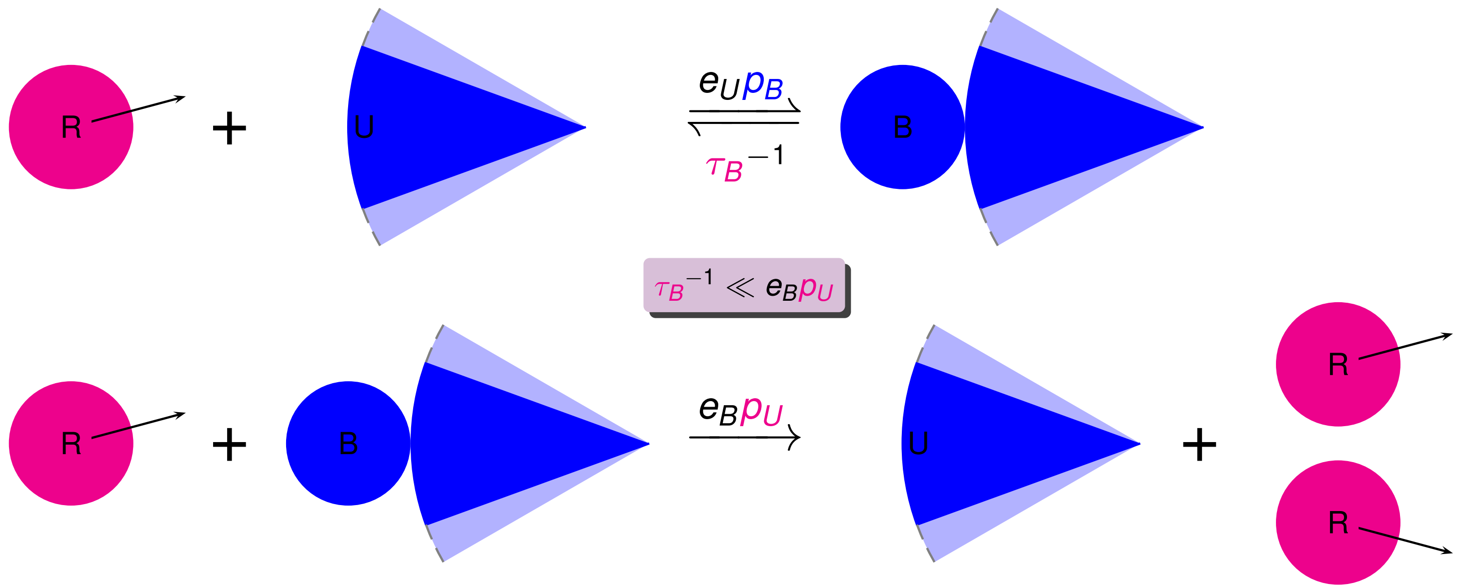

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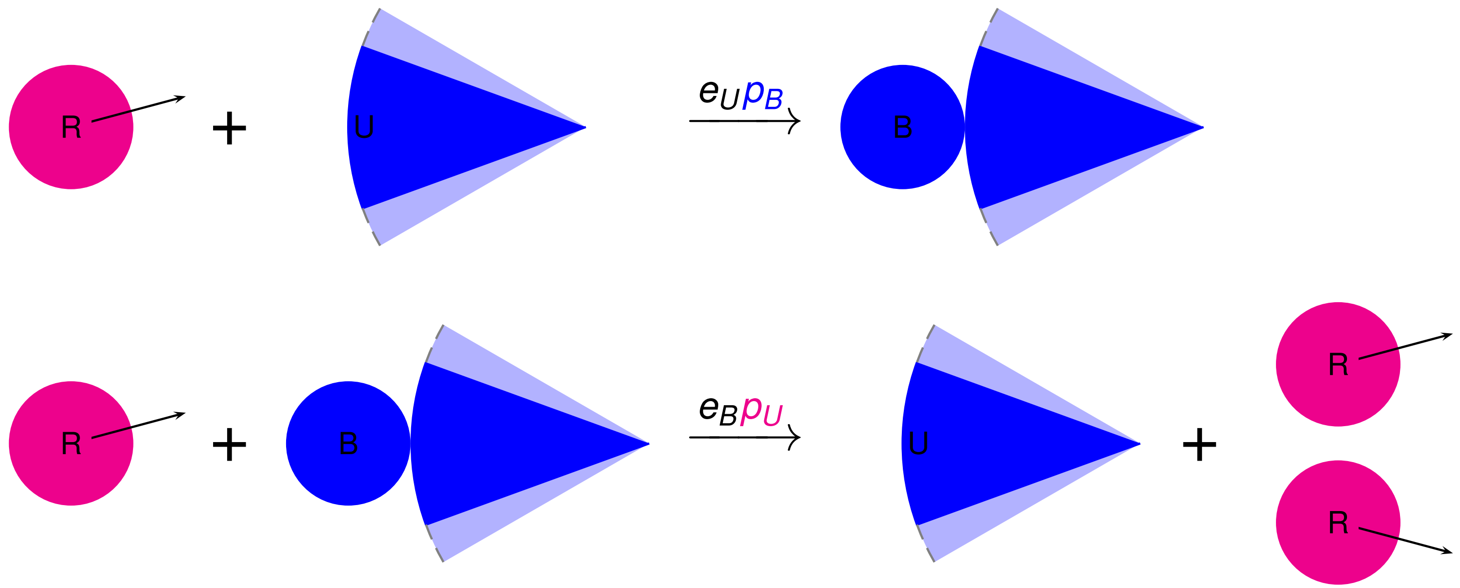

$$\frac{[B]}{[U]} = \frac{R_0 e_U p_B}{R_0 e_B p_U} \approx \frac{p_B}{p_U}$$

R_0: free-robot concentration
e_U: robot–load-site encounter rate
p_B: probability of binding
e_B: robot–bound-complex encounter rate
p_U: probability of unbinding

- **Control strategy:** Choose probabilities p_B and p_U for desired allocation.

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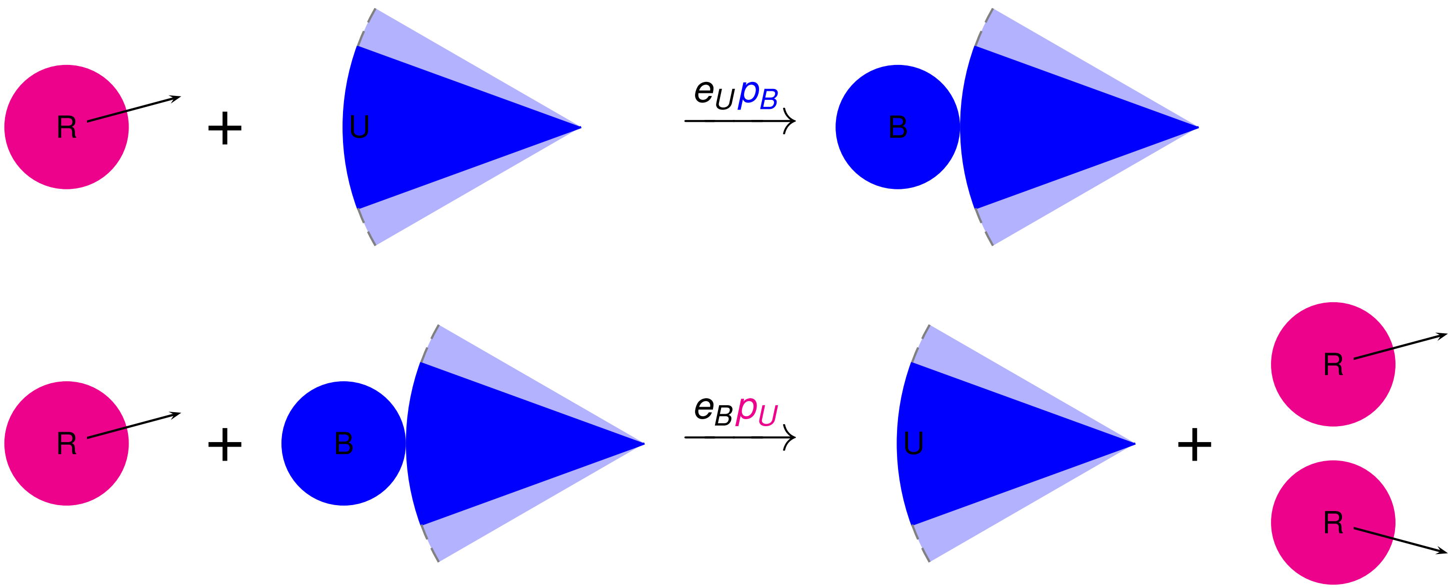

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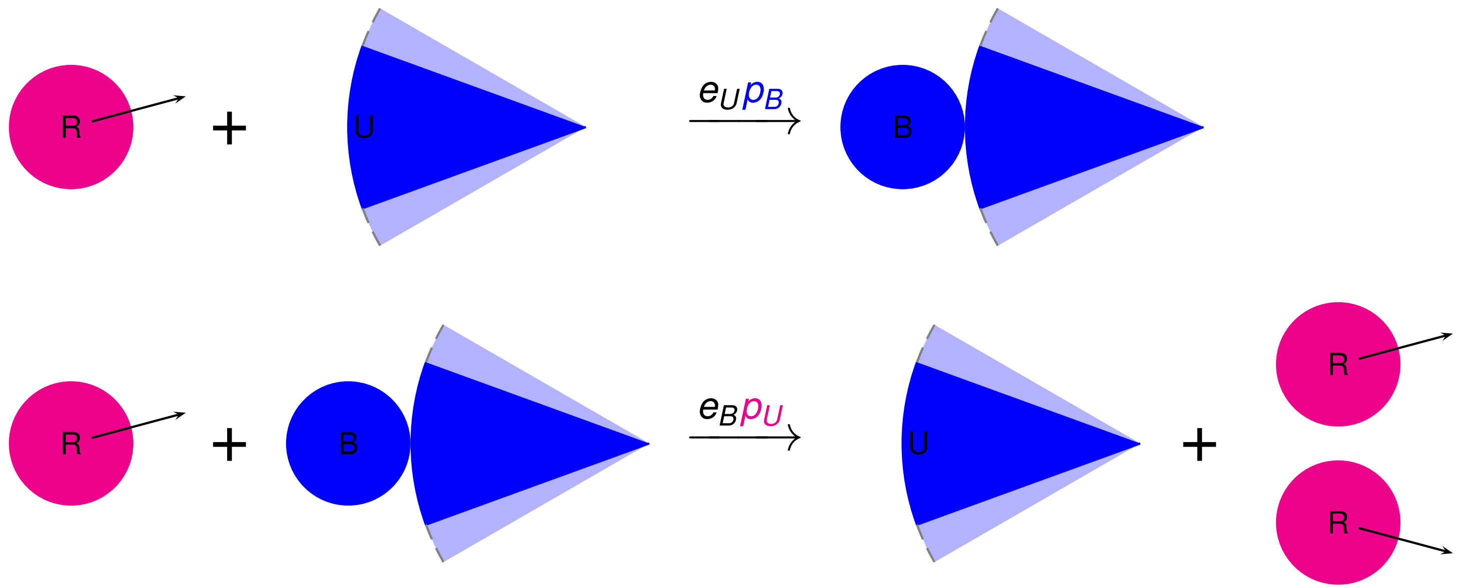

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e_B: robot–bound-complex encounter rate
p_U: probability of unbinding

- **Control strategy:** Choose probabilities p_B and p_U for desired allocation.
- Scalable.
- Choices depend on $e_U/e_B =$ constant ≈ 1, which has geometric derivation.

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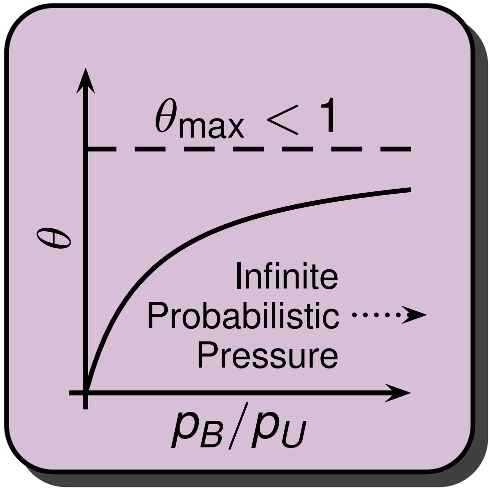
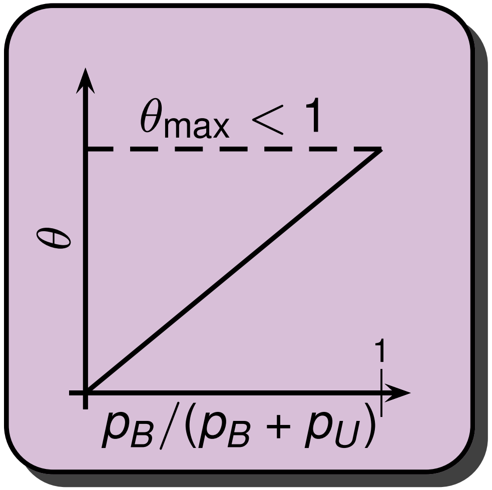


sensu Langmuir



Design case?

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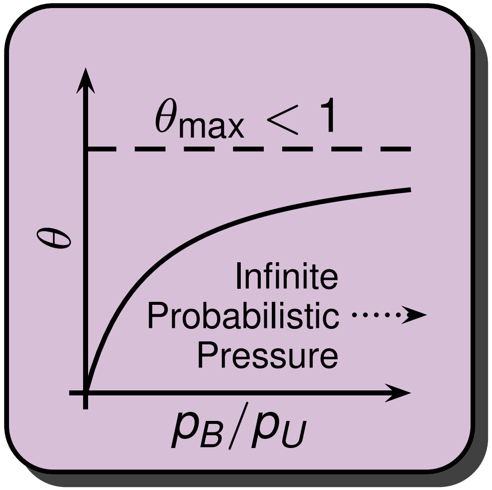
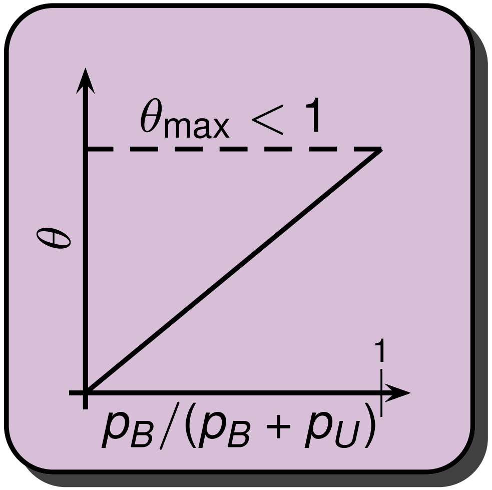


sensu Langmuir



Design case?

$$\theta_{\text{max}} \overset{?!}{=} 0.75$$

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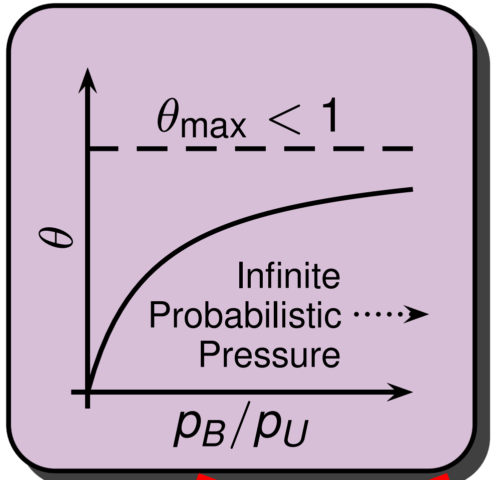
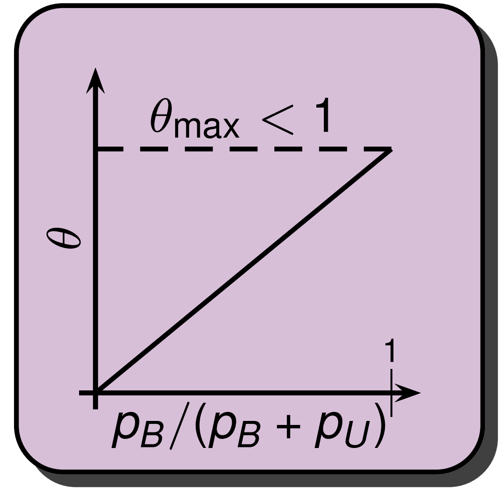


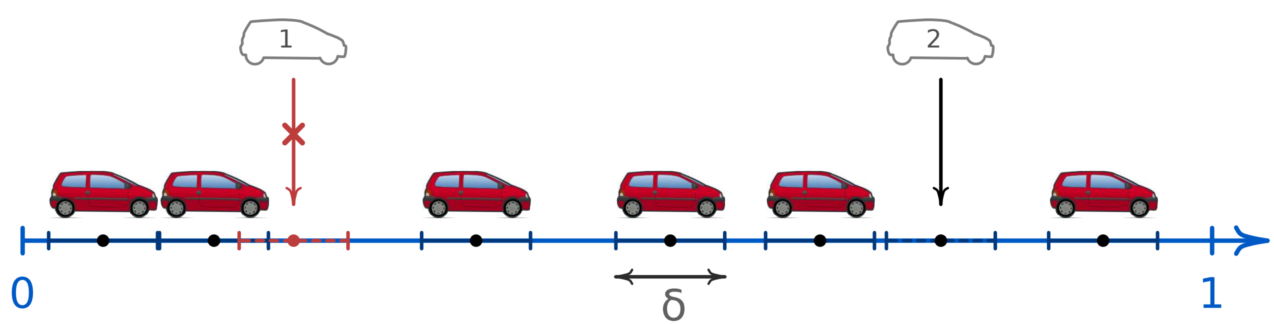
sensu ~~Langmuir~~



Design case?

Rényi!

$$\theta_{\max} = 0.7475979202534114351\ldots$$



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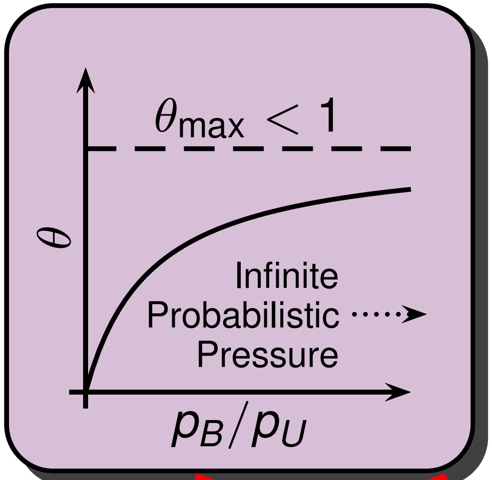
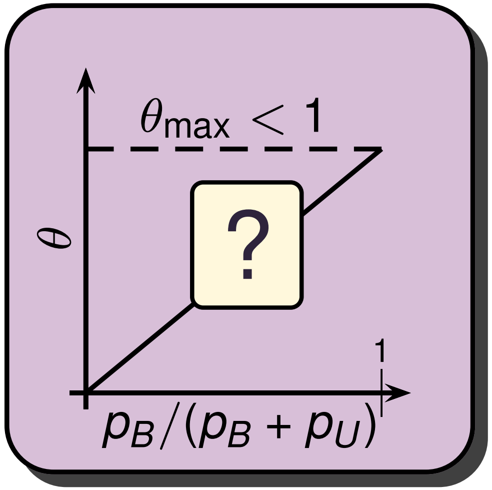


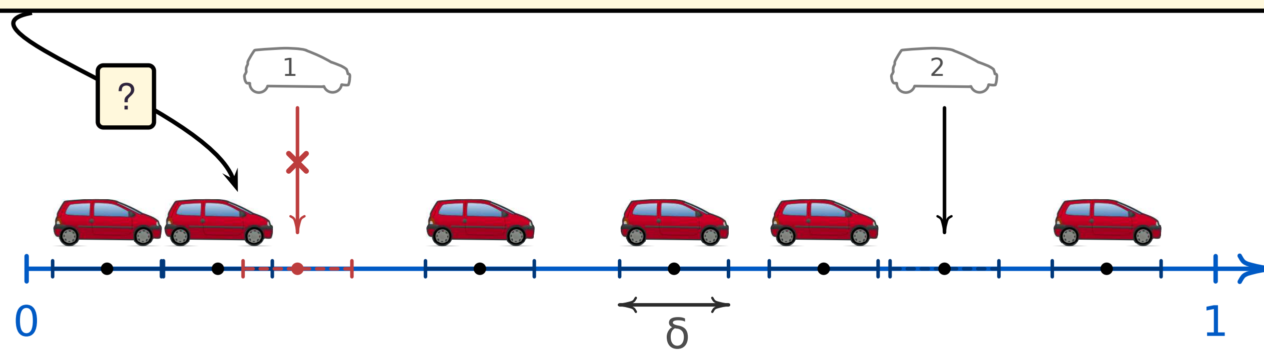
~~*sensu* Langmuir~~



Design case?

