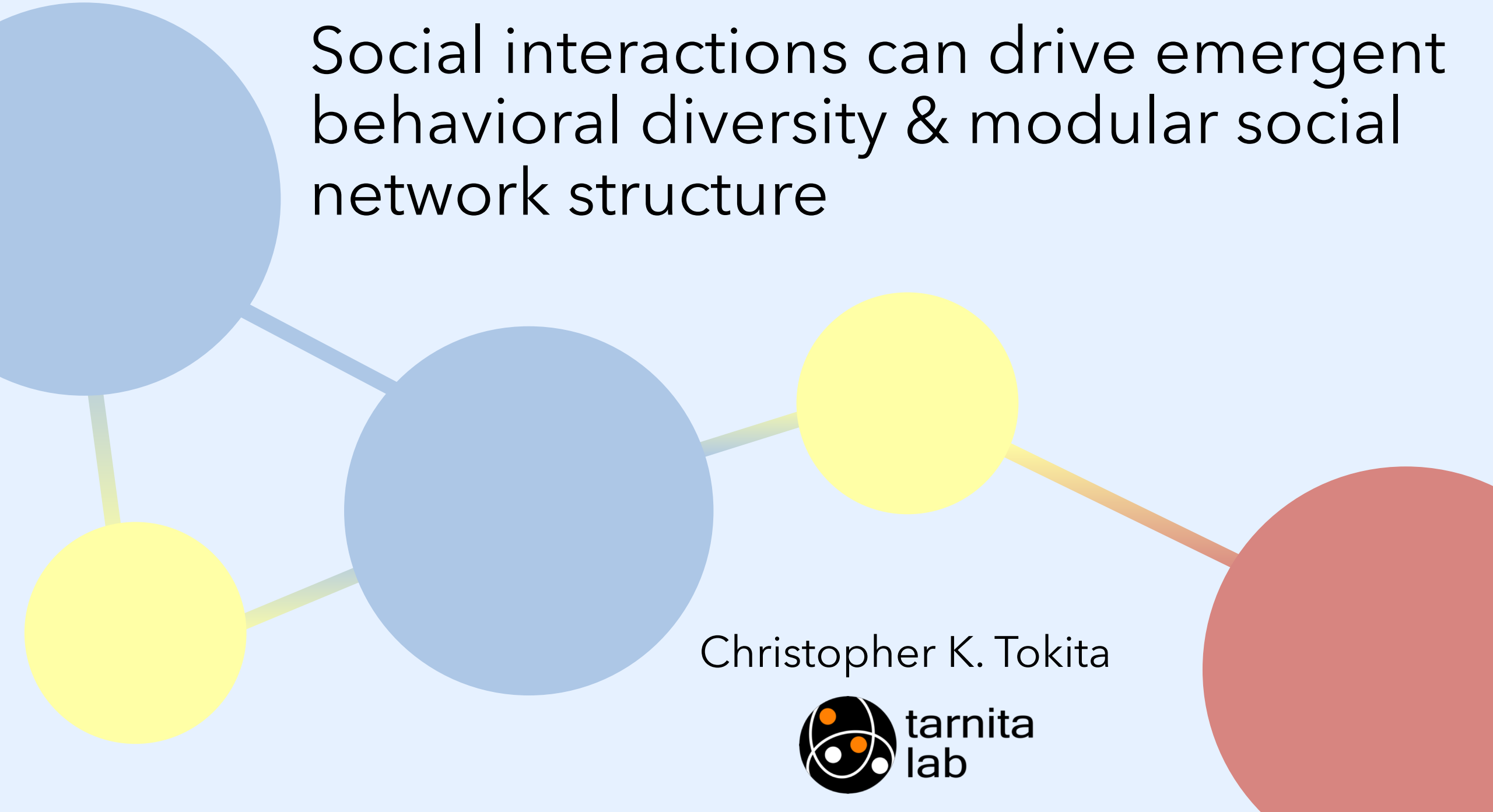
Social interactions can drive emergent behavioral diversity & modular social network structure

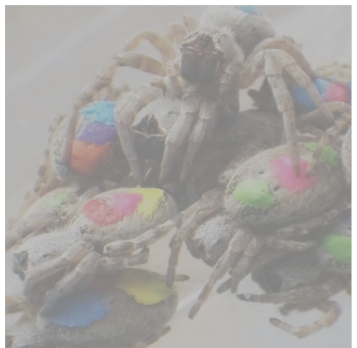


Christopher K. Tokita

tarnita lab

Describing social systems



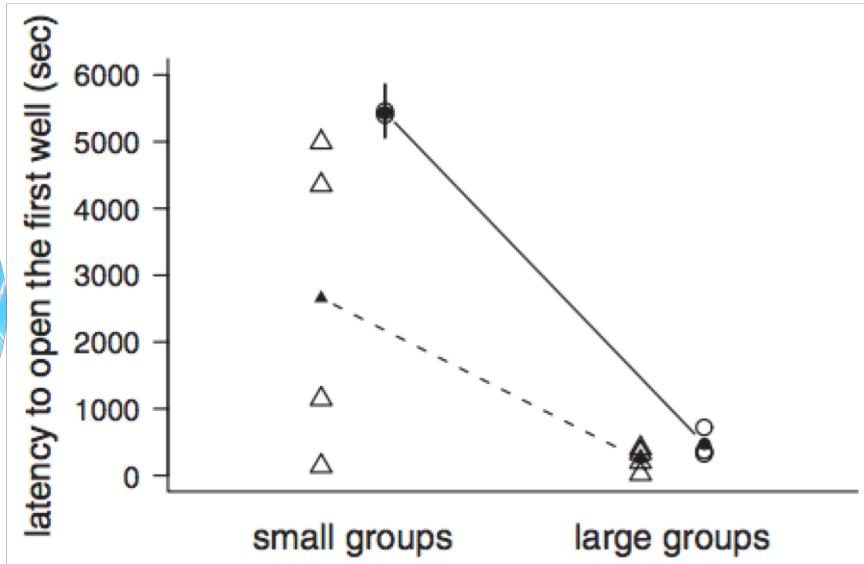



Group size

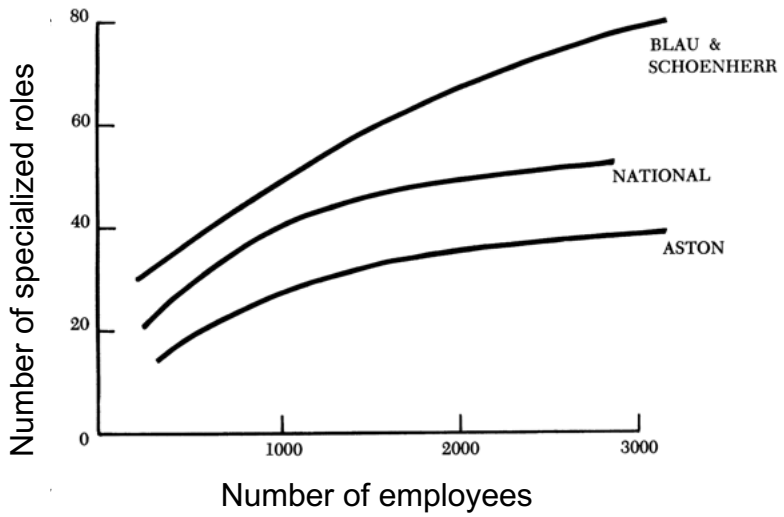
Diversity

Pattern of interactions

Group size, descriptor and effects



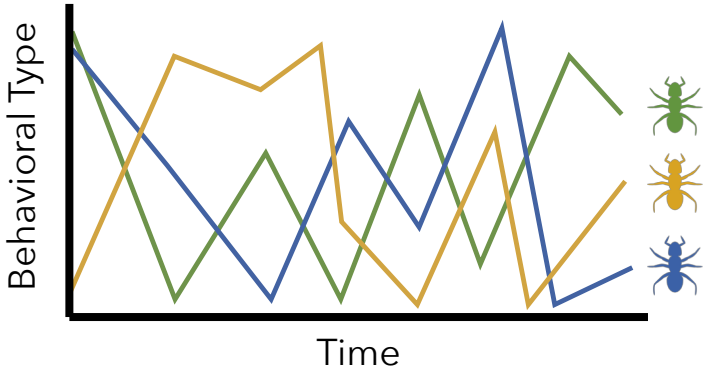
Liker & Bokony 2009 *PNAS*



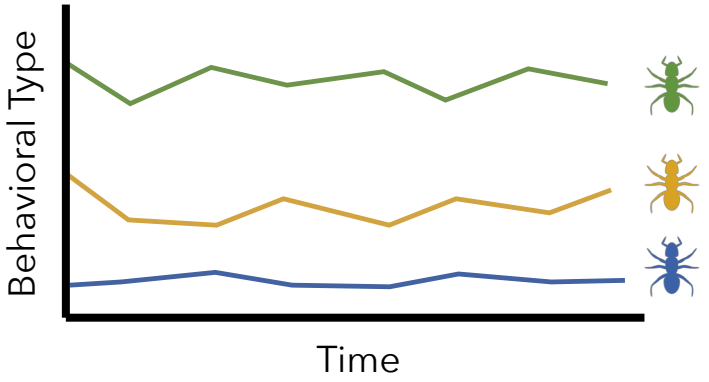
Child 1973 *Adm. Sci. Q*

Behavioral **diversity:** descriptor and effects

Behavioral variation



Behavioral variation &
Behavioral consistency

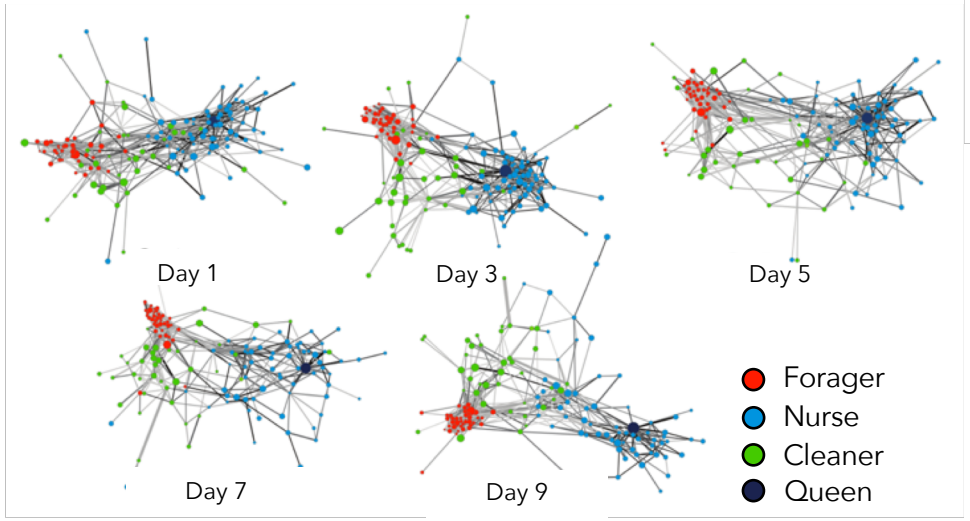


Behavioral diversity in groups can alter

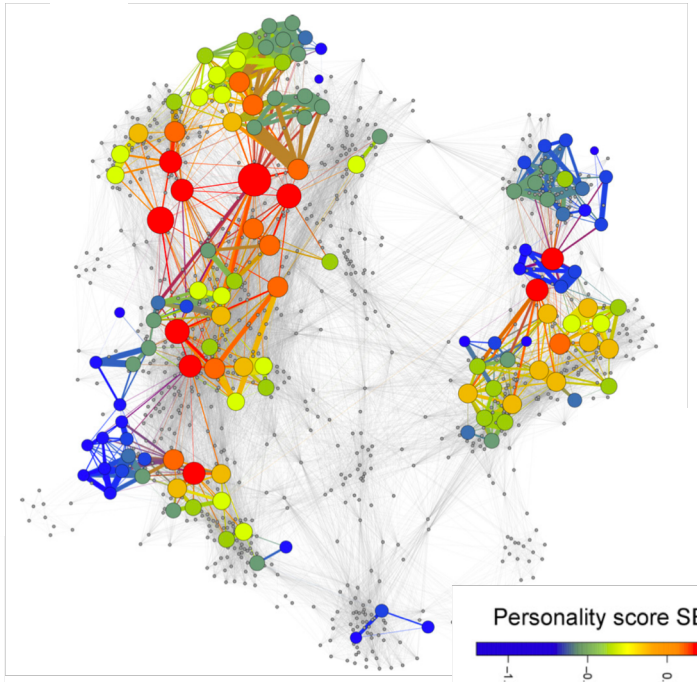
- Collective decision-making
- Foraging patterns
- Group-level personality
- Offspring rearing and nest building
- Within-group Cooperation

Pattern of interactions: social networks as an important descriptor of social systems