Rényi!

What about when encountered cars sometimes leave?



Stochastic Boundary Coverage

Random Sequential Attachment with Detachment (Pavlic et al. 2014)

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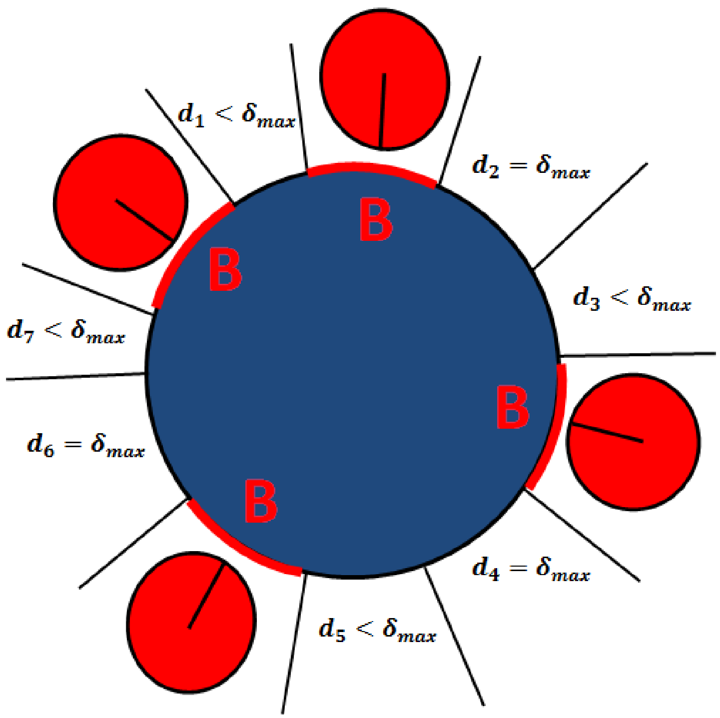

$$\overbrace{\frac{1+\delta}{1+\delta\frac{[B]}{[U]}}}^{\text{Spatial correction}} \frac{[B]}{[U]} = \frac{e_u p_b}{e_b p_u}$$

δ: Mean length of free parking space at equilibrium

Stochastic Boundary Coverage

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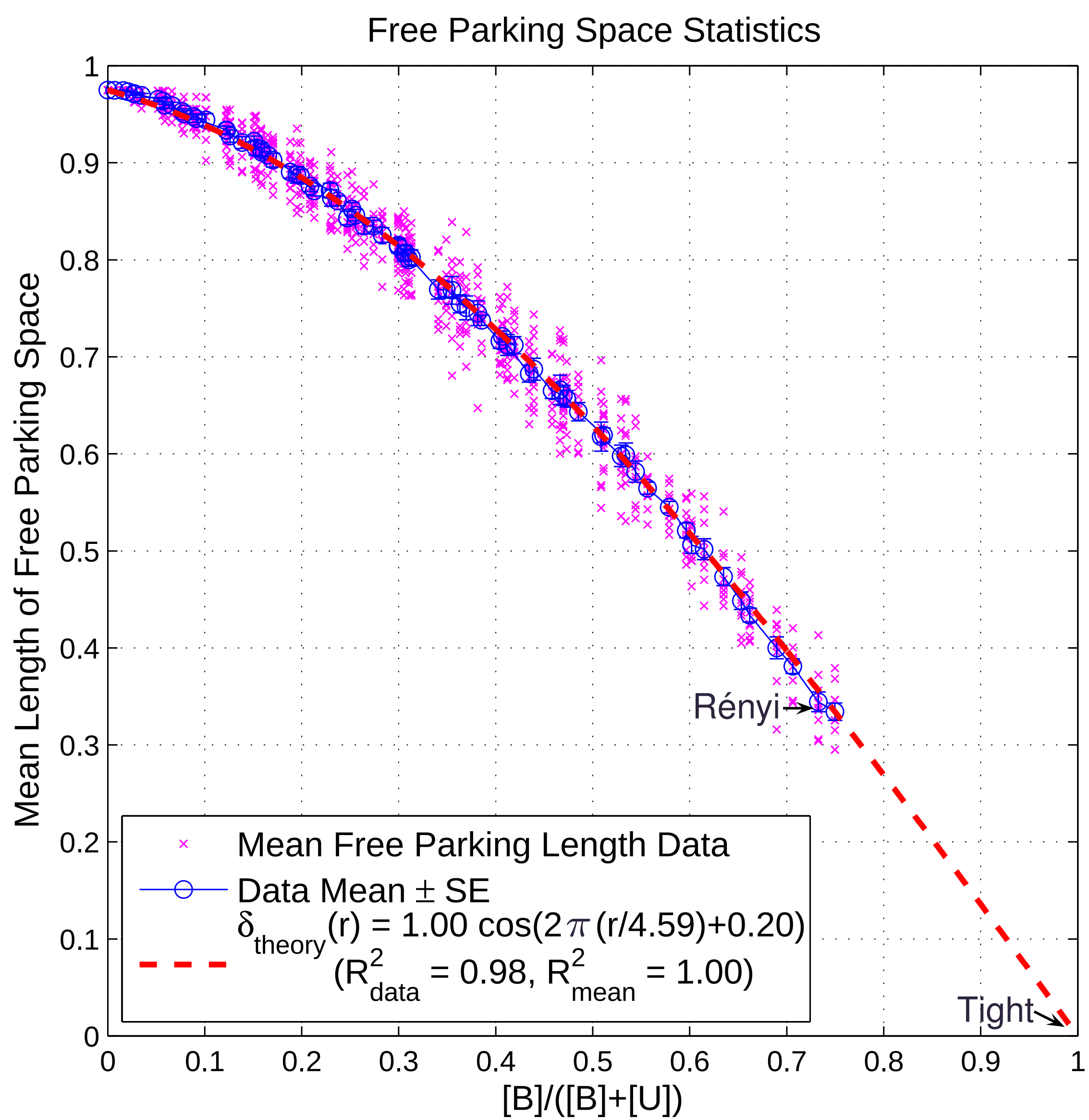

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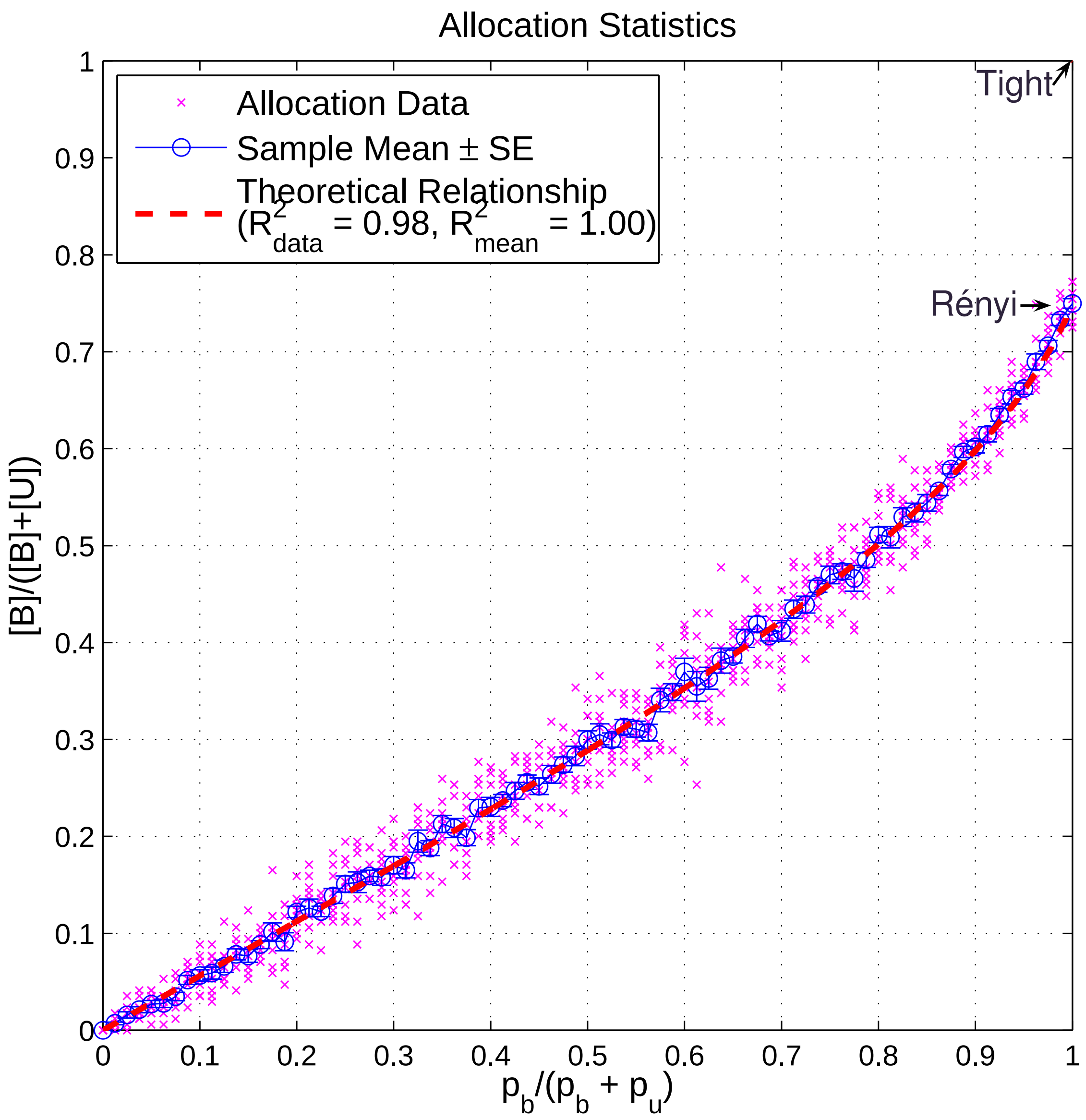

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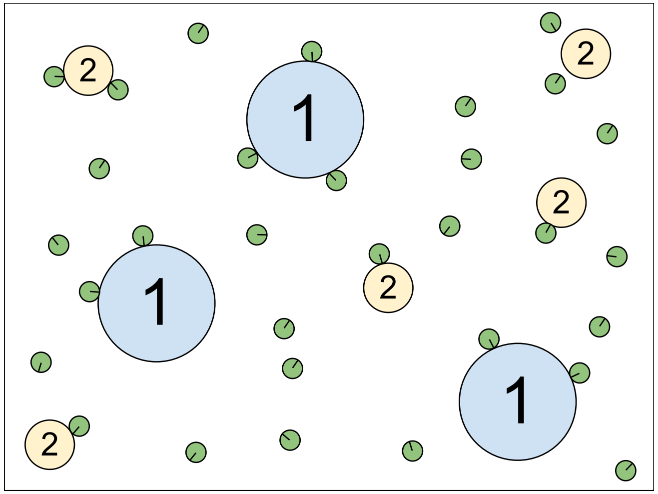

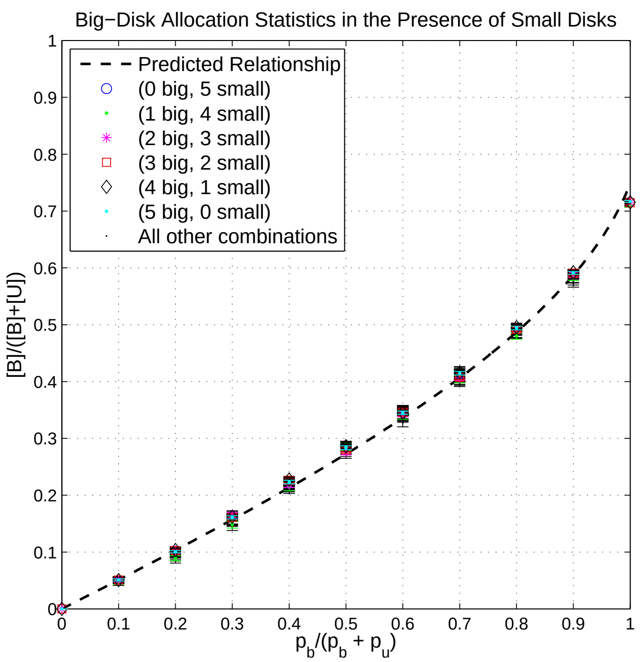

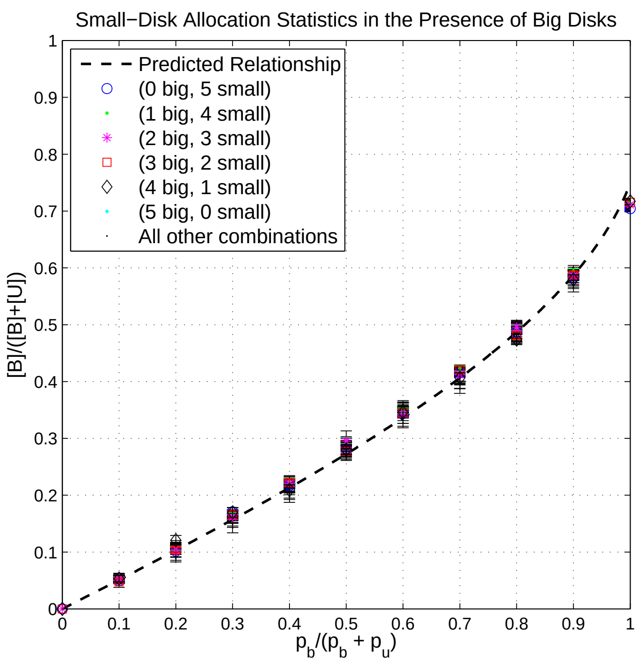

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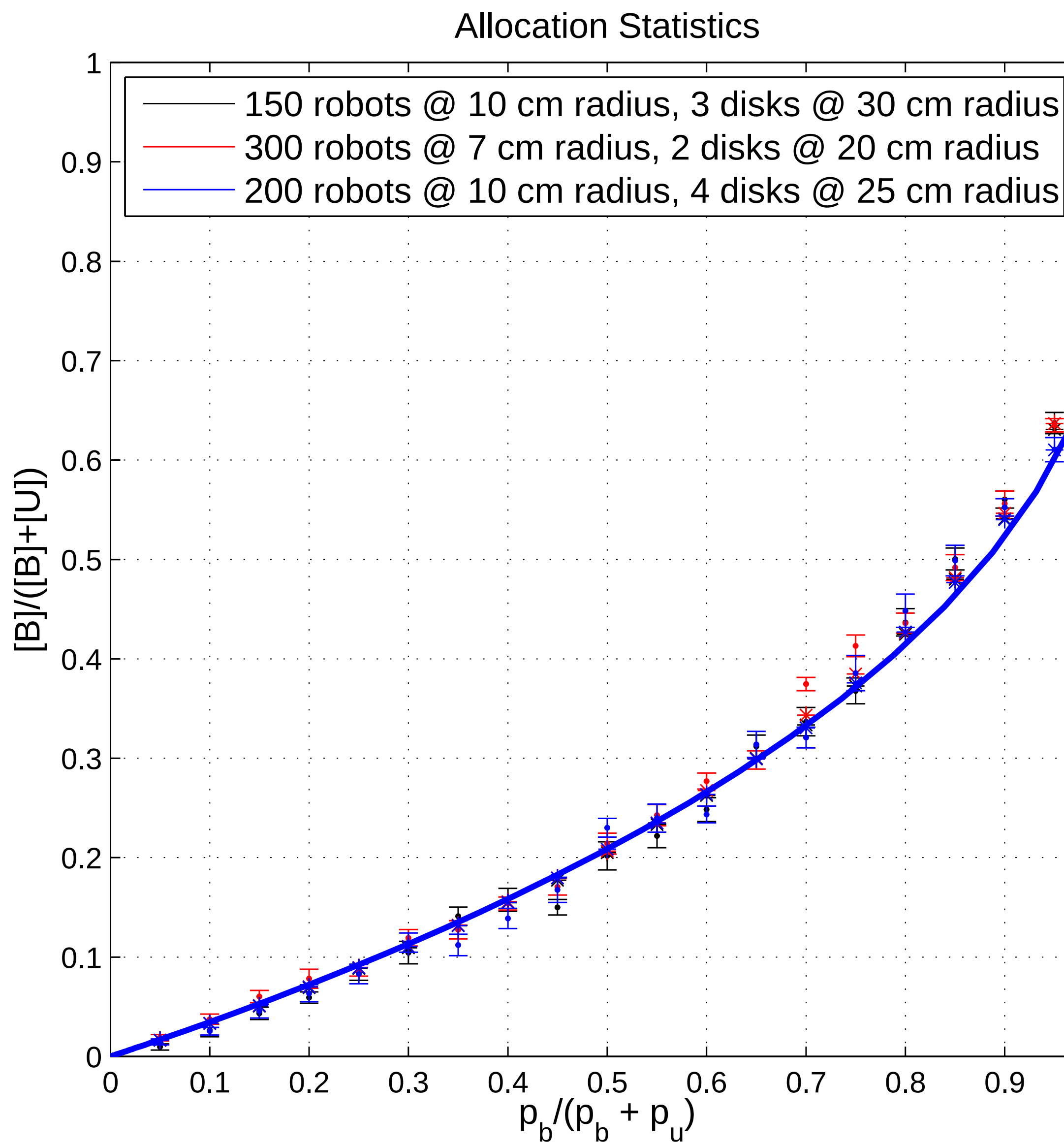

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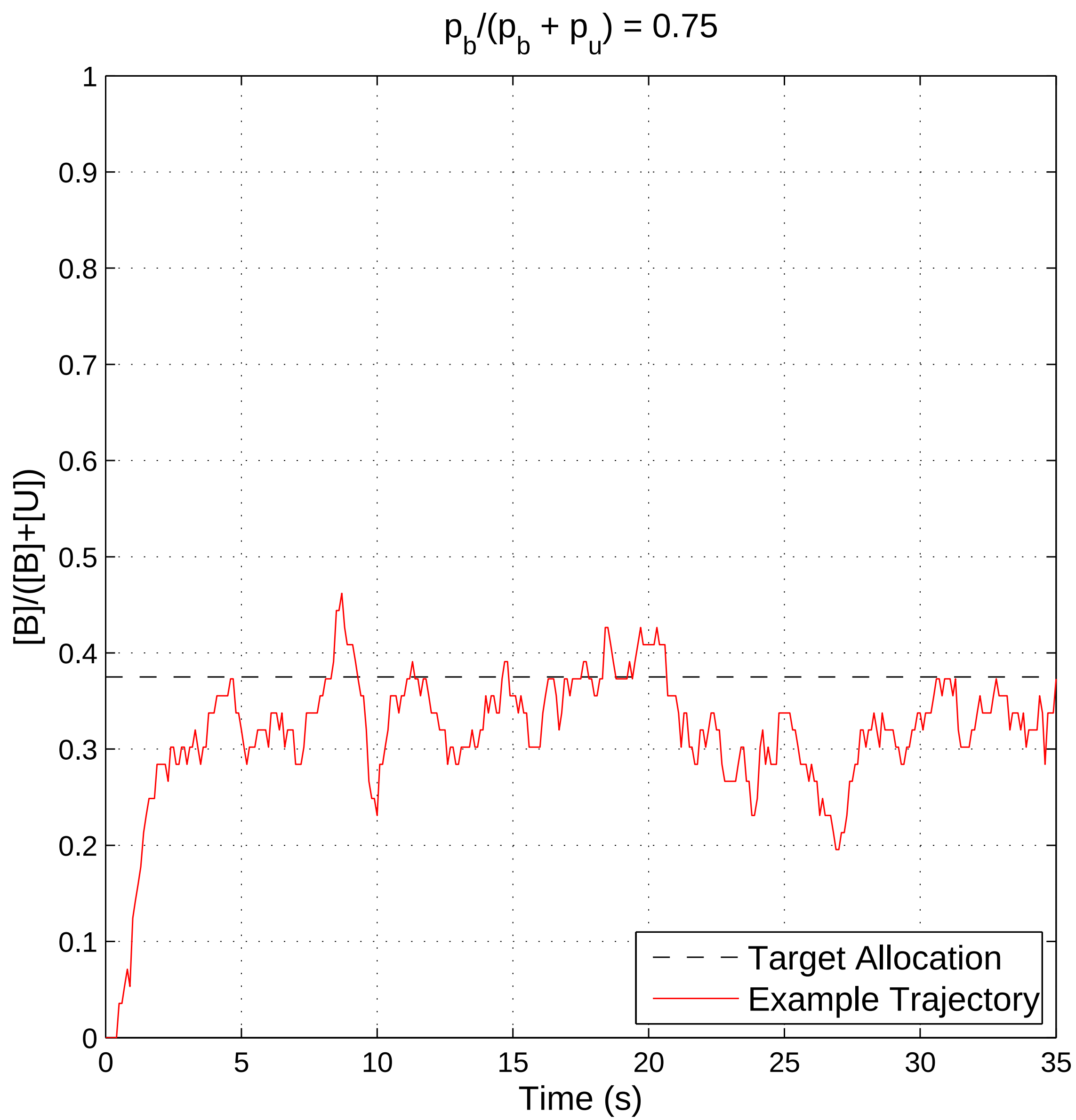