Division of Labor



Adapted from Mersch, Krespi, & Keller 2013 *Science*



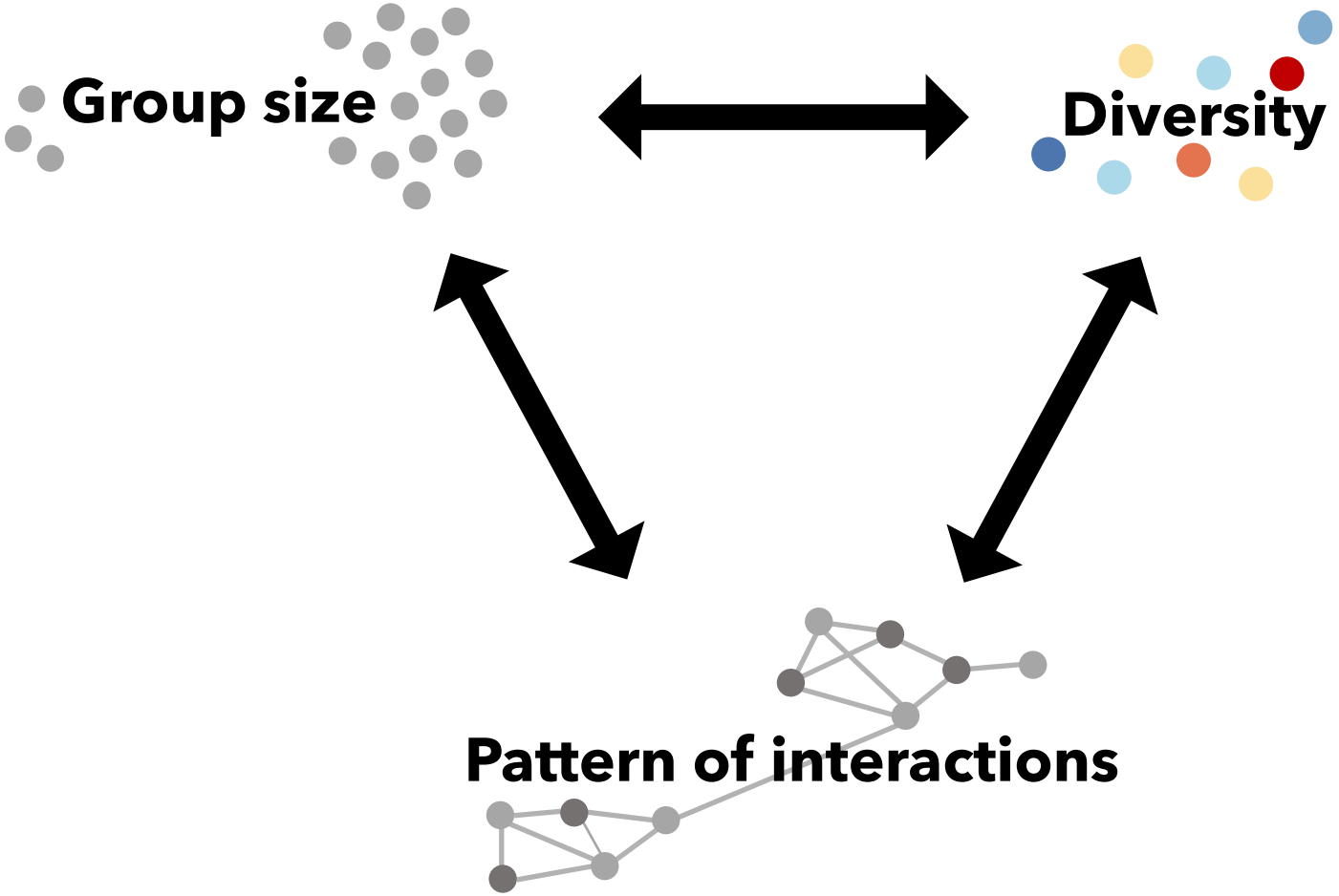
Personality/Behavioral Consistency

Alptin *et al.* 2013 *Ecol Lett*

Human society

Adamic & Glance 2005 *Proceedings of the 3rd international workshop on Link discovery*

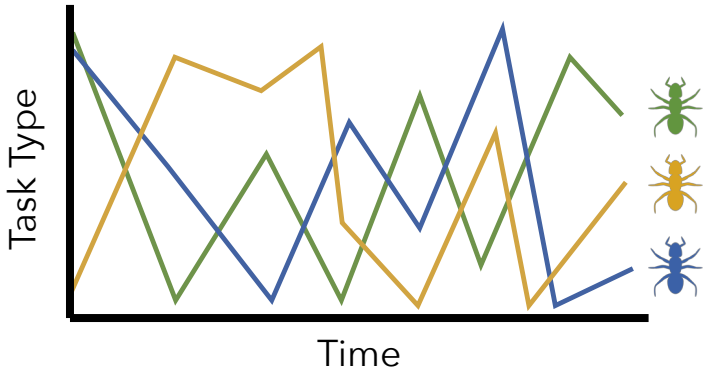
How do these properties interact?



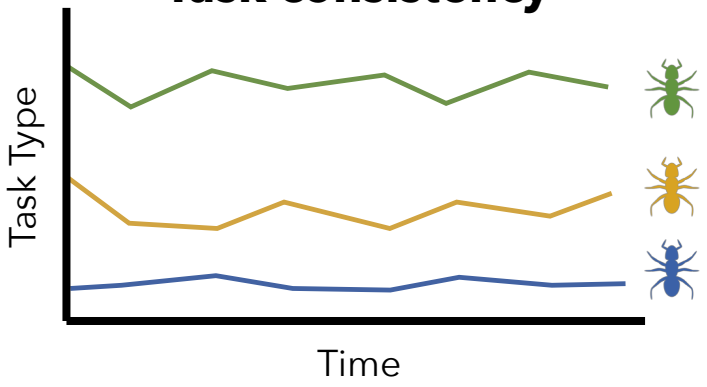
Through the lens of **division of labor (DOL)**

Behavioral diversity

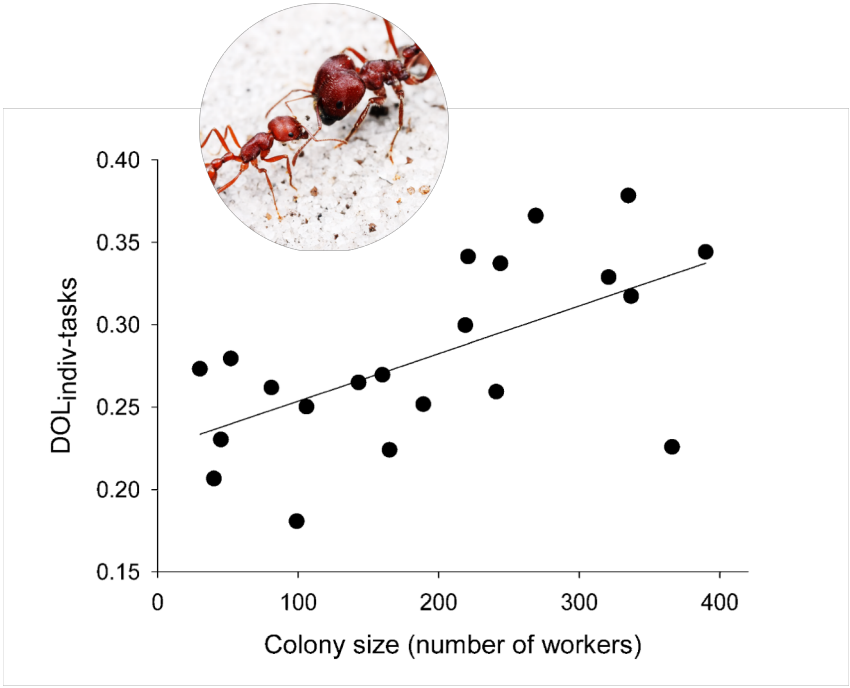
Task variation



Task variation &
Task consistency

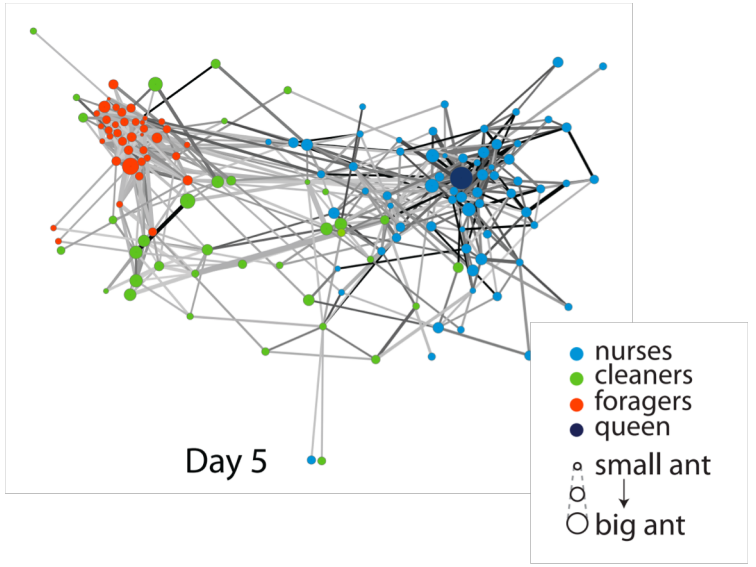


Affected by **group size**



Holbrook, Barden, & Fewell 2011 *Behav. Ecol. Sociobiol.*

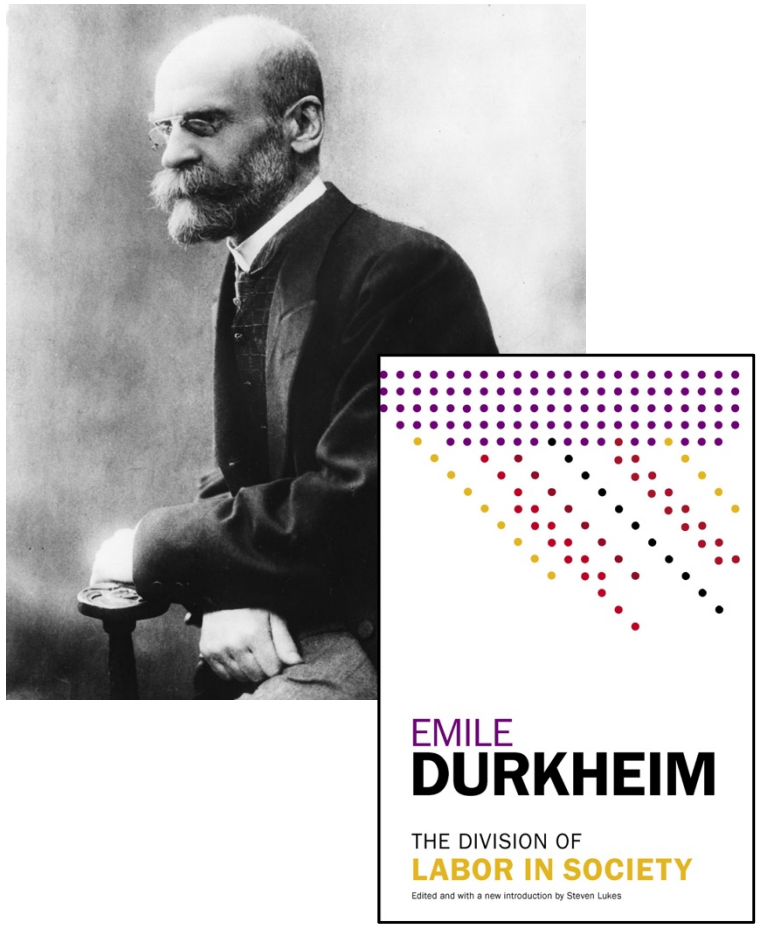
Intertwined with **pattern of interactions**