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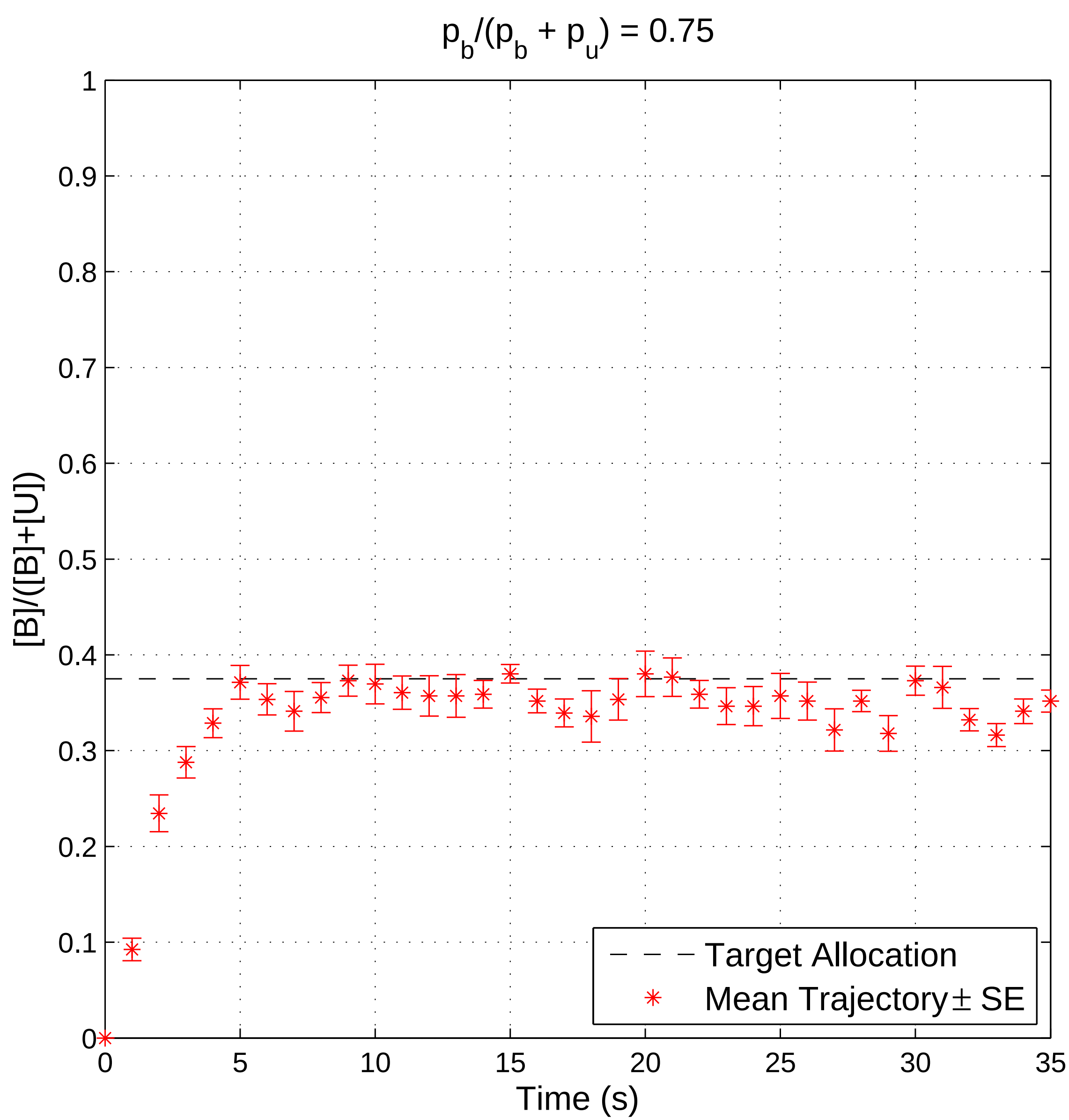

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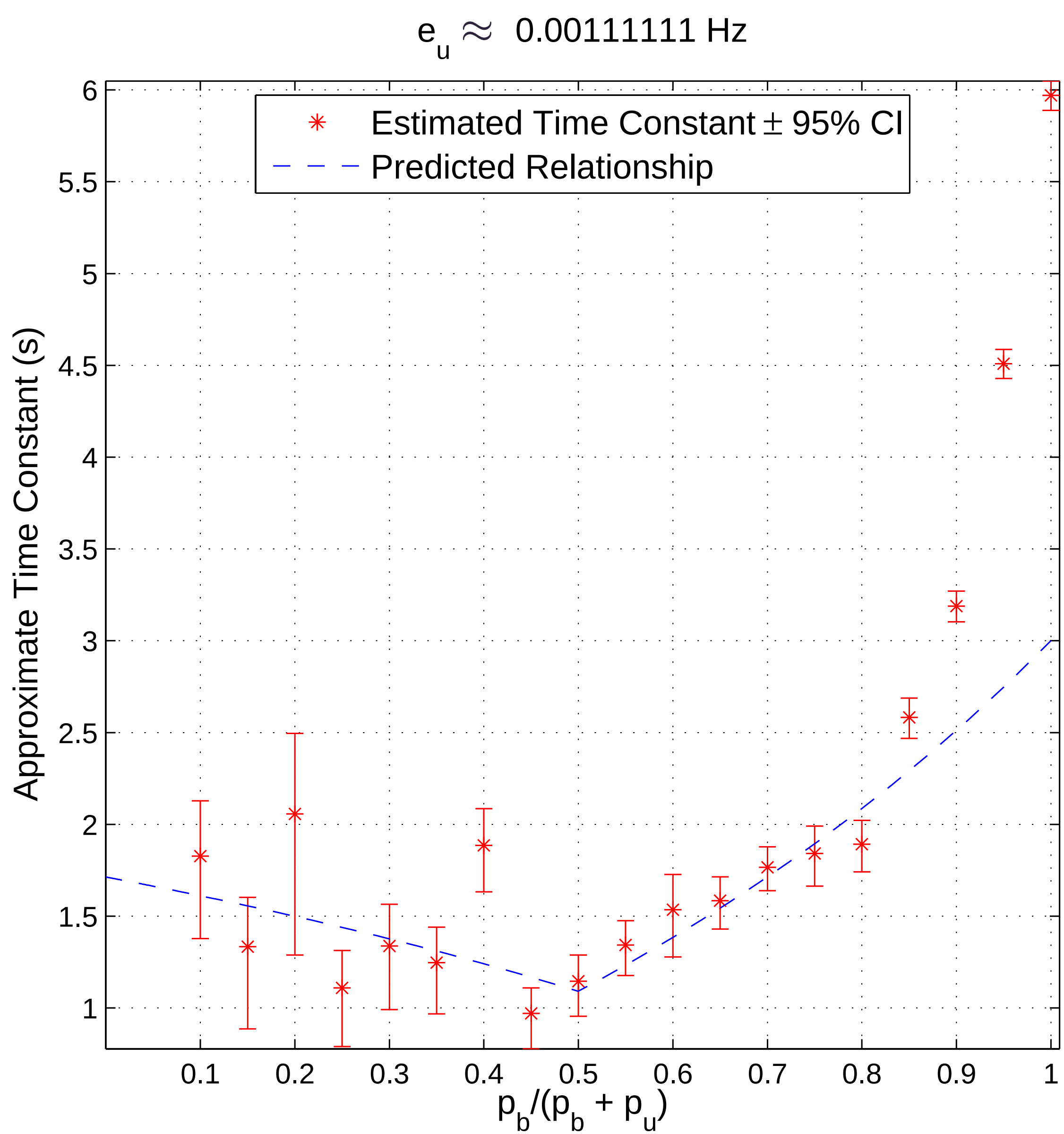

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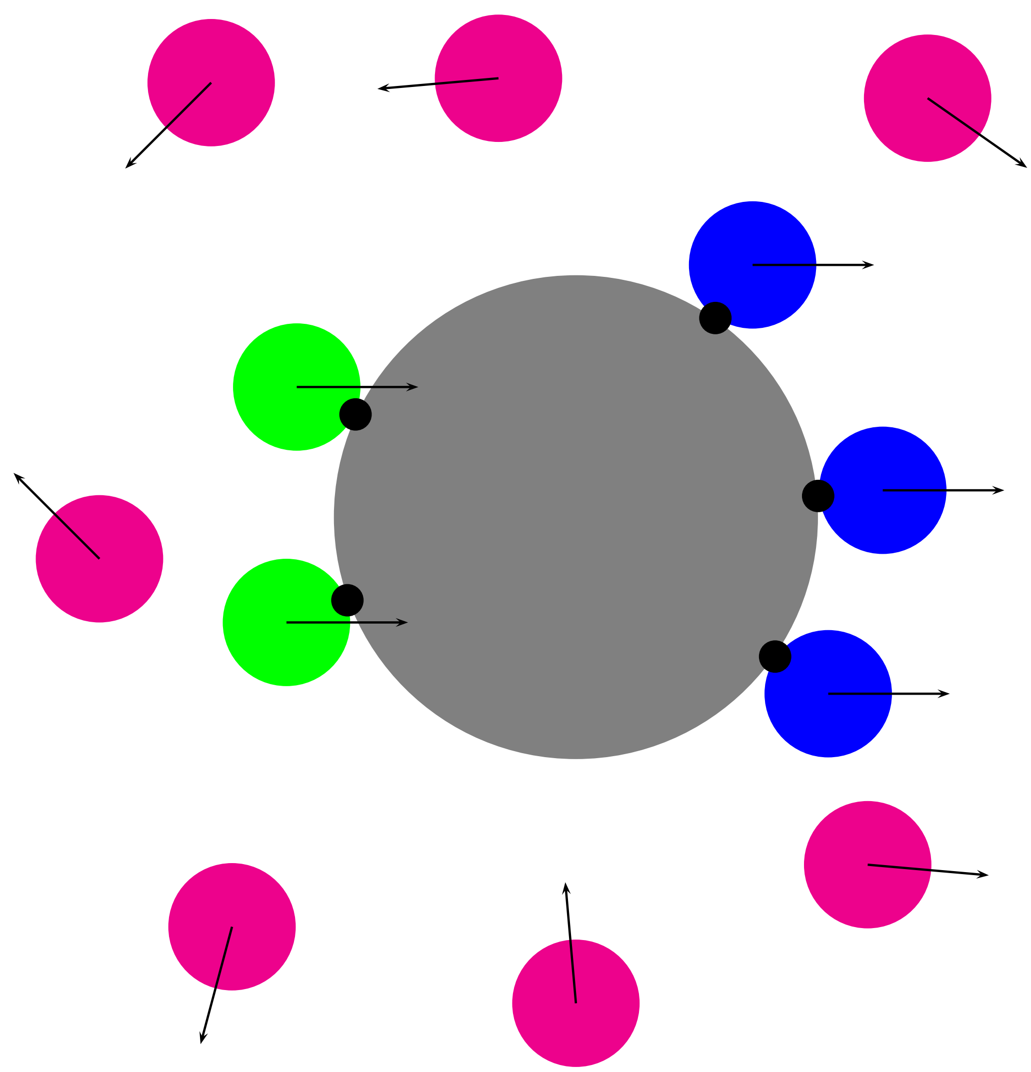

Collective Transport
(Wilson et al. 2014)

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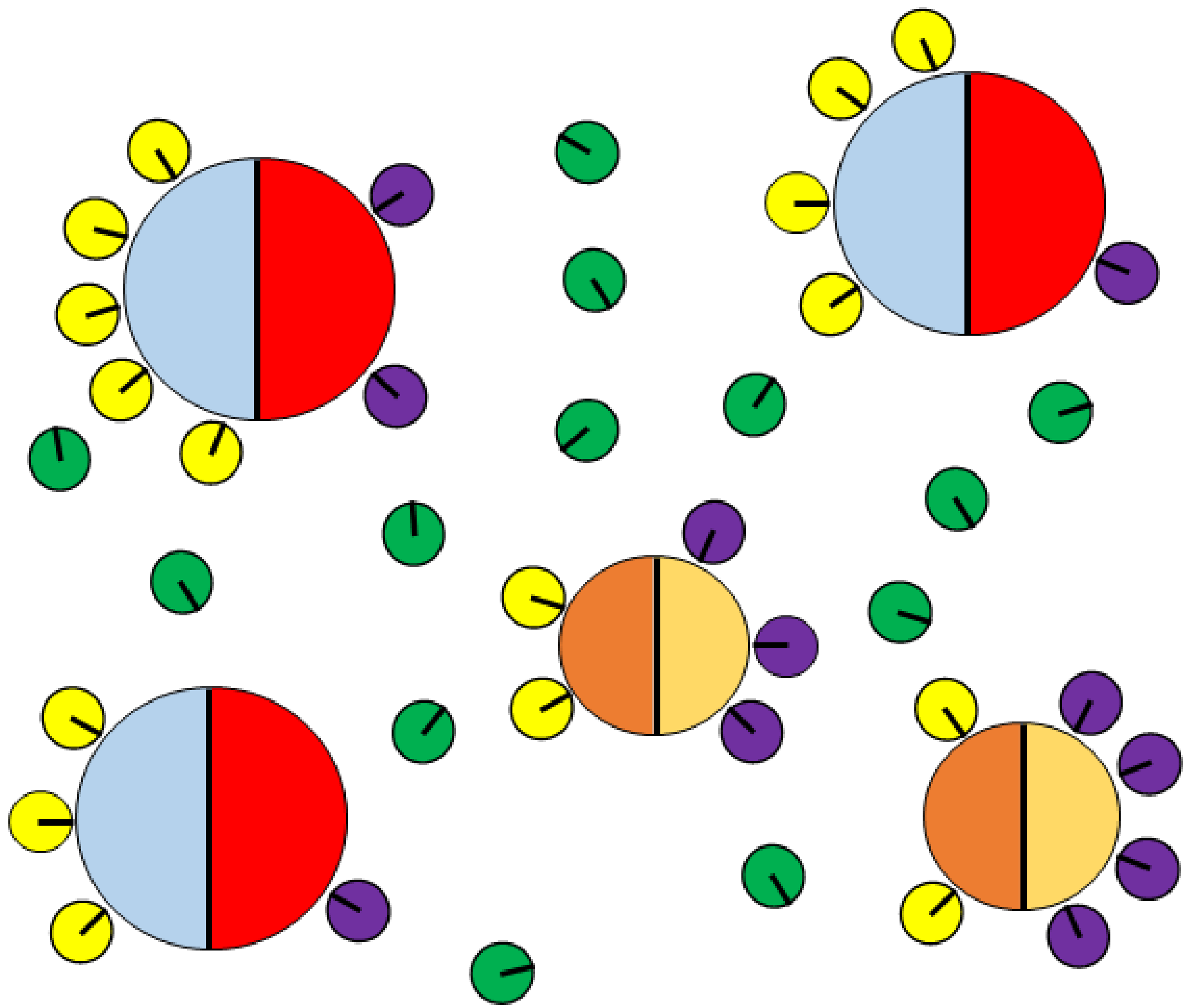

Collective Transport
(Wilson et al. 2014)

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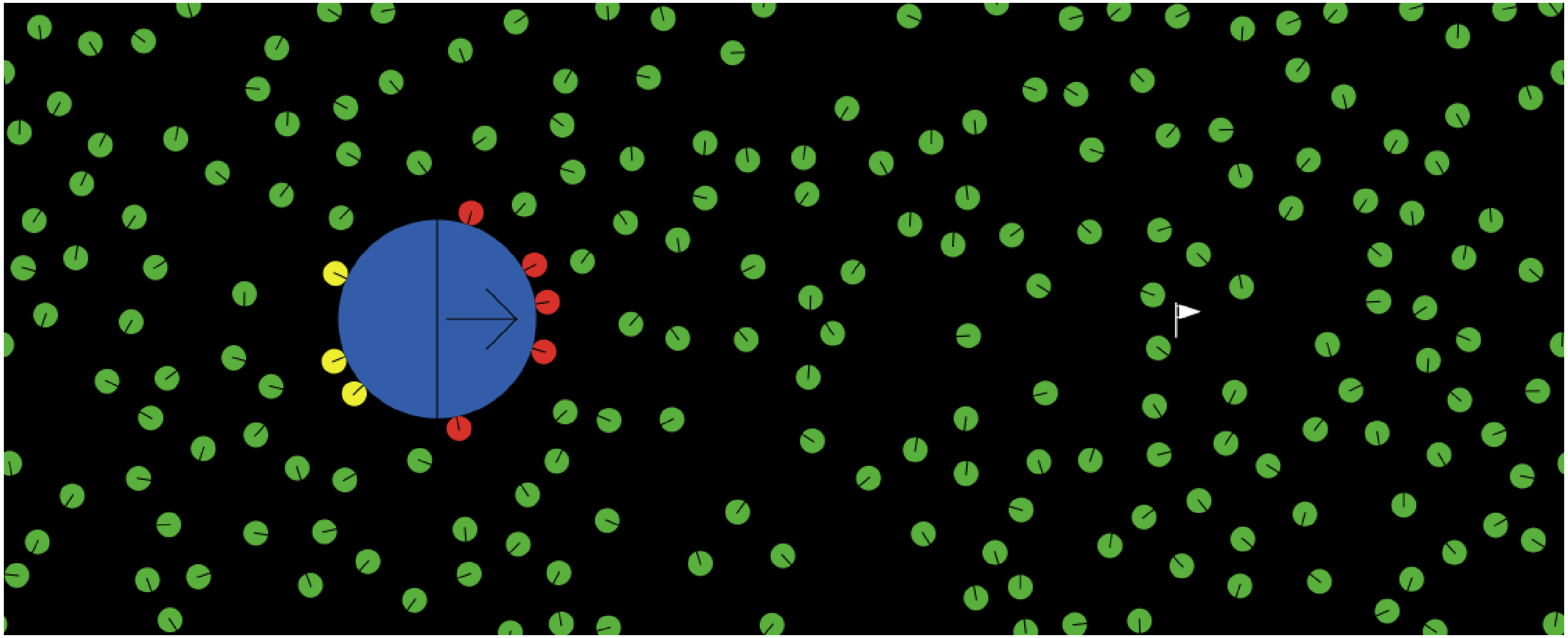

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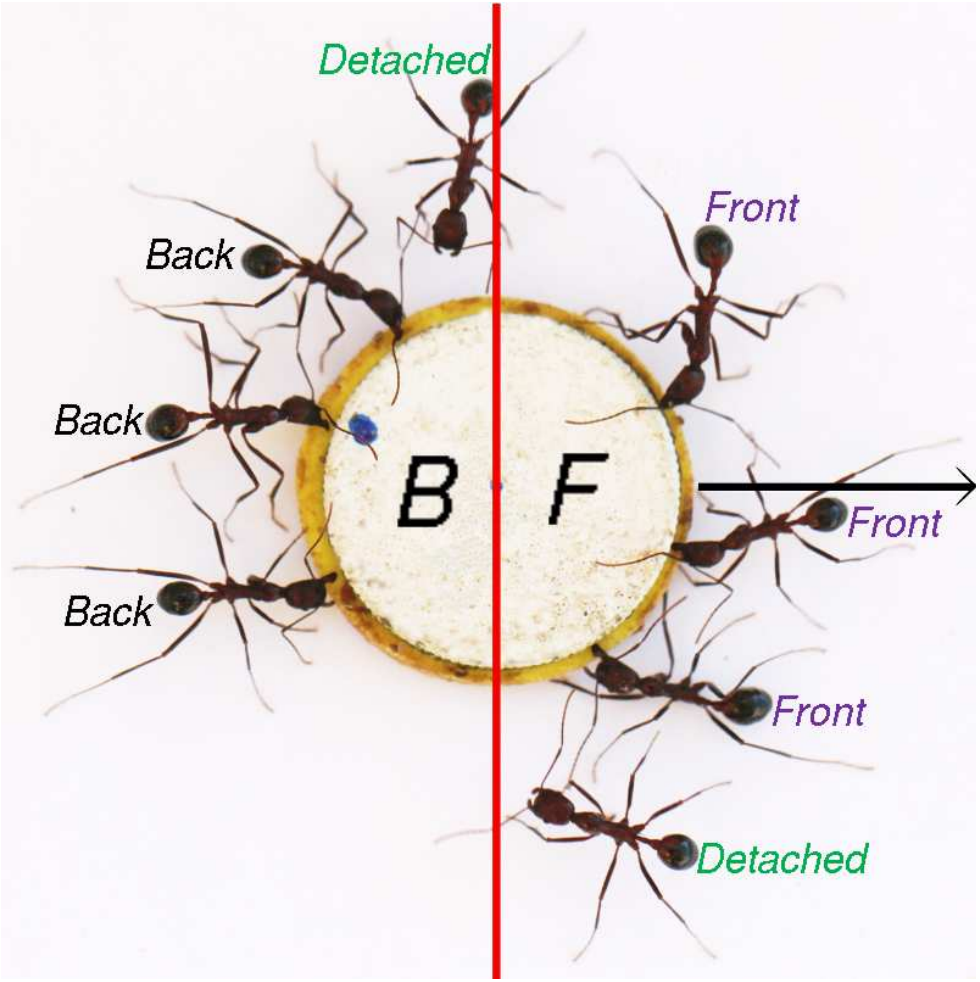