Adapted from Mersch, Krespi, & Keller 2013 *Science*

A tempting parallel?: An eye to the **social sciences**

The Division of Labor in Society (1893)



The evolution of society:

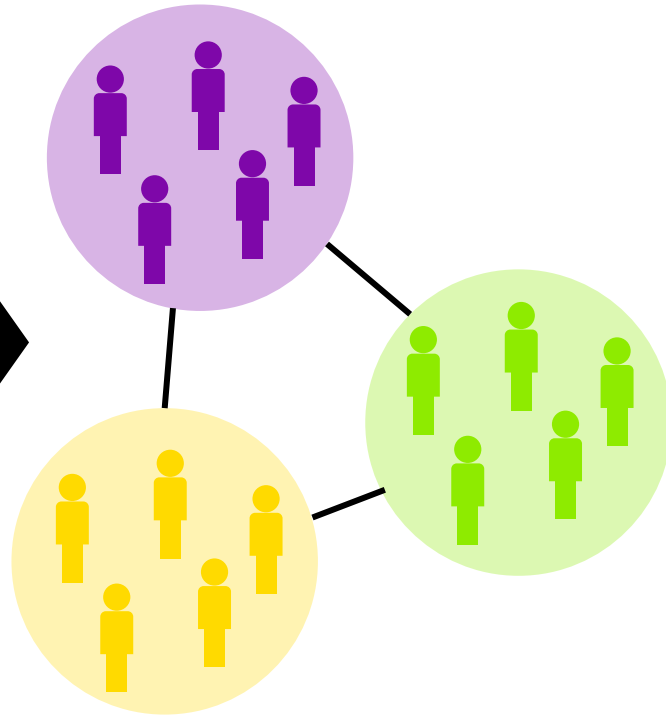
"A natural law"

Mechanical Solidarity

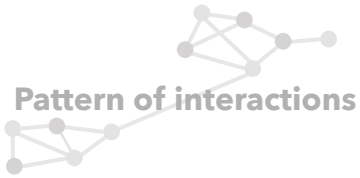
Homogenous
Generalists
Linked by similarity

Larger population
+
The density of interactions

Organic Solidarity



Heterogeneous
Division of labor
Linked by interdependence



Exploring self-organization of DOL at the onset of group living

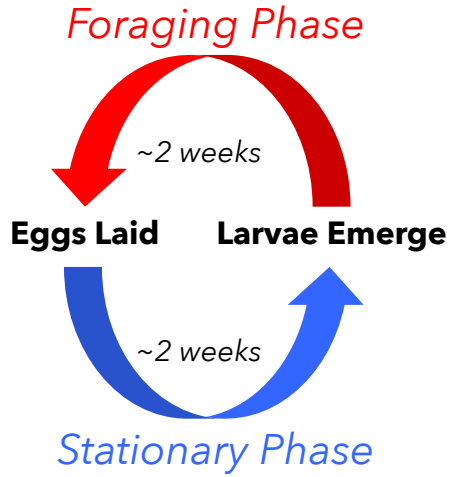
Ooceraea biroi,
the clonal raider ant

- No queen
- Clonal reproduction
- Synchronous, cyclical reproduction and behavior.

Ancestral-like state

Remove confounds

What are the benefits that emerge early in group-living?




Yuko Ulrich


Looks familiar

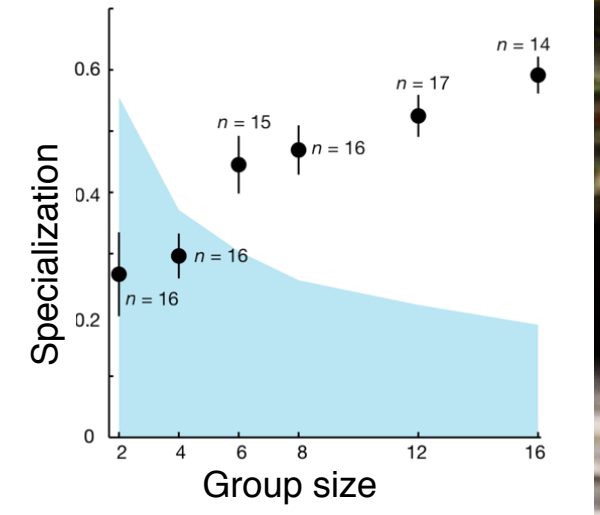

Jonathan Saragosti


Corina Tarnita

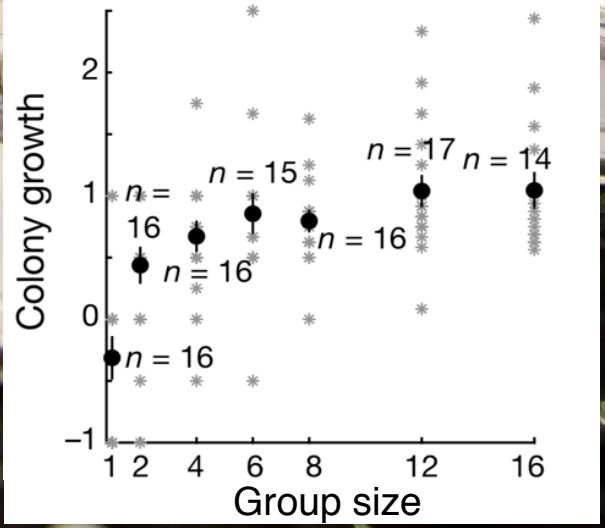

Daniel Kronauer

Camera-tracking experiments

DOL increases



Fitness increases

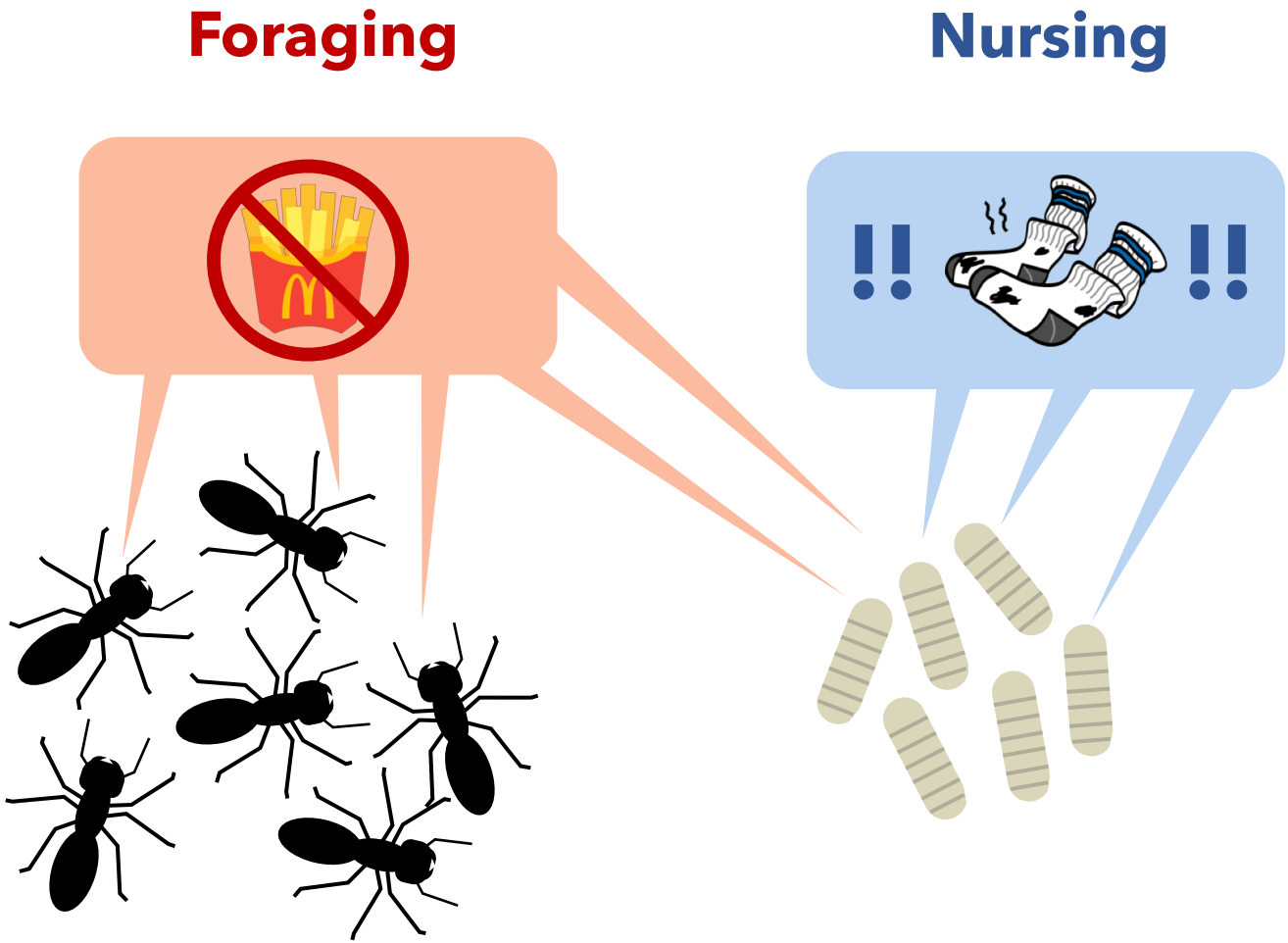


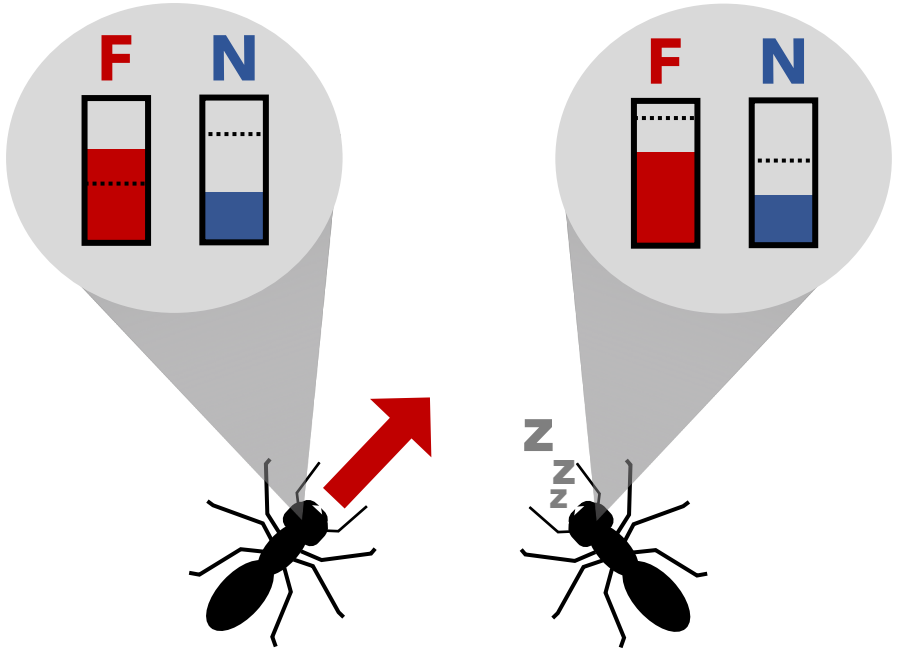
Ulrich, et al. 2018 *Nature*

Response thresholds: overview

1 Every **task/behavior *j*** has an associated stimulus

2 Every **individual *i*** has a threshold for *each* stimulus that determines behavior





Response thresholds: more detail

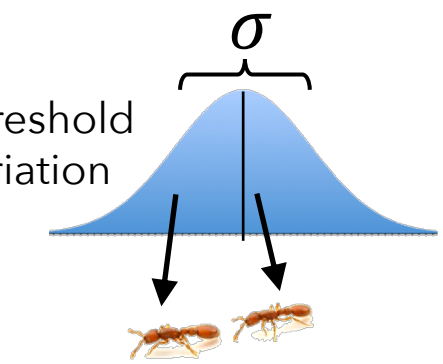
n individuals in the group, *m* tasks/behaviors

1. Every **task/behavior *j*** has an associated stimulus

$$s_{j,t+1} = \underbrace{s_{j,t}}_{\text{Previous stimulus level}} + \underbrace{\delta_j}_{\text{Demand rate}} - \underbrace{m\frac{\sum_i x_{ij,t}}{n}}_{\text{\% of colony doing task}}$$

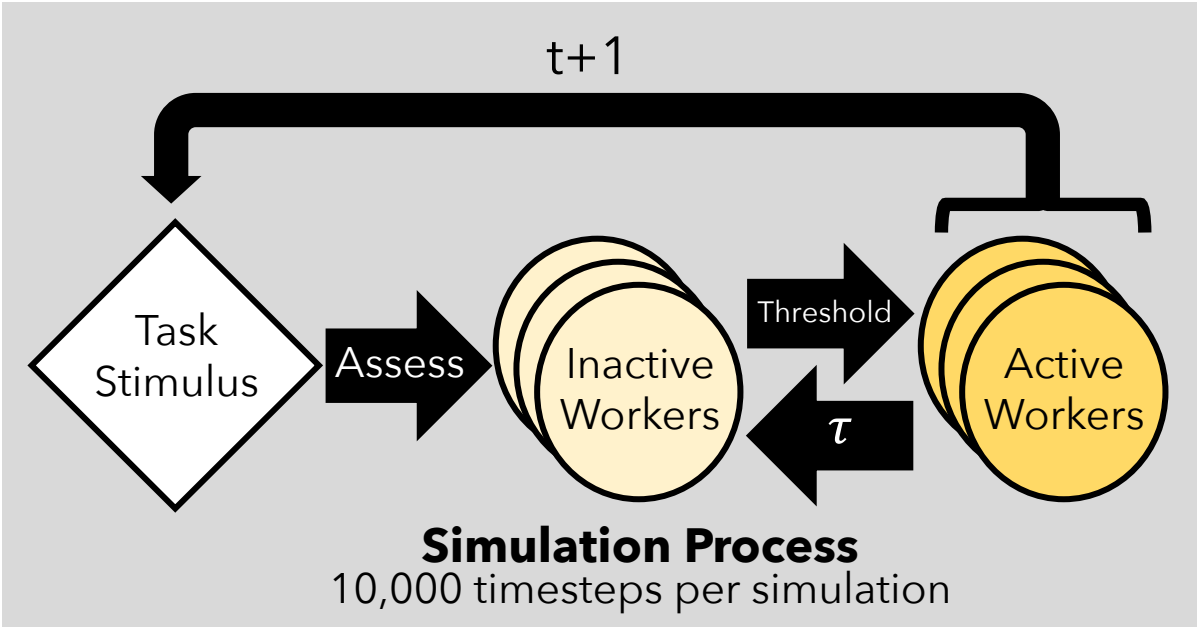
2. Every **individual *i*** has a **threshold** for *each* stimulus that determines behavior

$$\underbrace{x_{ij,t}}_{\text{Behavior state}} = \begin{cases} 1, & \underbrace{s_{j,t}}_{\text{Stimulus}} > \underbrace{\theta_{ij}}_{\text{Threshold}} \\ 0, & s_{j,t} \leq \theta_{ij} \end{cases}$$