Collective Transport
(Kumar et al. 2013)

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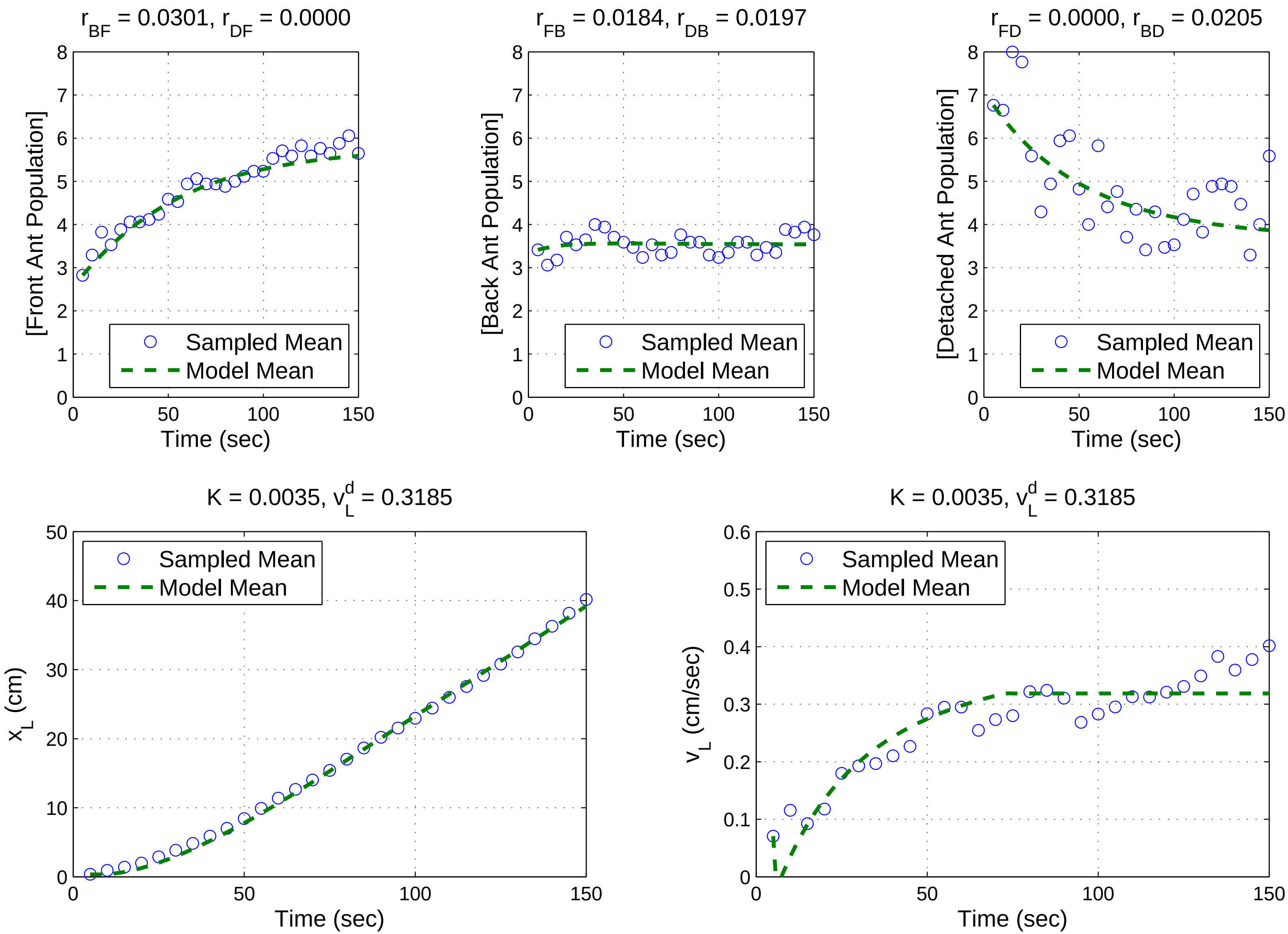
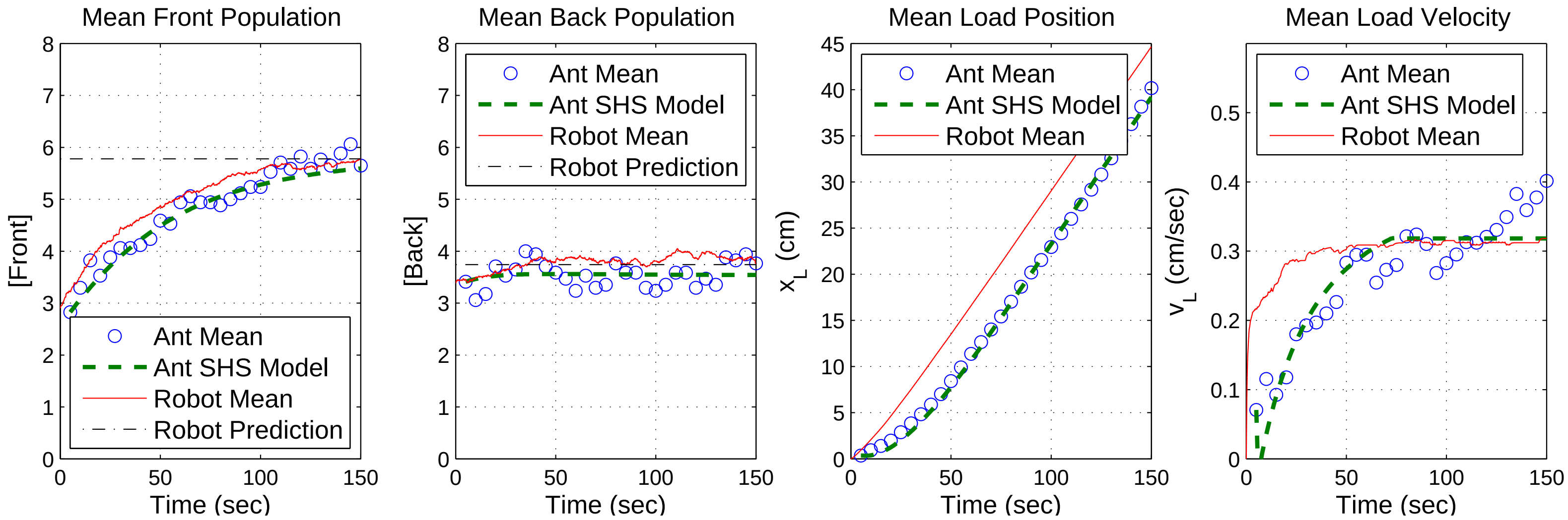


Collective Transport
(Wilson et al. 2014)



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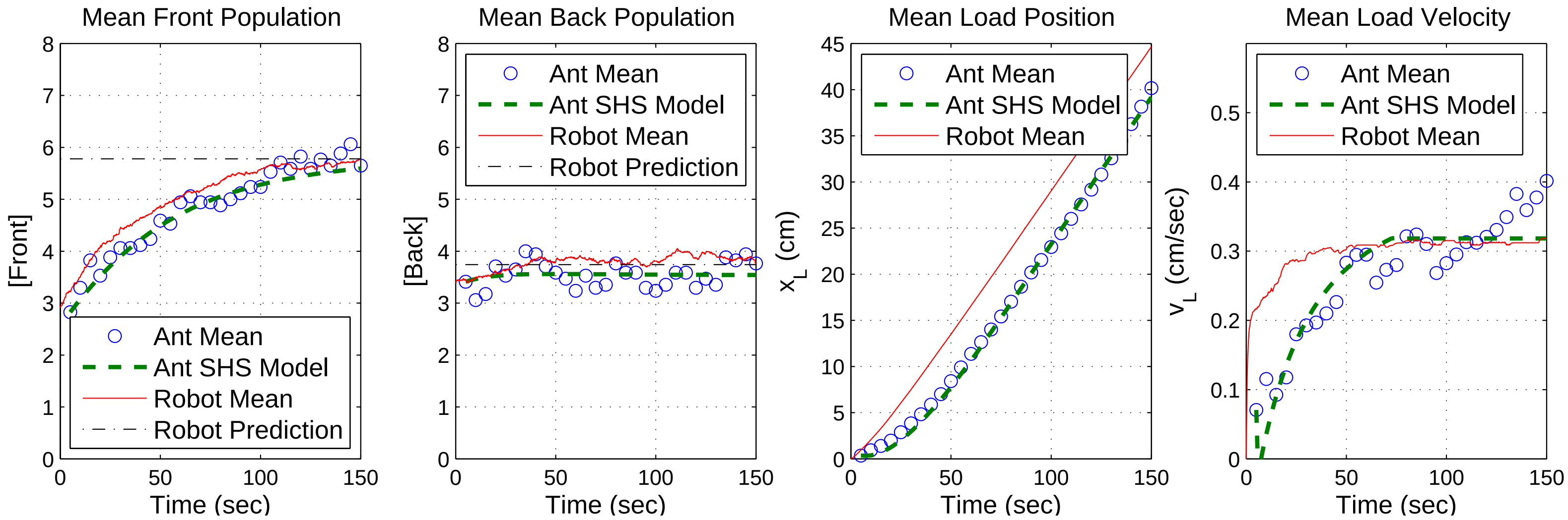

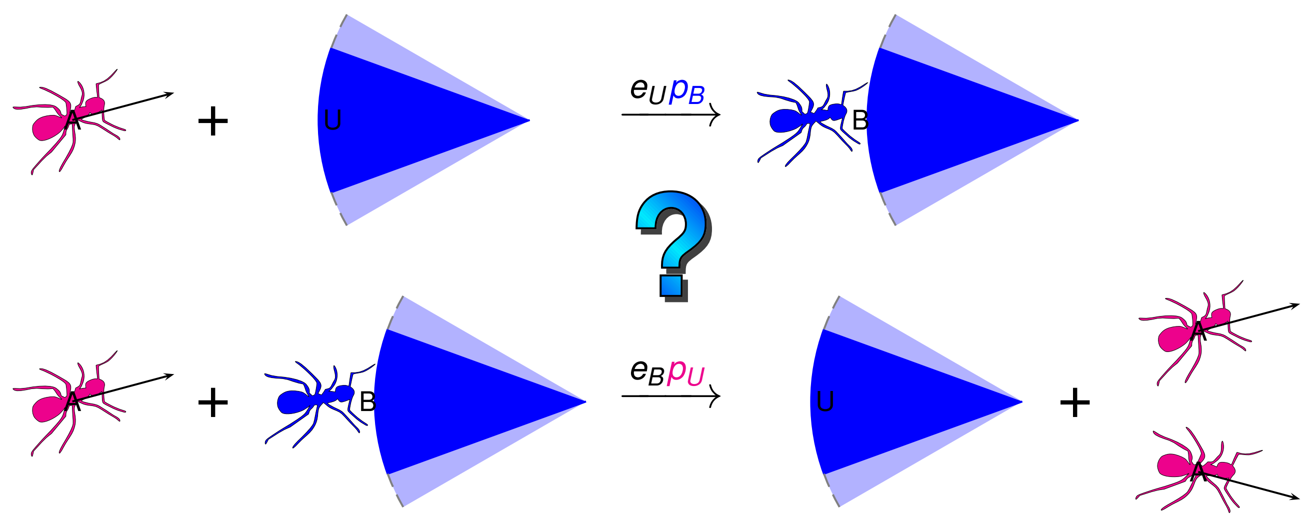

Decentralized Organization of *Ant* Teams Carrying Loads

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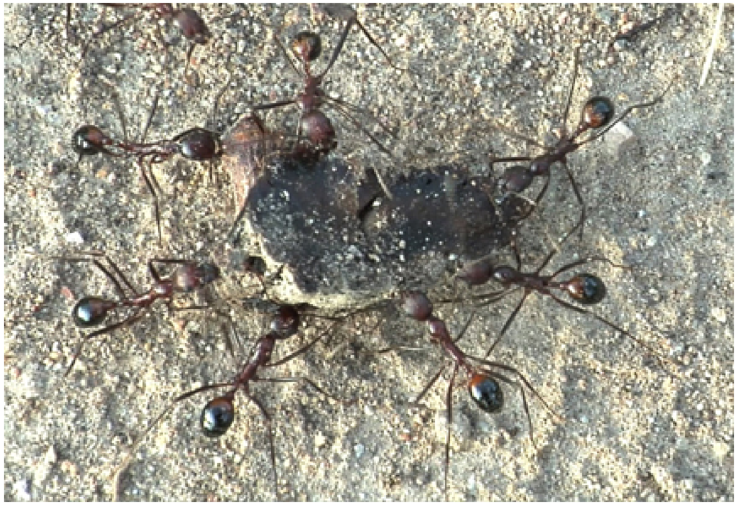

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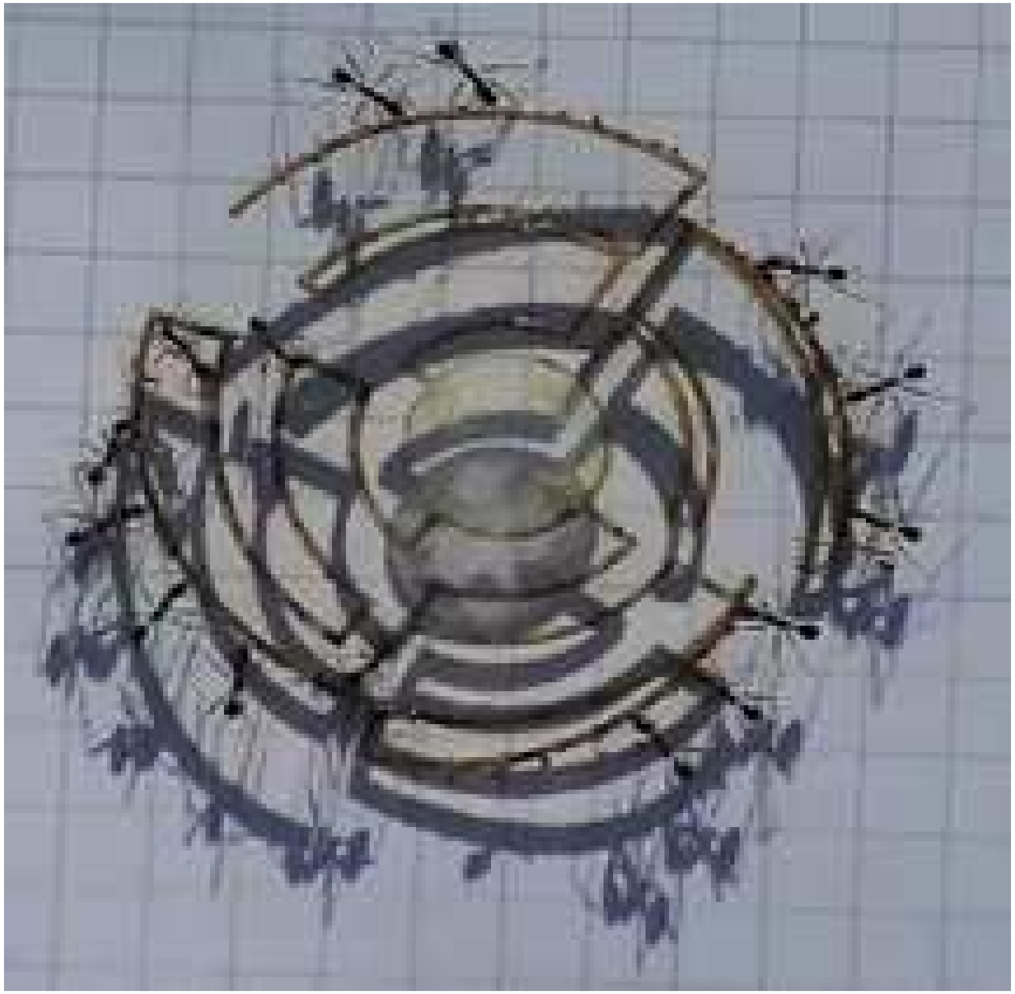
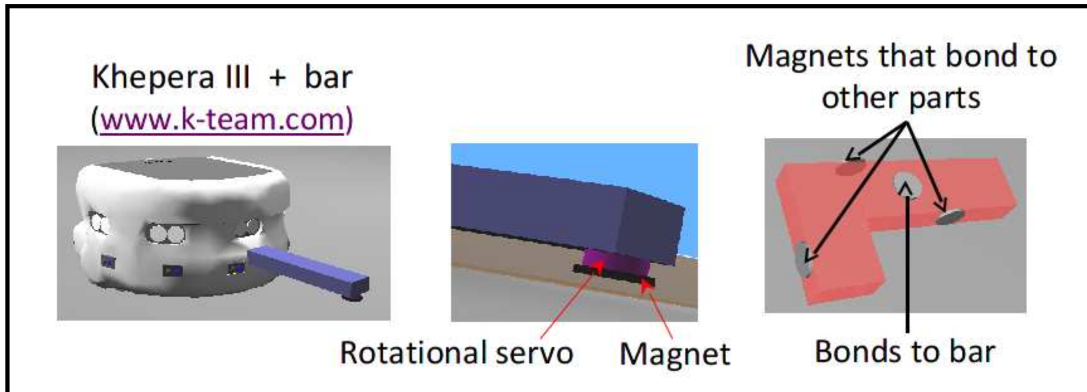
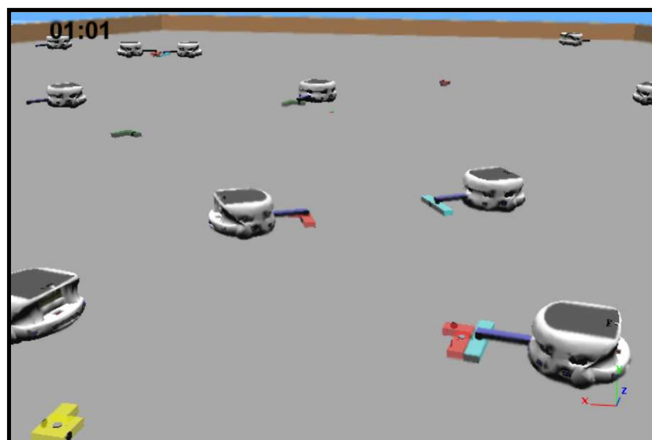


Possible Extension: Swarm Robotic Assembly
(Matthey et al. 2009)

Stochastic Strategies for a Swarm Robotic Assembly System

Loïc Matthey, Spring Berman and Vijay Kumar





Possible Extension: Swarm Robotic Assembly
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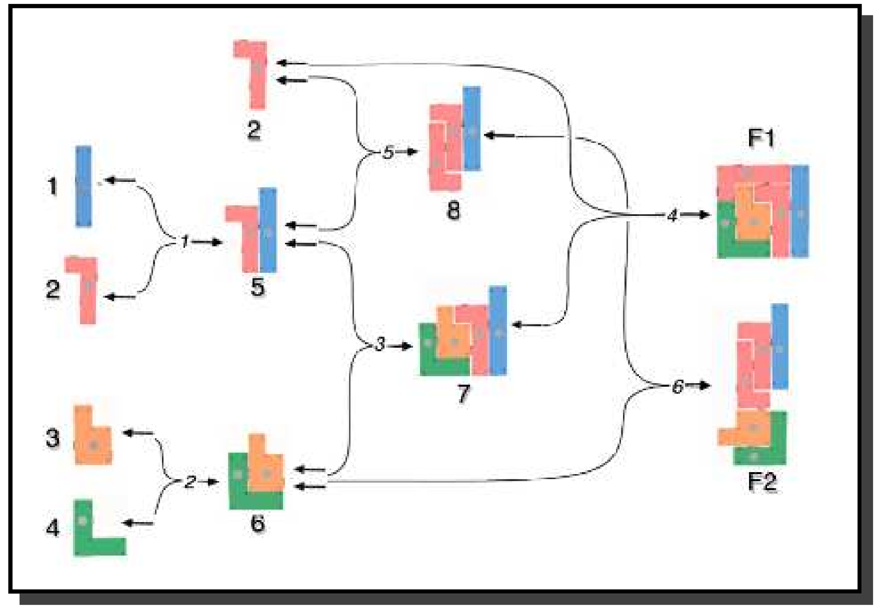

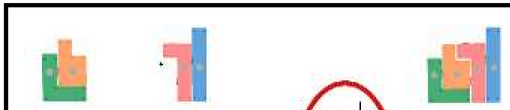

$$X_k + X_l \underset{k_j^-}{\overset{k_j^+}{\rightleftharpoons}} X_m$$

Goal: Regulate ratio of assembled parts at equilibrium (e.g., $x^*_{F1} = 2x^*_{F2}$).