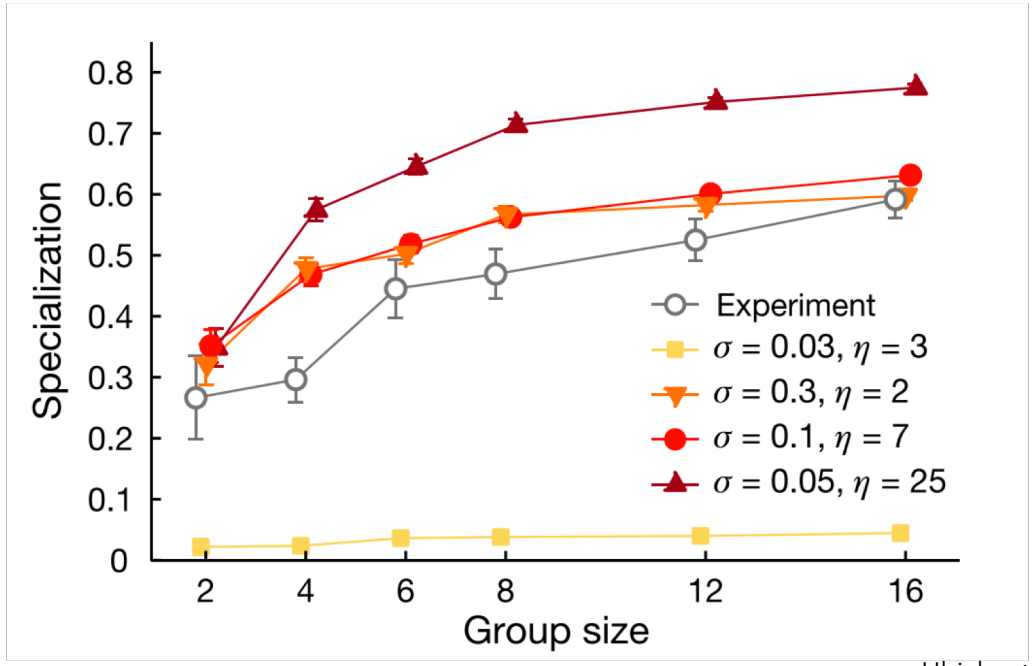


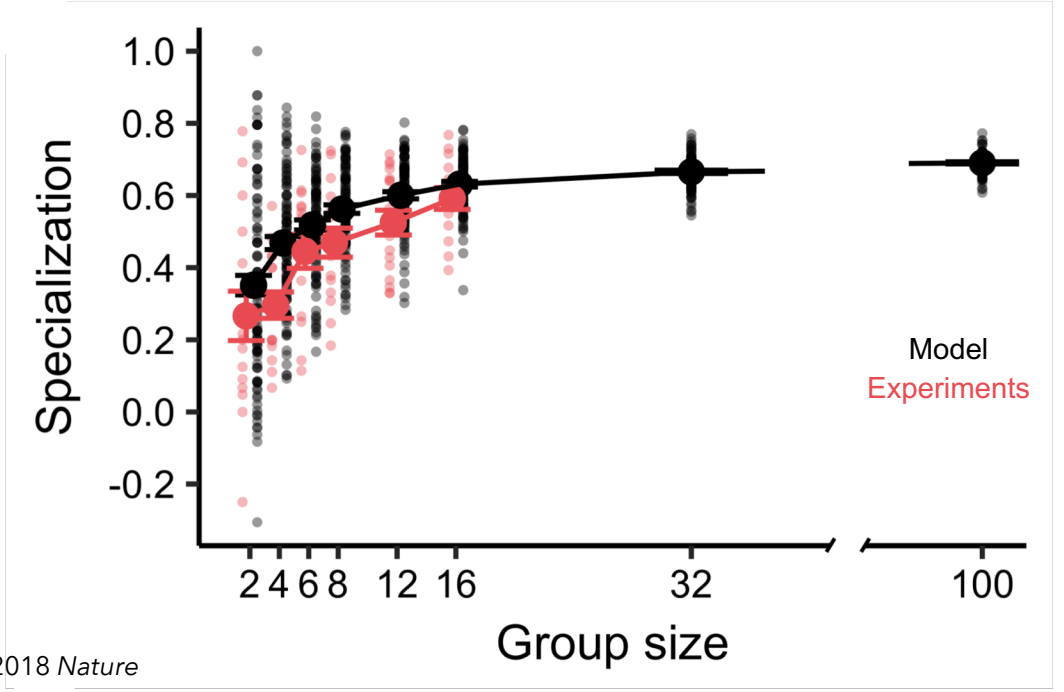
3. Only inactive workers assess stimuli and "decide" on new tasks