Possible Extension: Honeycomb Assembly?
(Seeley and Morse 1976; Pratt 2004; Cargel and Rinderer 2004; Livnat and Pippenger 2006)

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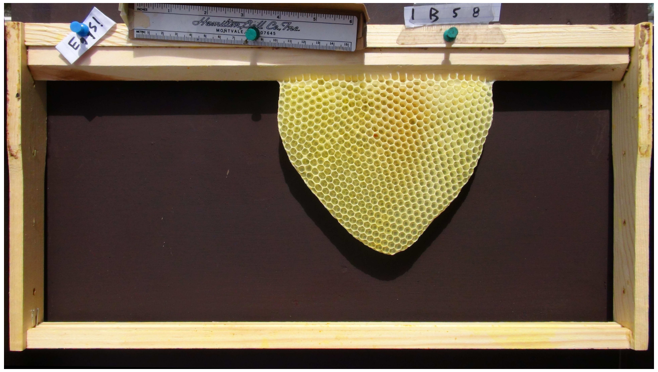

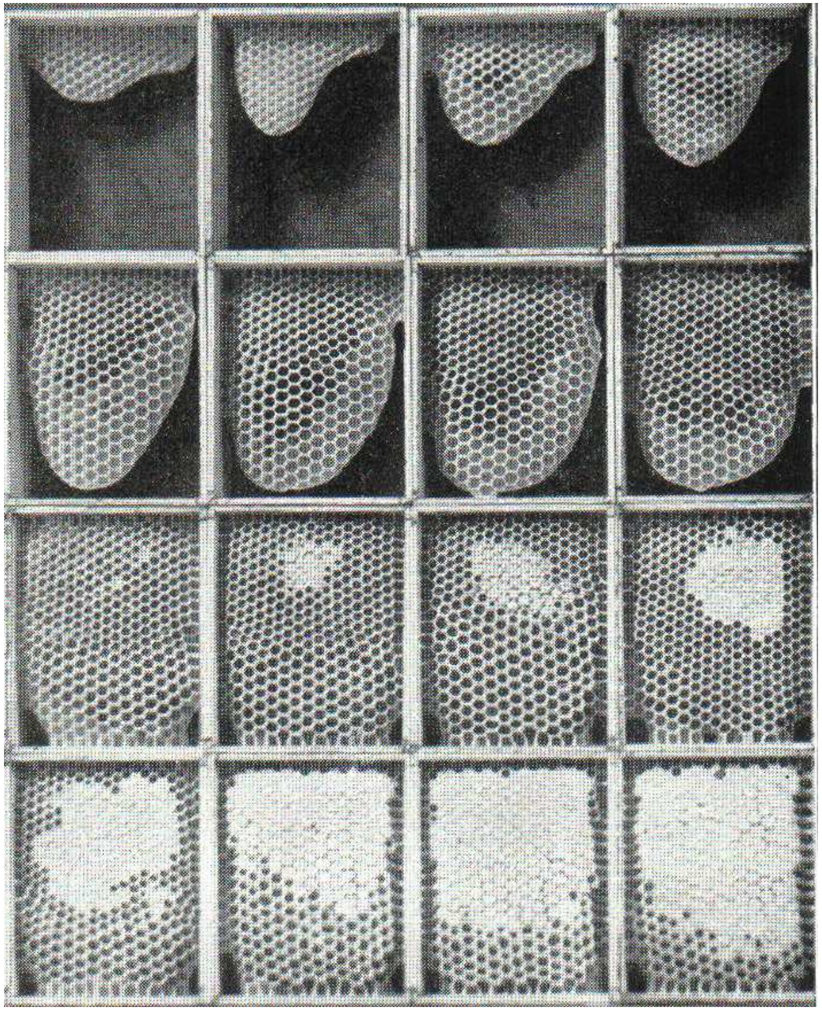

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$$\text{Worker} + \text{Earlier Cell} \xrightarrow{p_b e_c} \text{Worker} + \text{Later Cell}$$

$$\text{Worker} + \text{Later Cell} \xrightarrow{p_u e_c} \text{Worker} + \text{Earlier Cell}$$

$$\text{Active Cell} \xrightarrow{\text{SLOW}} \text{Finished Cell}$$

Stochastic Assembly in Honeybee Colonies
A Simple Model

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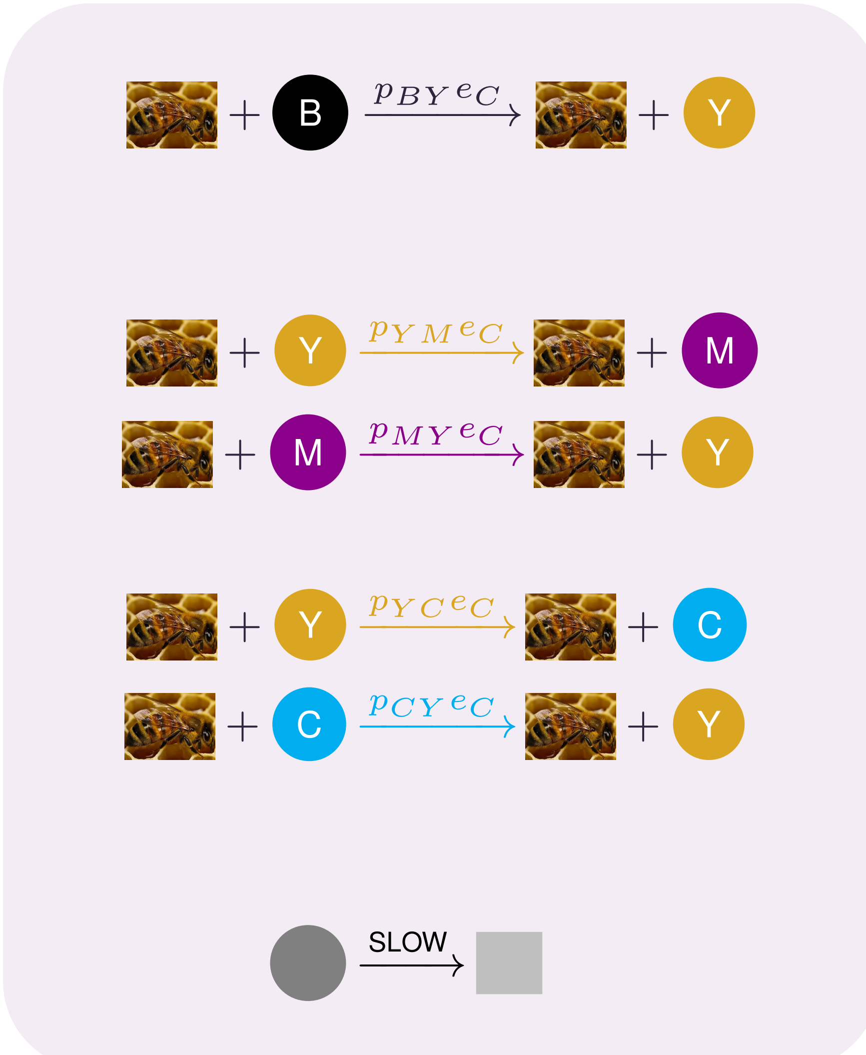

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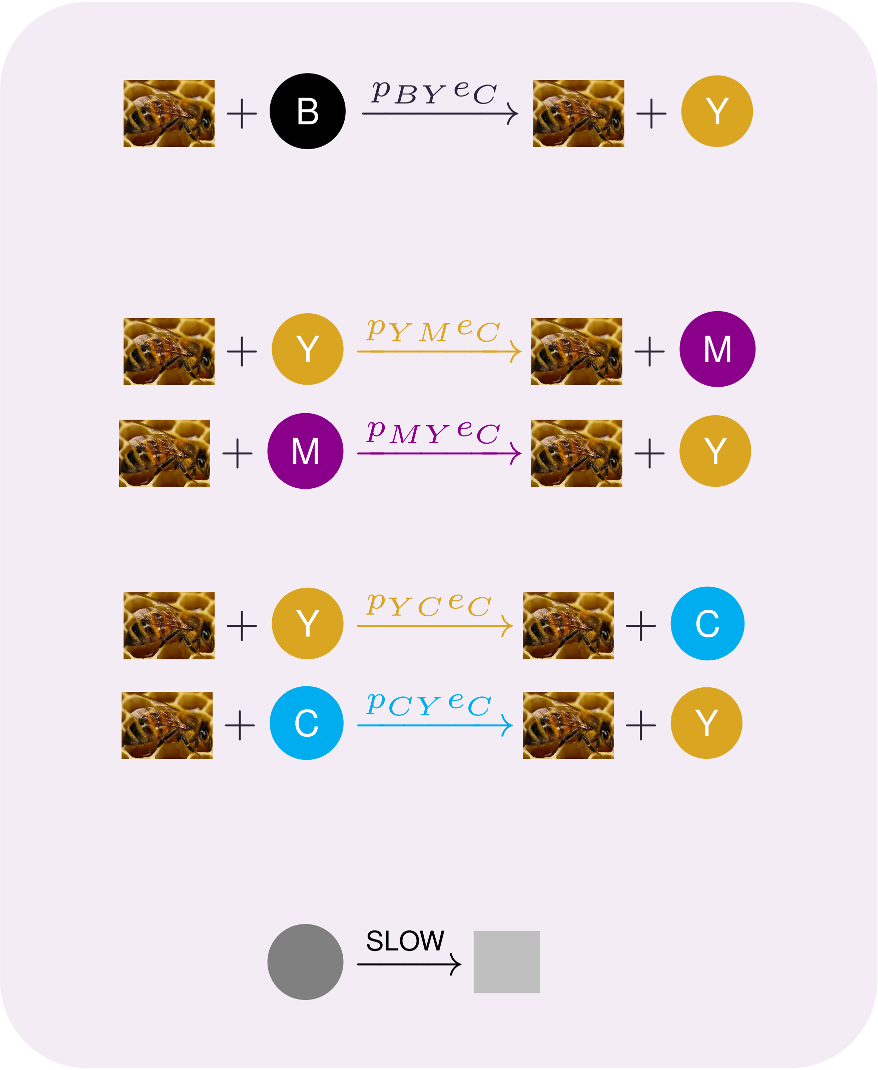

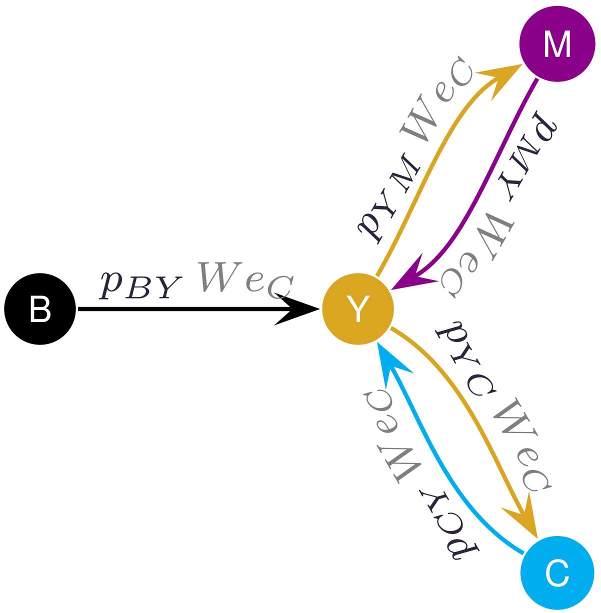

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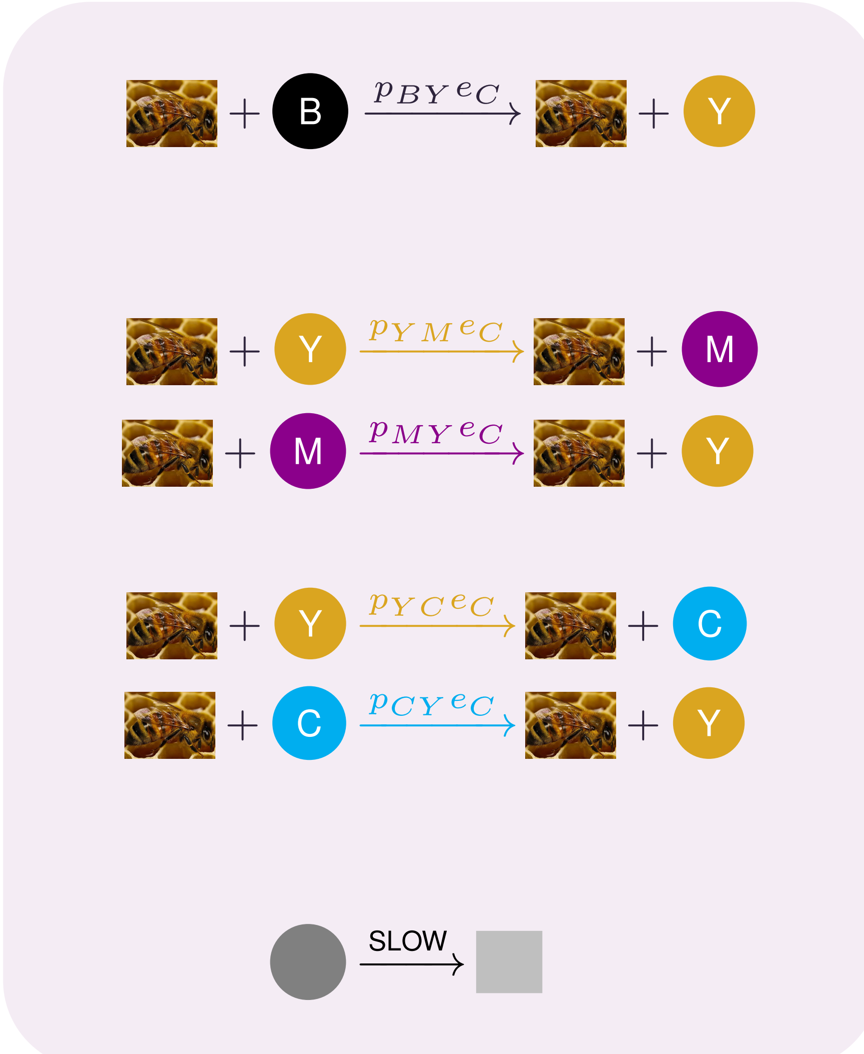

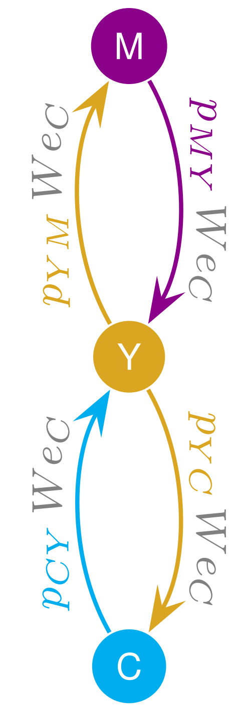

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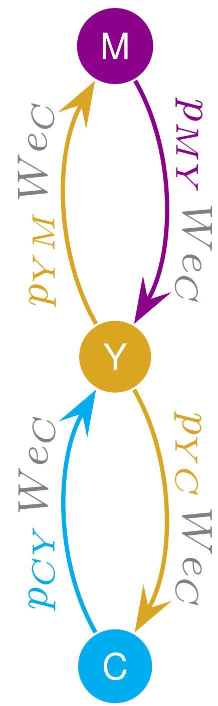
$$Y p_{YM} - M p_{MY} = 0$$
$$Y p_{YC} - C p_{CY} = 0$$
$$Y + M + C = 1$$



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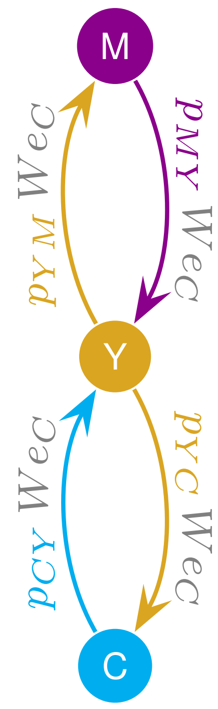
$$\begin{bmatrix} Y \\ M \\ C \end{bmatrix} = \frac{\begin{bmatrix} p_{MY} p_{CY} \\ p_{YM} p_{CY} \\ p_{MY} p_{YC} \end{bmatrix}}{p_{YM} p_{CY} + p_{MY} p_{YC} + p_{MY} p_{CY}}$$



Stochastic Assembly in Honeybee Colonies
A Simple Model

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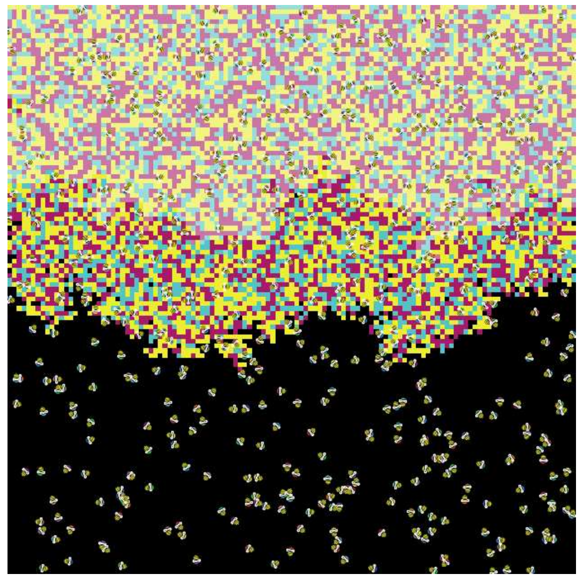

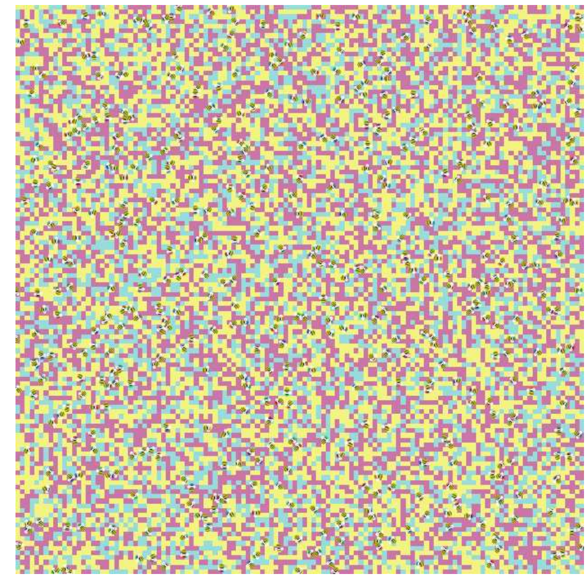

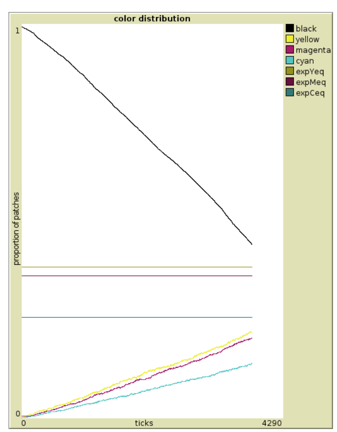

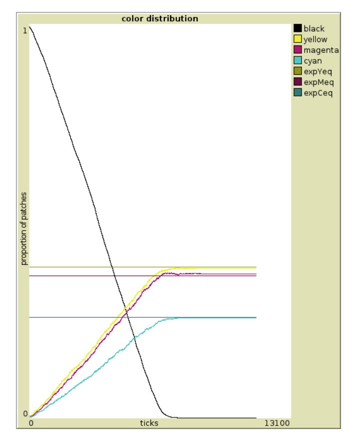

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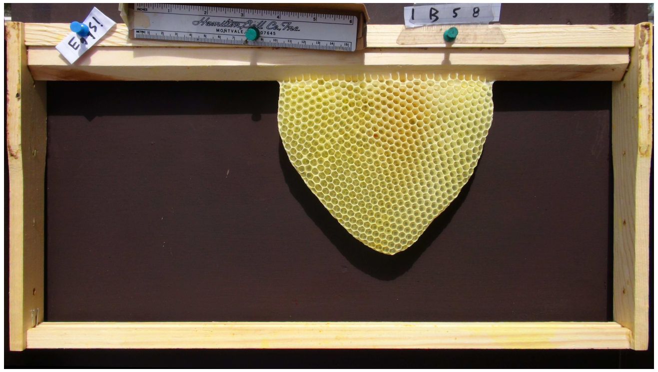

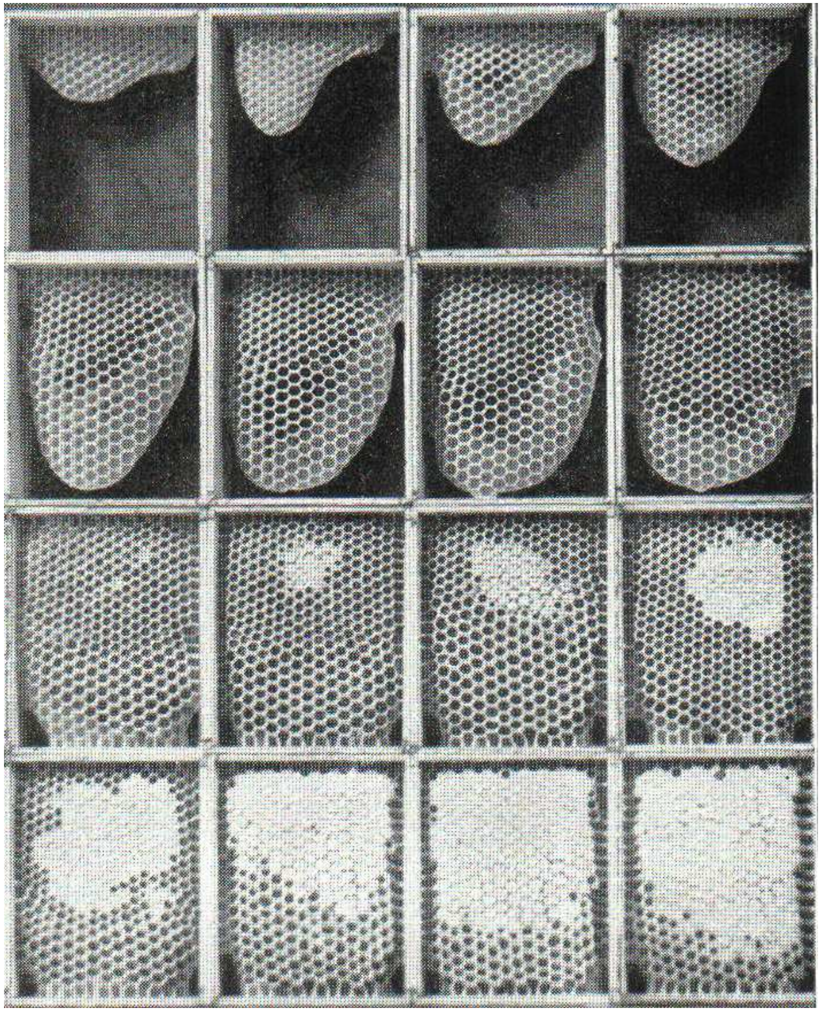

Temnothorax nest-site selection

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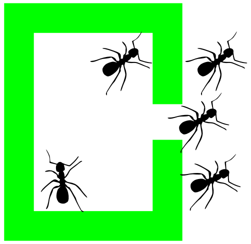

Photo: Takao Sasaki, James S. Waters

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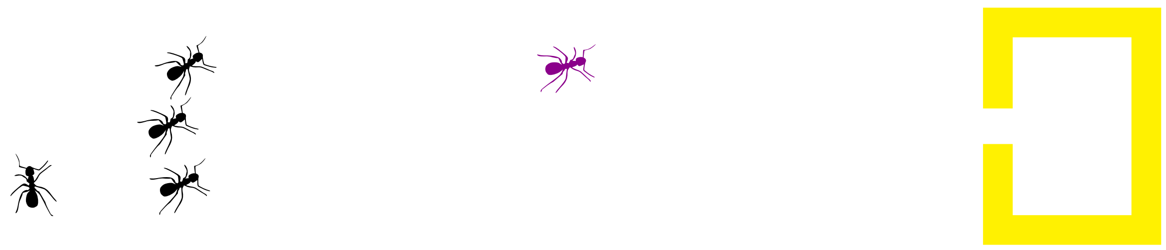

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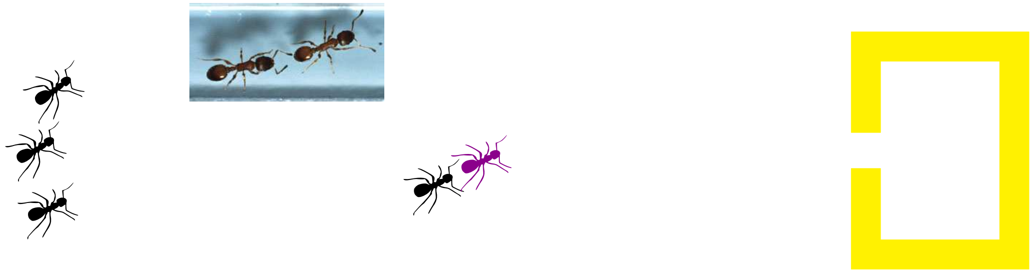

“Tandem run”

Slow transit, but adds one more recruiter.

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Temnothorax nest-site selection

“Transport”

Fast transit, but no additional recruiter.

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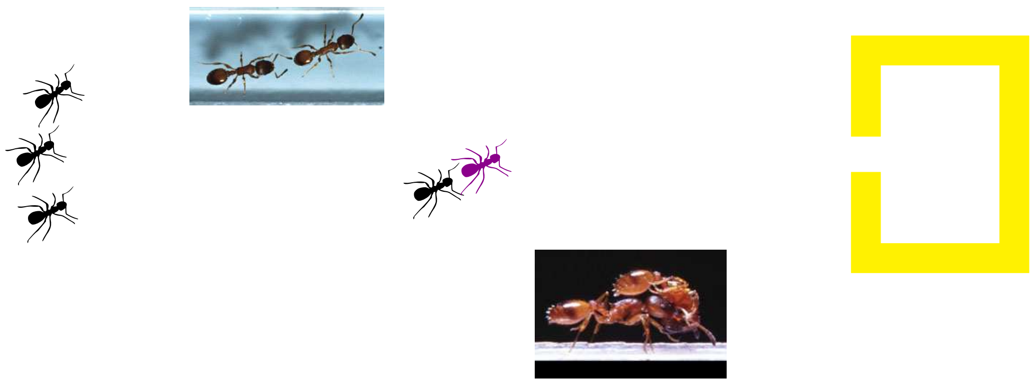
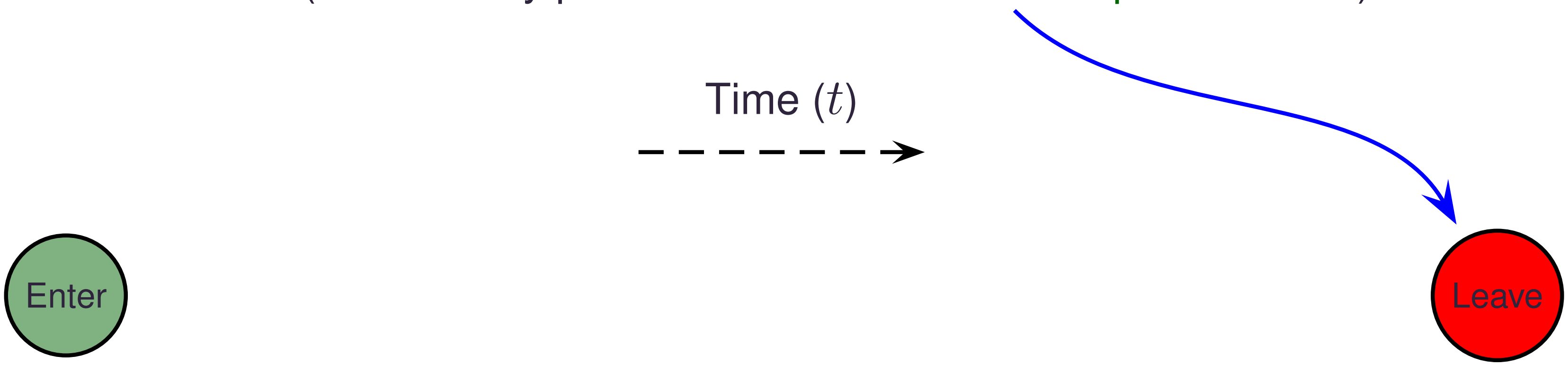


When to switch?

Recruitment decision process

Inside the nest (immediately prior to a tandem-run or transport decision):



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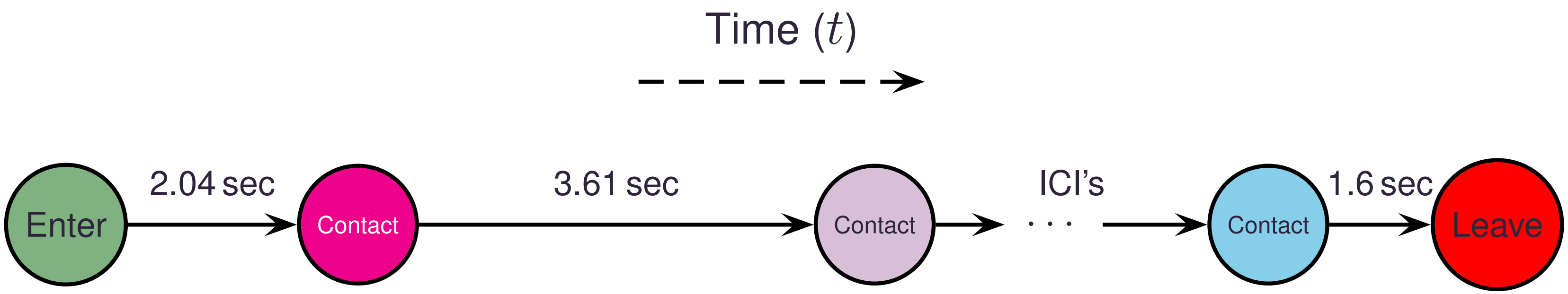
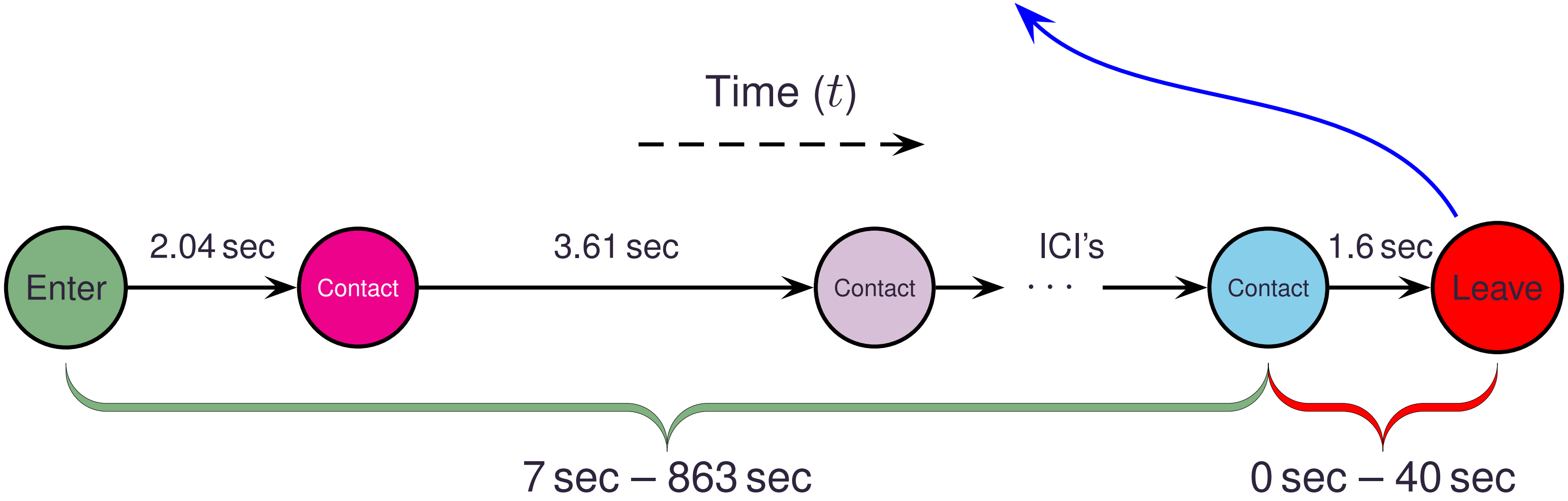


Recruitment decision process

Inside the nest (immediately prior to a tandem-run or transport decision):



Role of encounter rate
(Pratt 2005)

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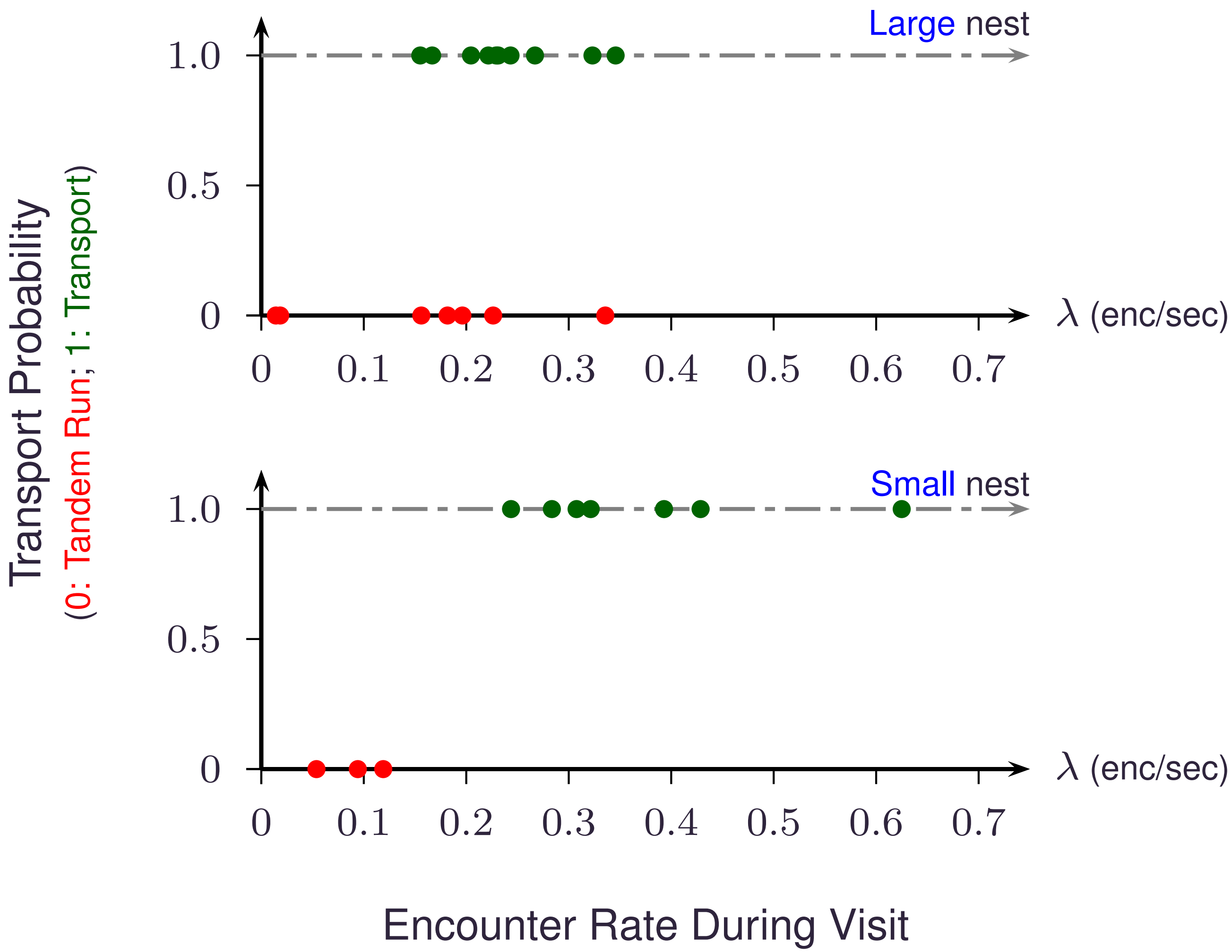