4. Active workers quit probabilistically: τ

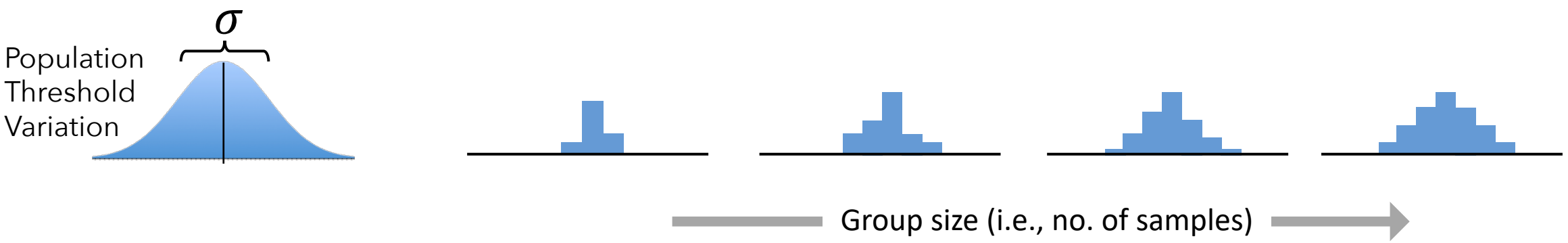


Fixed response thresholds: explaining emergent DOL at small group sizes

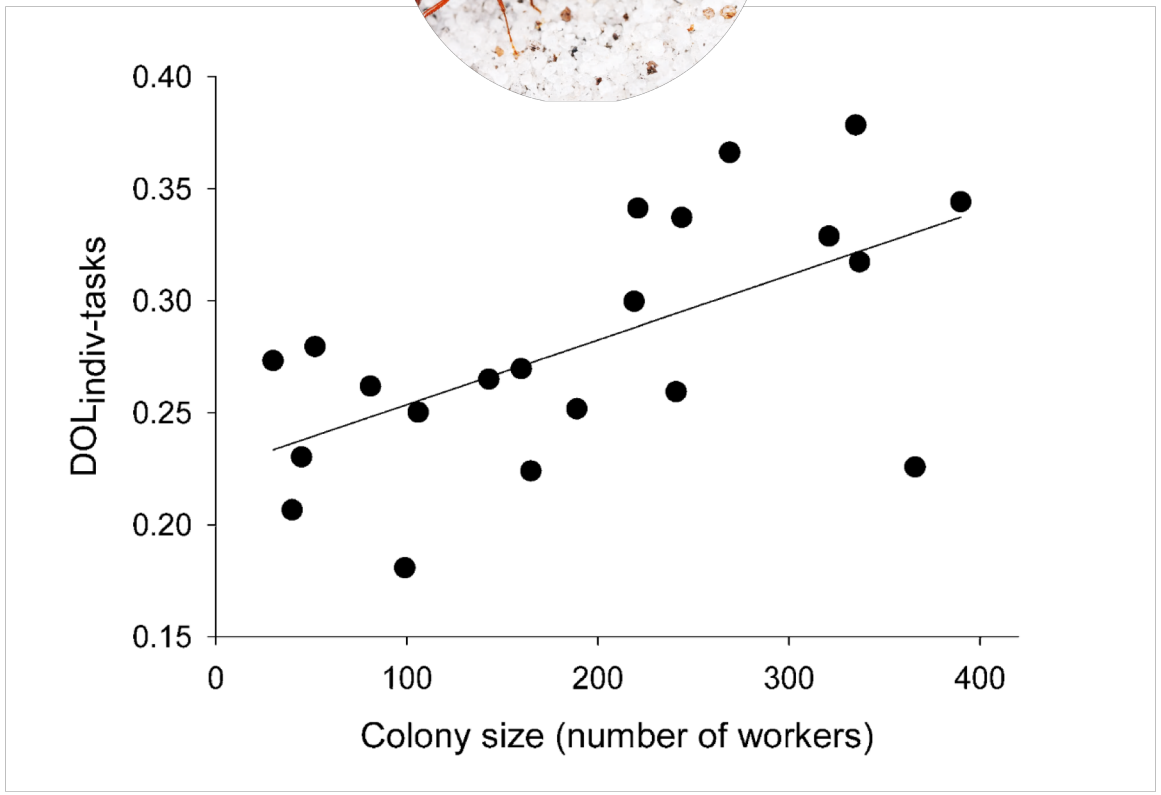




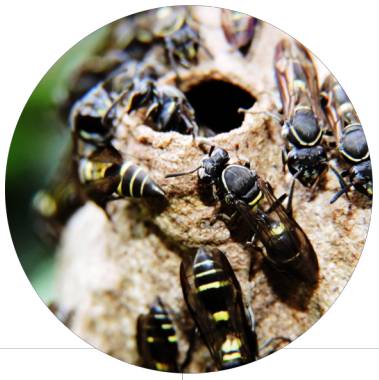
Ulrich, et al. 2018 *Nature*

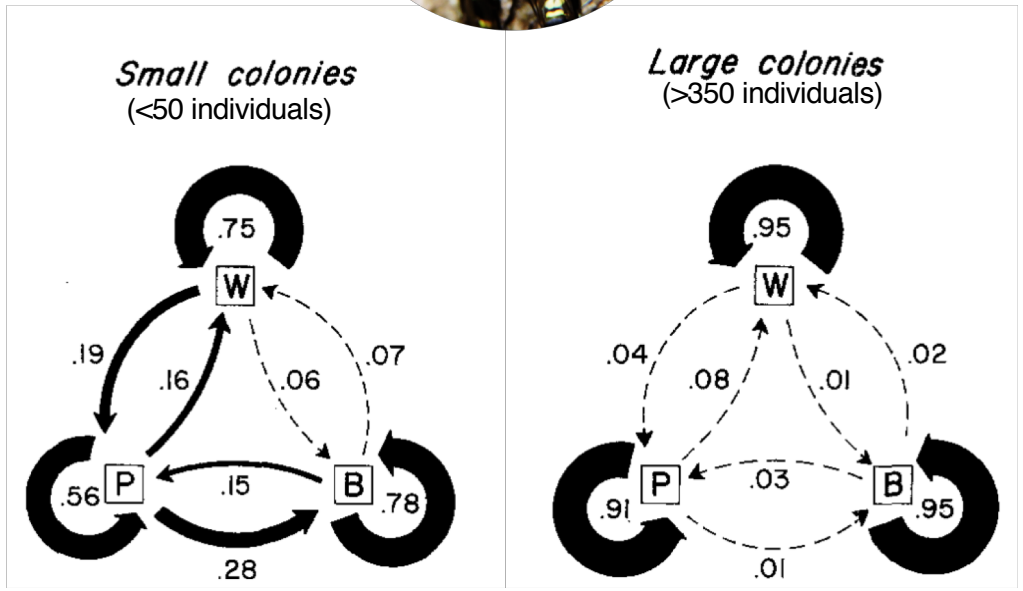


Yet, DOL & behavioral diversity **increase** beyond small group sizes



Holbrook, Barden, & Fewell 2011 *Behav. Ecol. Sociobiol.*





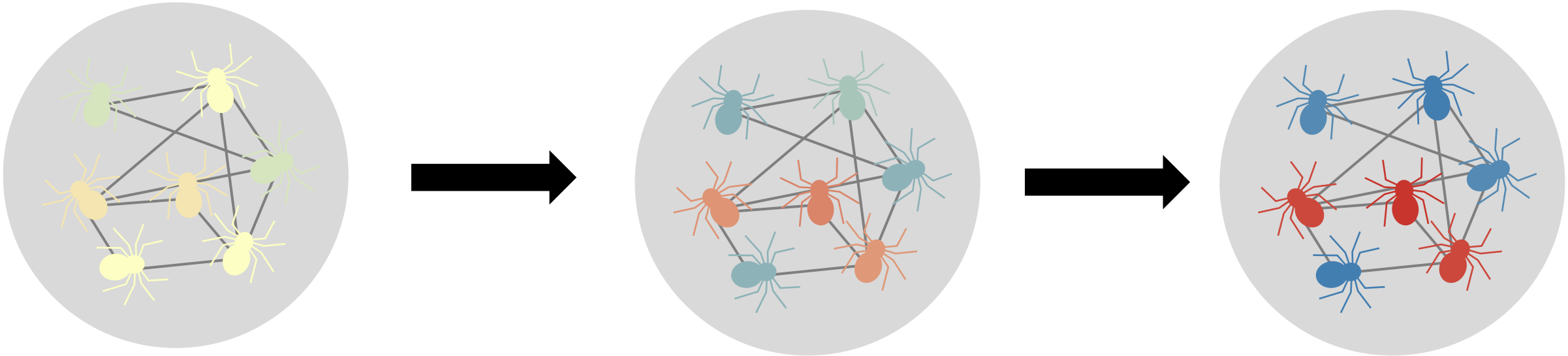
Jeanne 1986 *Behav. Ecol. Sociobiol.*

What about **social interactions**?: evidence for influence on behavioral diversity