Role of encounter rate
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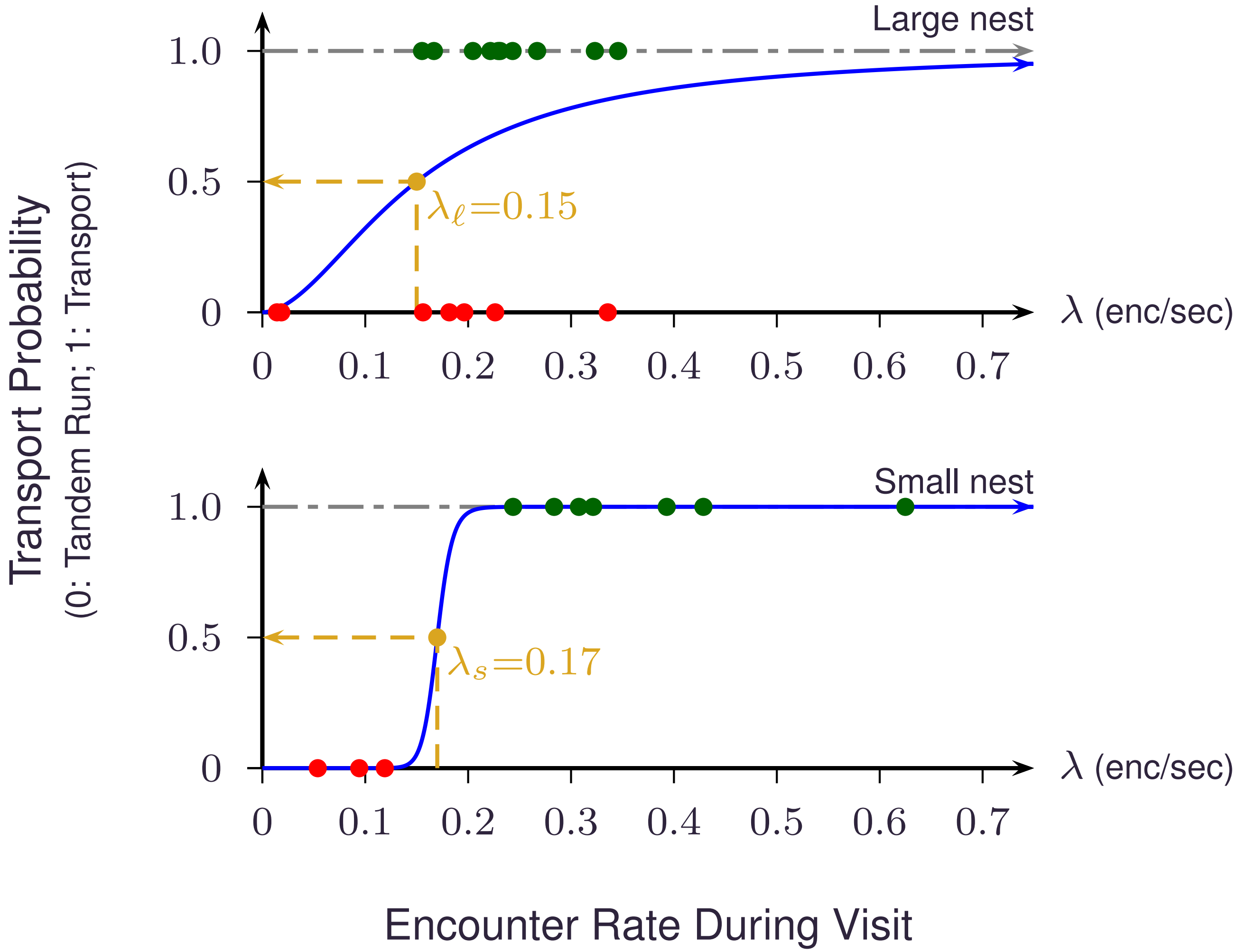
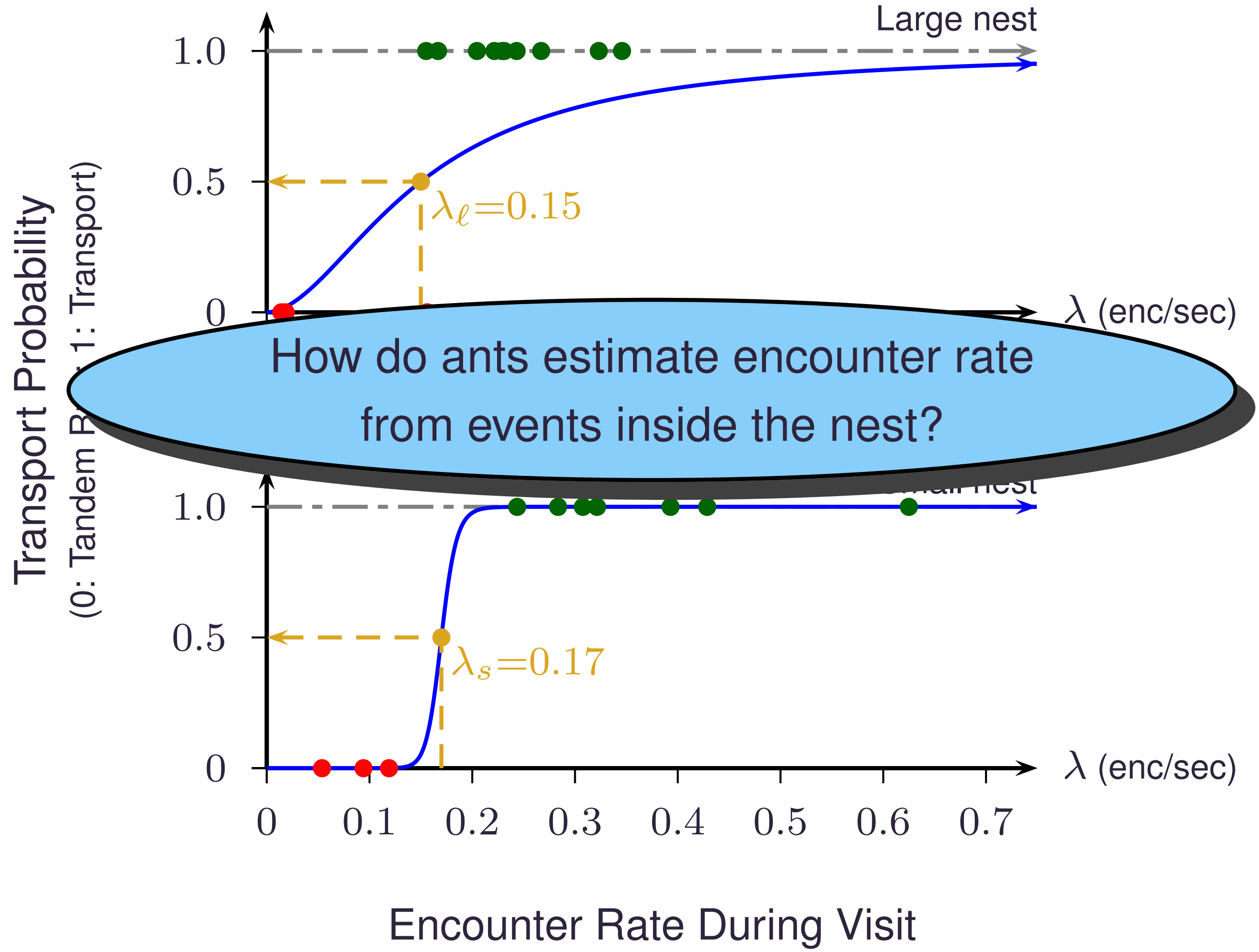


Role of encounter rate
(Pratt 2005)



How do ants estimate encounter rate from events inside the nest?

Encounter-rate detection and estimation?

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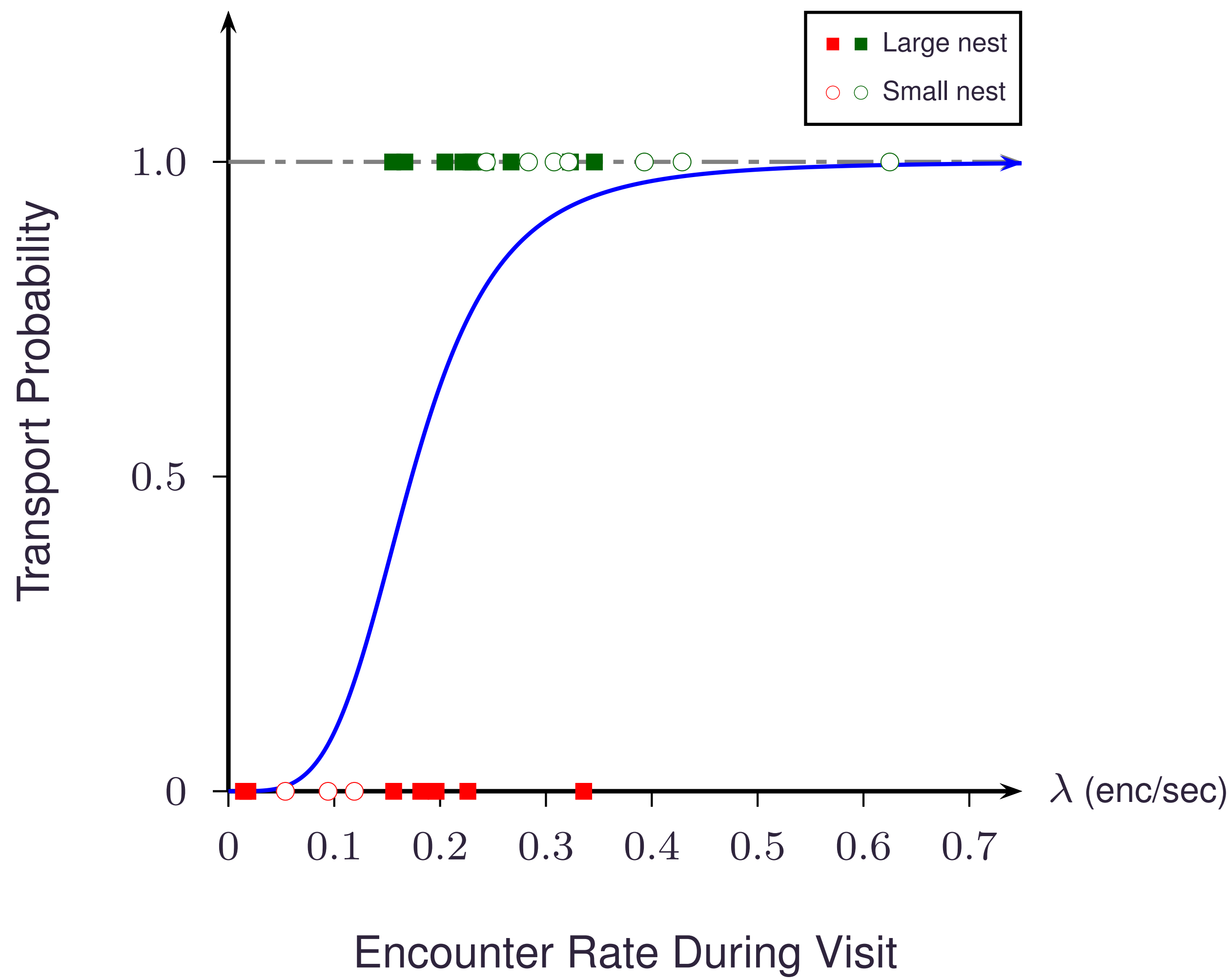

Encounter-rate detection and estimation?

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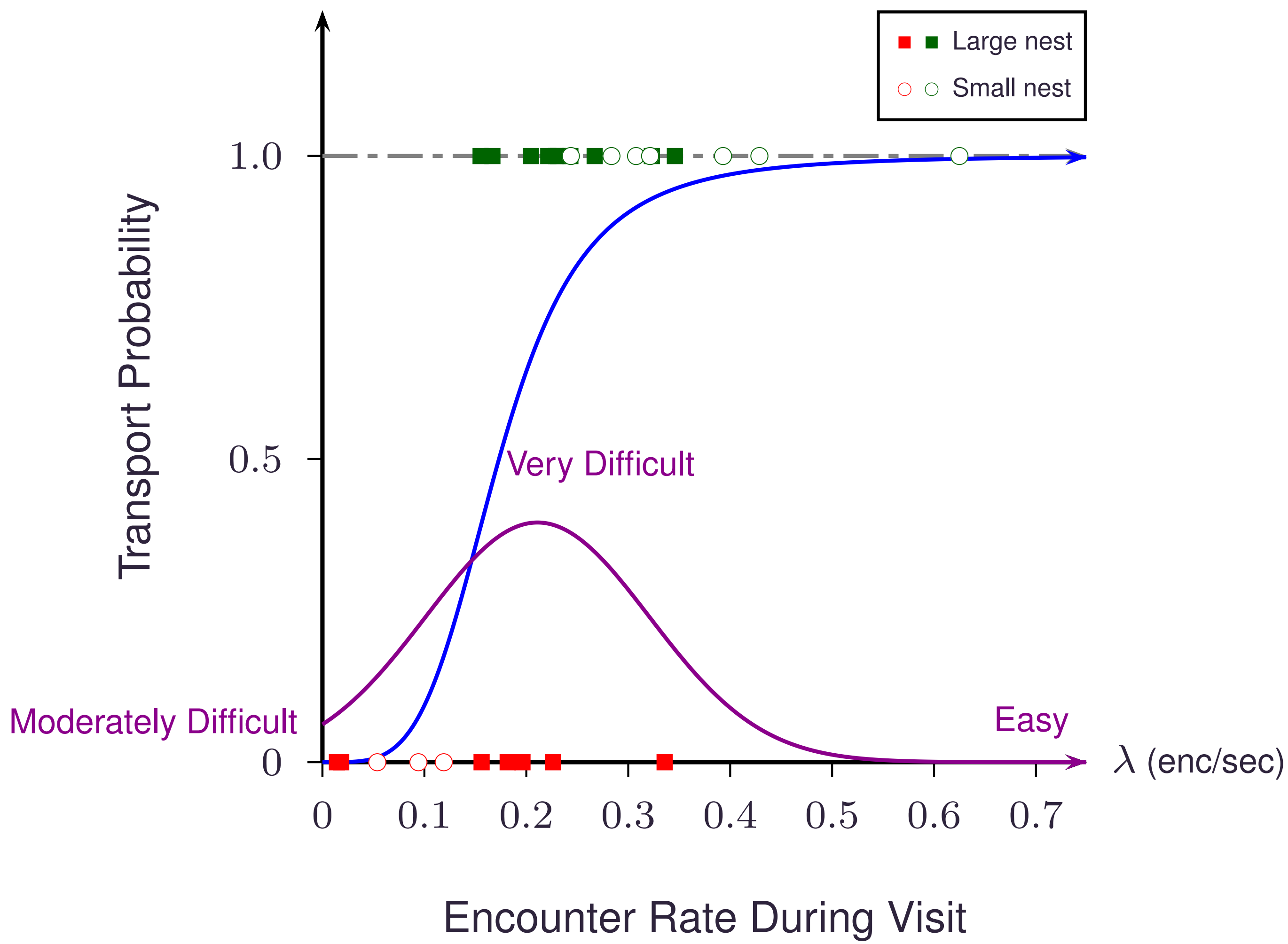

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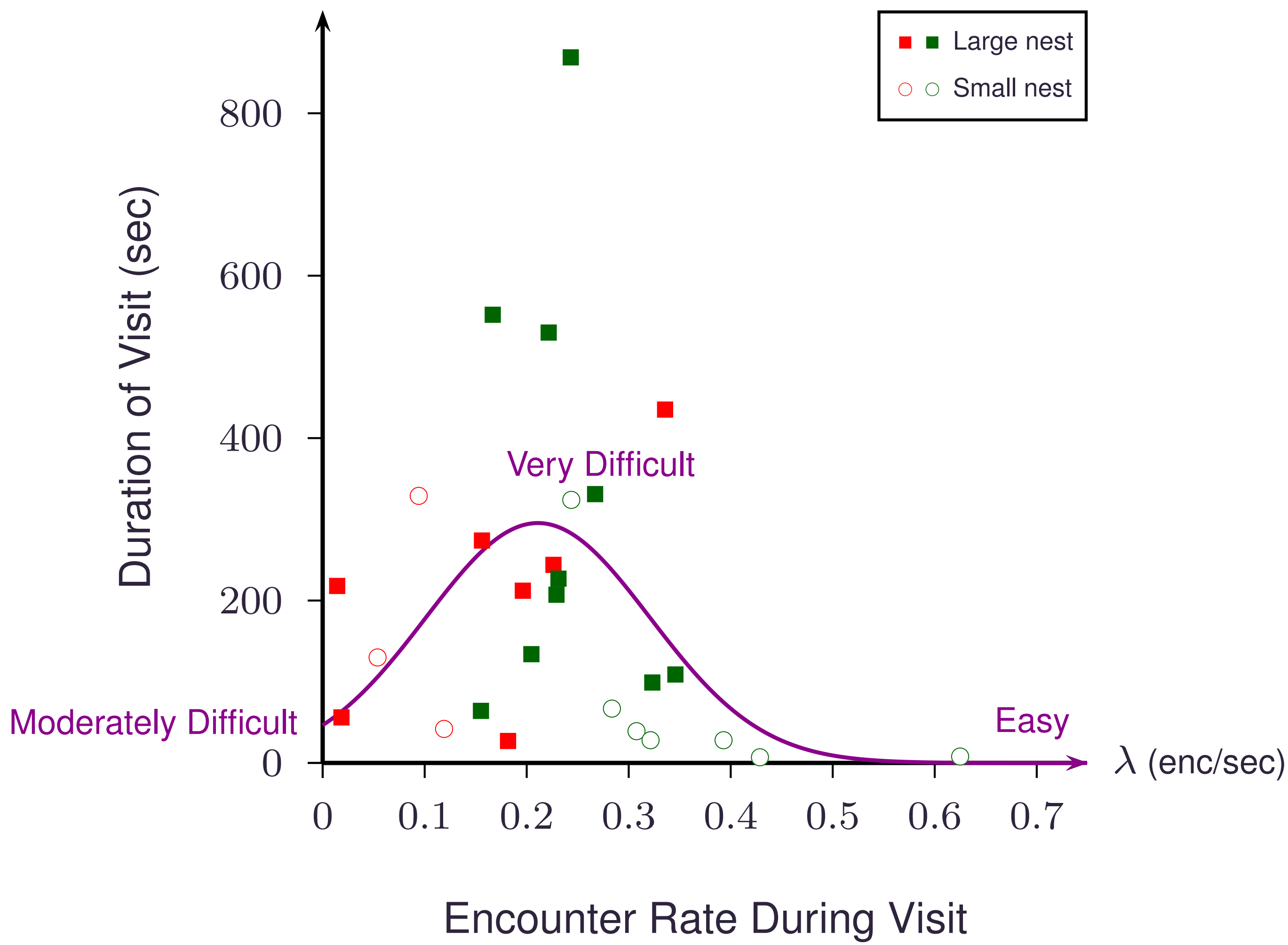

Encounter-rate detection and estimation?

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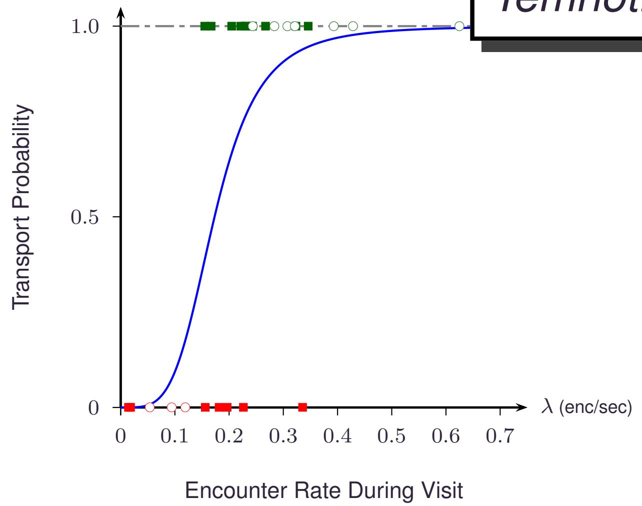
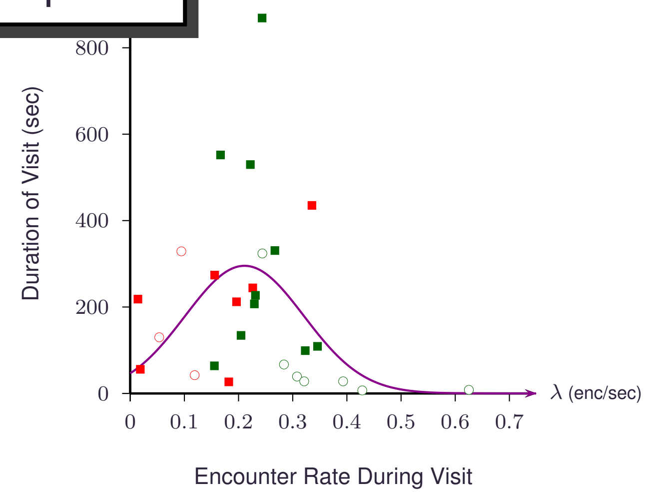
Temnothorax Response

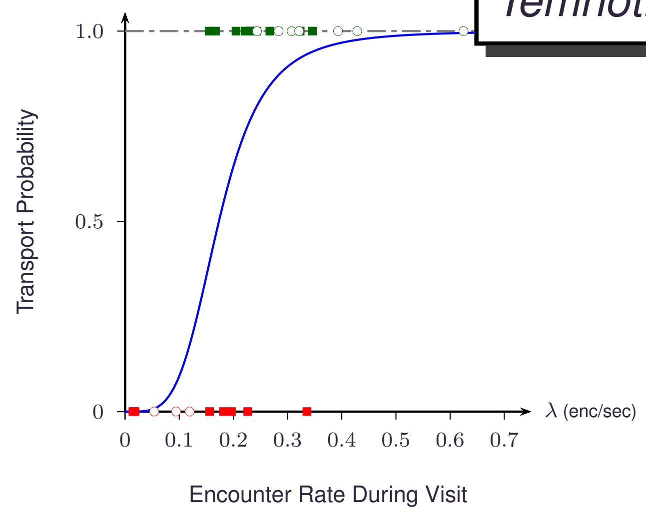


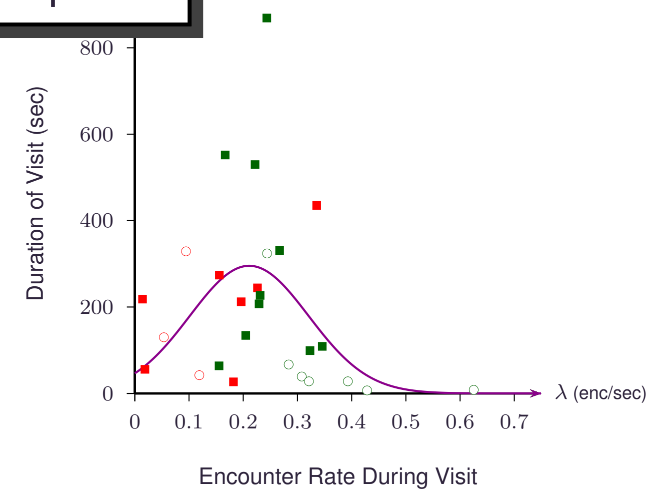


Encounter-rate detection and estimation?

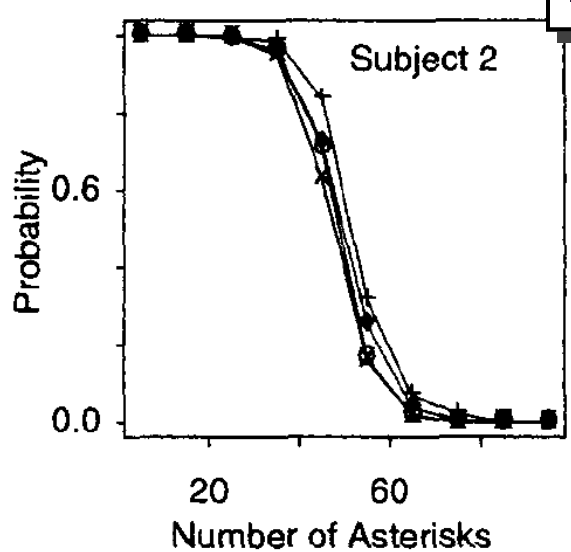
(Ratcliff et al. 1999)

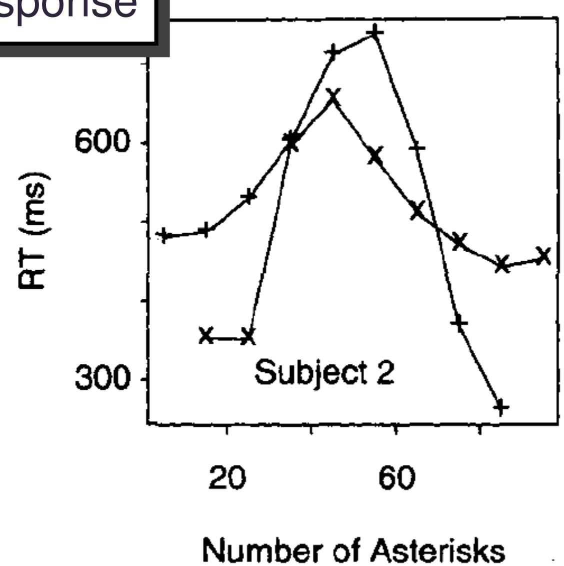
Temnothorax Response





Homo Response





Drift–diffusion model for two-choice tasks

(Ratcliff 1978; Ratcliff et al. 1999)

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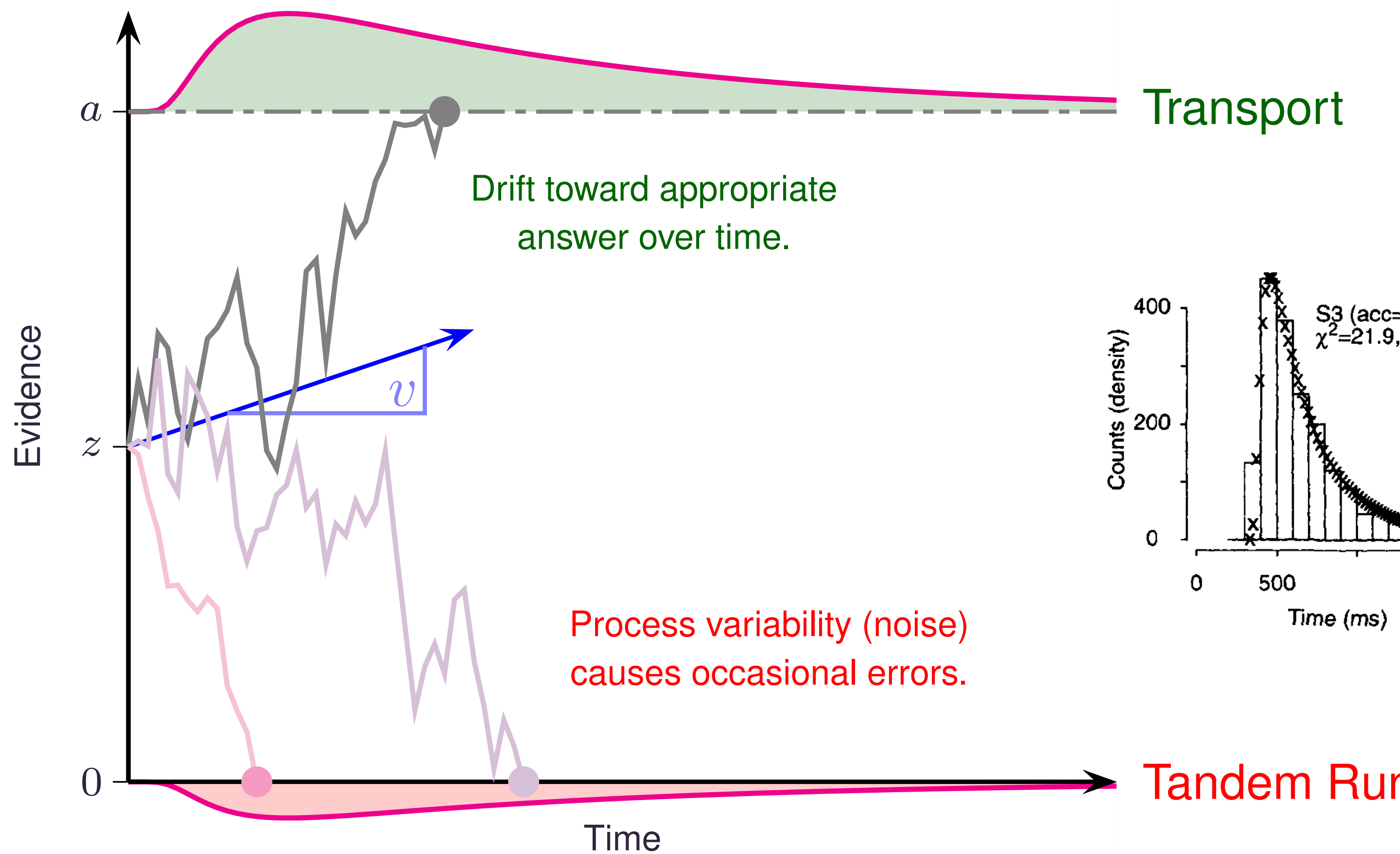

Drift–diffusion model for quorum detection in *Temnothorax*

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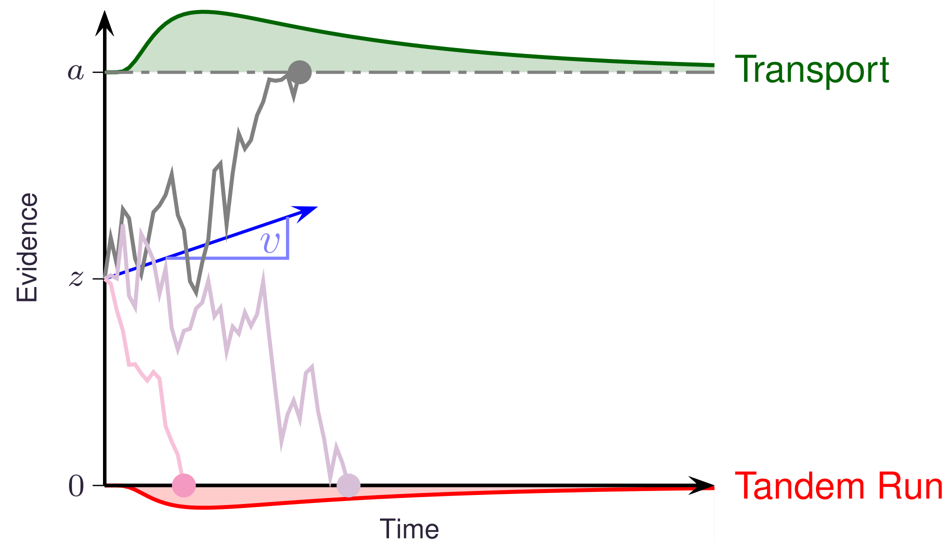

- Per-ant parameters of the model (generalized across sisters):
  - ☐ a: Barrier separation (response time)
  - ☐ z: Initial evidence variable (bias)
  - ☐ T_{nd}: Non-decision time (actuation)
  - ☐ λ_c: Critical encounter rate to detect
- Model of condition-dependent confidence/difficulty
  - ☐ $v \triangleq \lambda - \lambda_c$: Drift rate ($\lambda$ measured from encounter data)

Drift–diffusion model for quorum detection in *Temnothorax*

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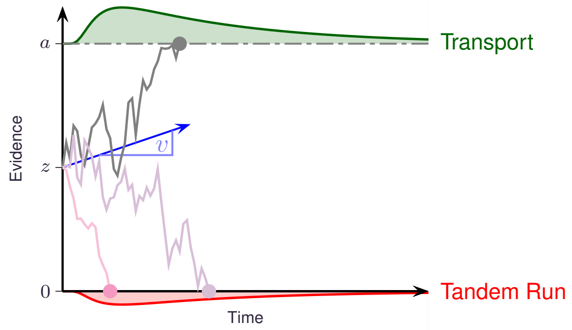
- Best-fit parameter results:
  - $a = 26.729$
  - $z = 8.0$
  - $T_{nd} = 6.564$ sec
  - $\lambda_c = 0.173$ enc/sec



Drift–diffusion model for quorum detection in *Temnothorax*

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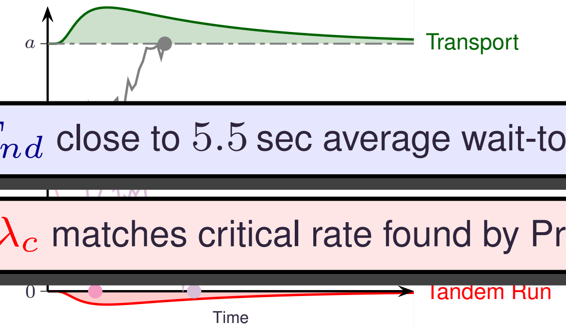

T_{nd} close to 5.5 sec average wait-to-leave time

λ_c matches critical rate found by Pratt (2005)

Drift–diffusion model for quorum detection in *Temnothorax*

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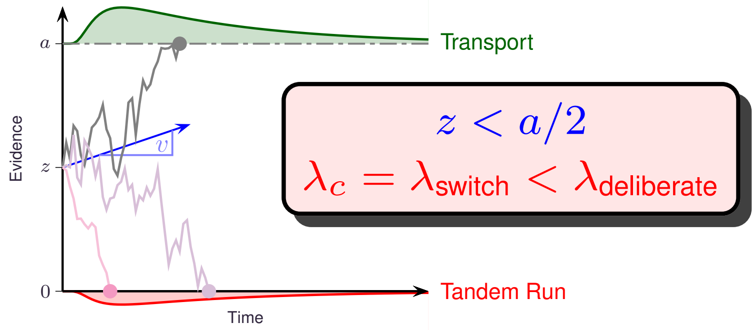

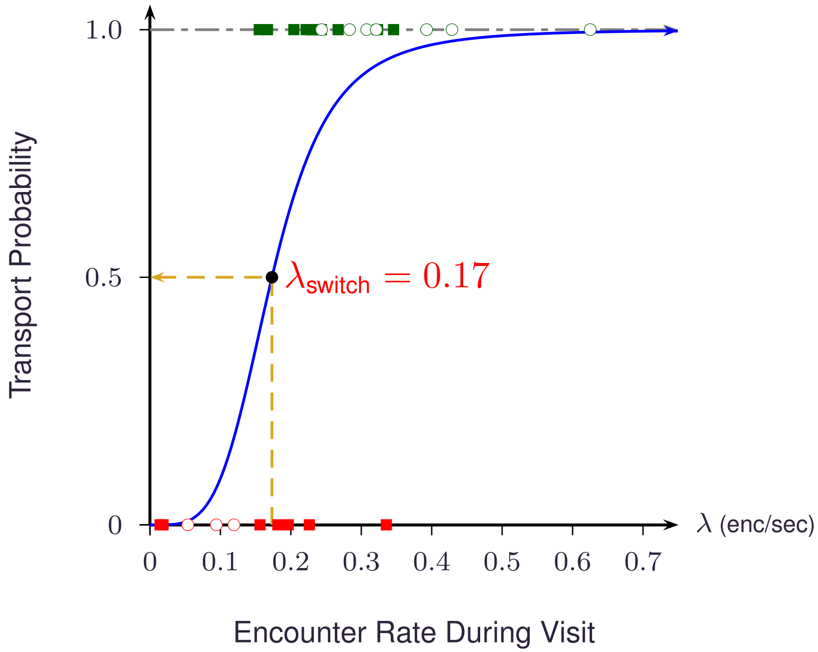

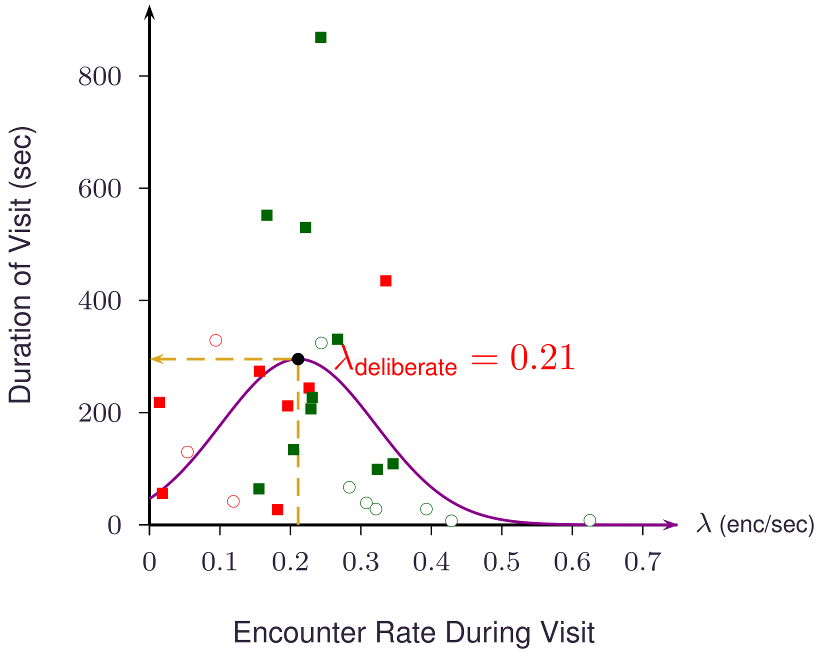

Random walk: internal or external?

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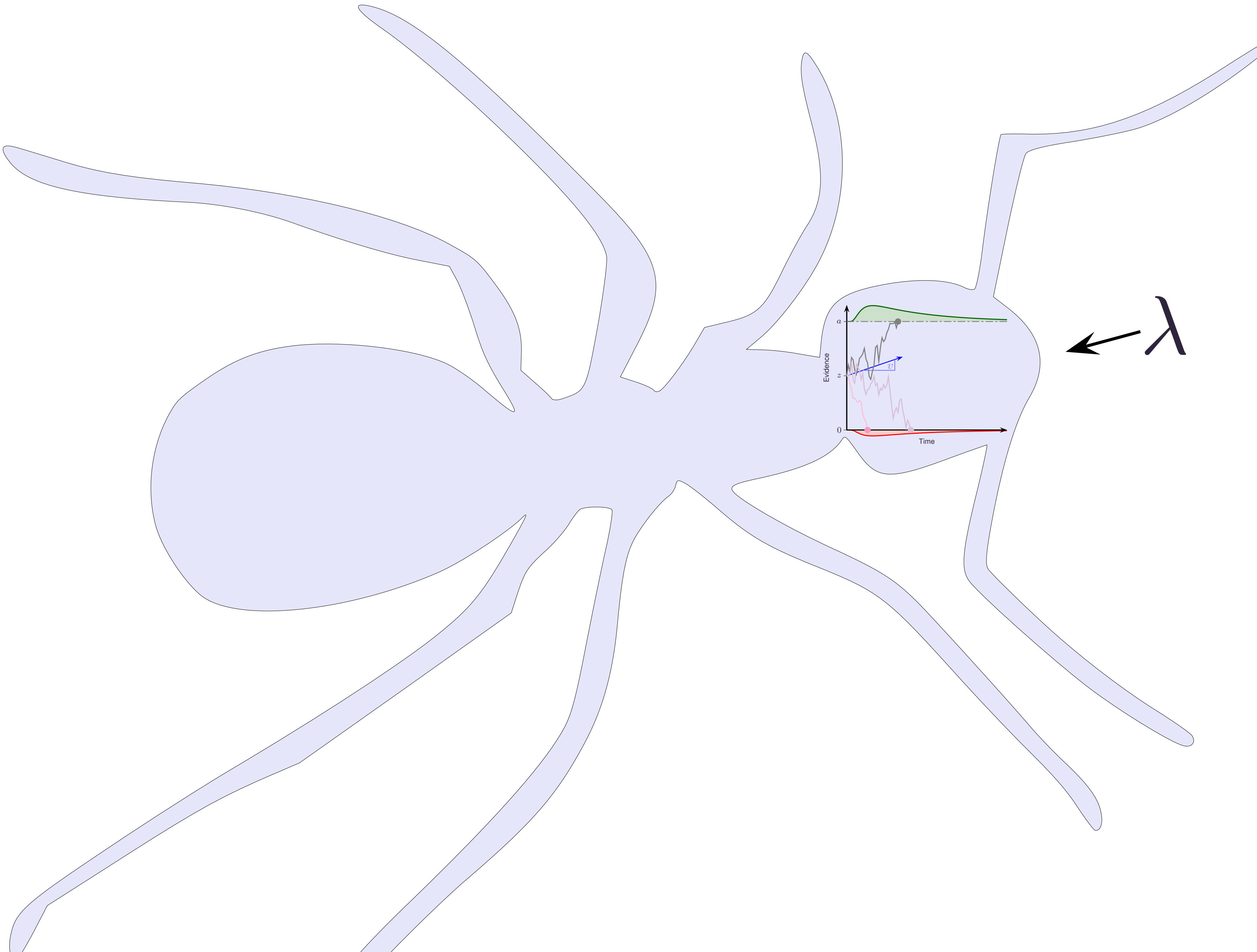

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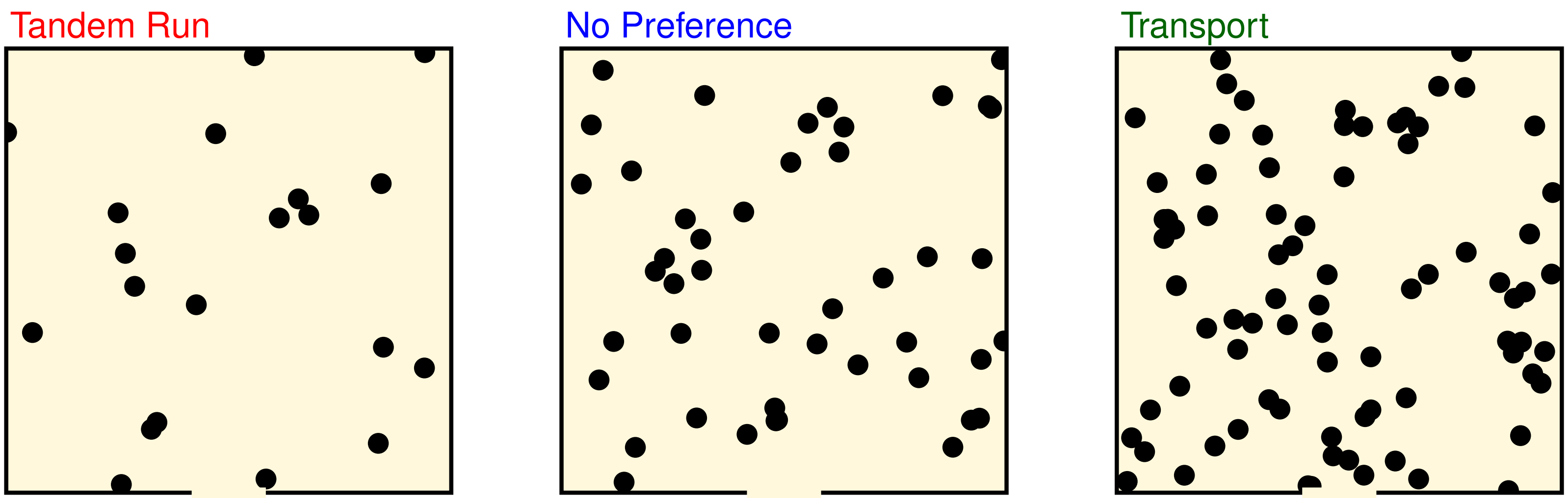
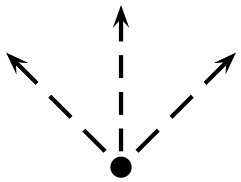
Random walk: internal or external?



$\lambda = 0.1$ enc/sec $\lambda = 0.24$ enc/sec $\lambda = 0.5$ enc/sec



Recurrence time distributions?

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- Coarse-graining introduces ambiguity
- Macroscopic consistencies can come about through multiple mechanisms

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- Coarse-graining introduces ambiguity
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- Simplest mechanisms are great candidates for engineering design
- Nature’s adaptive mechanisms are constrained by phylogeny, ontogeny, and the environment (Tinbergen!)

Conclusions

- Coarse-graining introduces ambiguity
- Macroscopic consistencies can come about through multiple mechanisms
- Simplest mechanisms are great candidates for engineering design
- Nature's adaptive mechanisms are constrained by phylogeny, ontogeny, and the environment (Tinbergen!)
- Acknowledgments:

  - Spring M. Berman (ASU, SEMTE) + laboratory
  - Stephen C. Pratt (ASU, SOLS) + laboratory