Stegodyphus dumicola
Modlmeier *et al.* 2014 *Biol Lett*

Stegodyphus mimosarum
Laskowski & Pruitt 2014 *Proc R Soc B*

Shy Bold

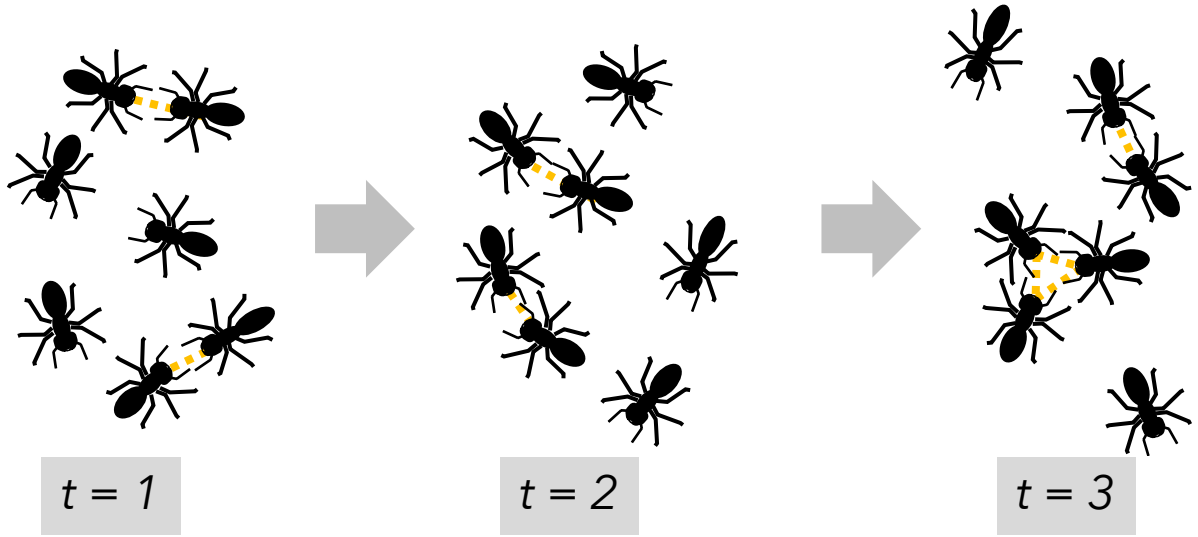


Week 1 Week 3 Week 5

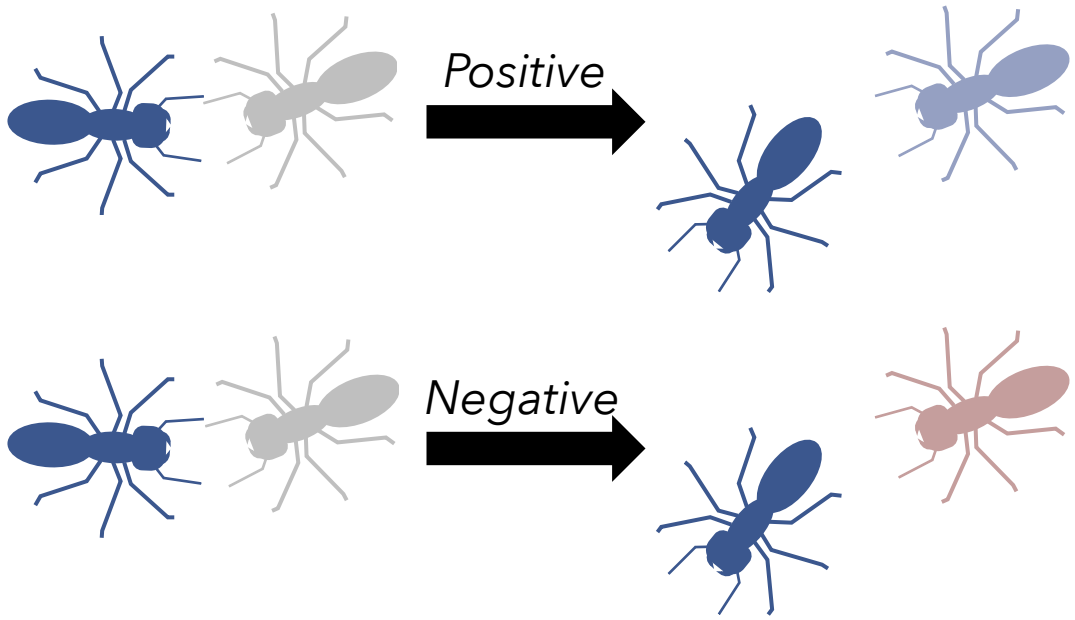
Group size Diversity Pattern of interactions

Adding social interactions to response threshold model

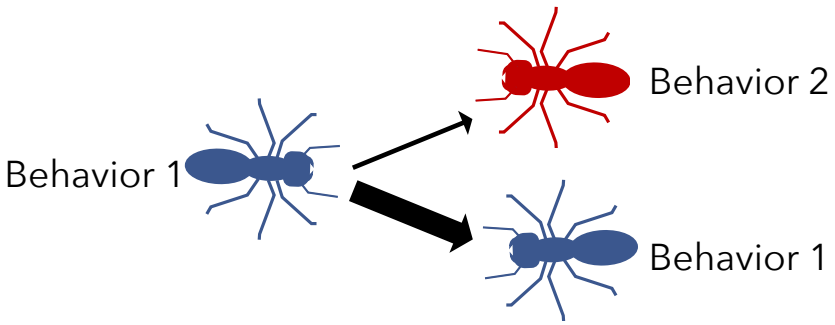
Model **interactions dynamically**



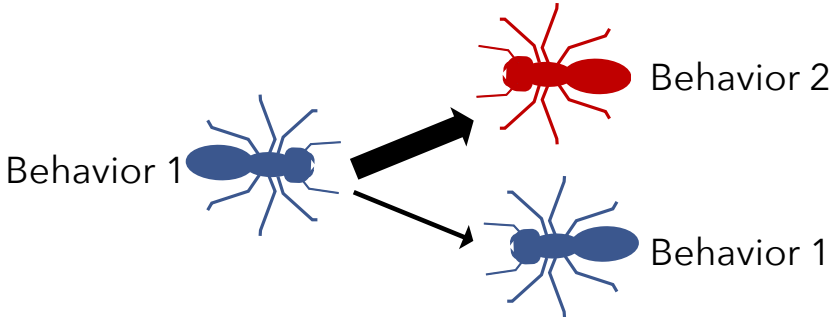
Allow **social influence**



Allow **interaction bias**



Homophily

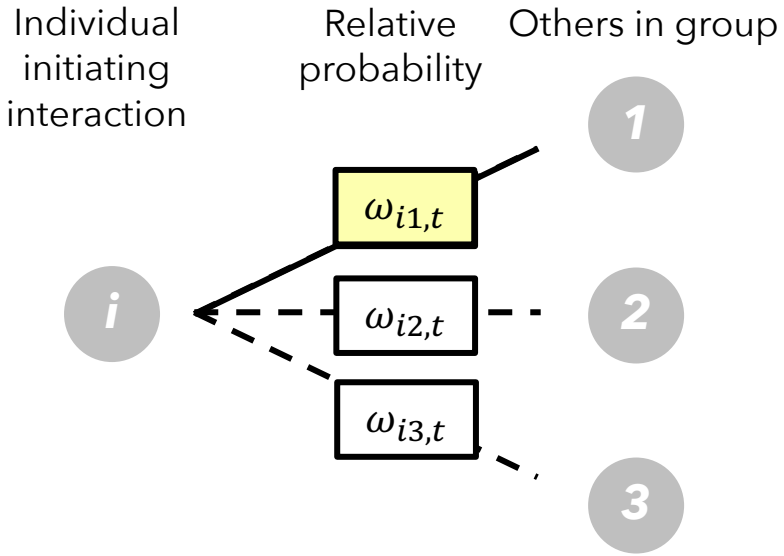


Heterophily

Model description: Dynamic interactions

1. Every individual initiates an (*undirected*) interaction with **exactly one** other individual every time step *t*

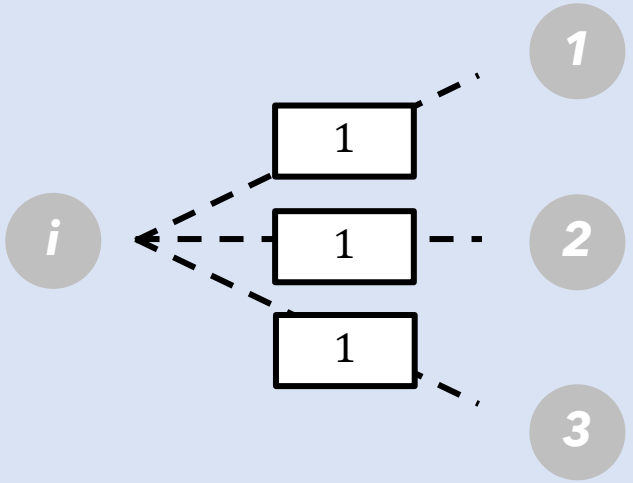
Weighted random sample
(Efraimidis & Spirakis 2006)



Probability individual *k* is interacted with by individual *i:*

$$\Omega_{ik,t} = \frac{\omega_{ik,t}}{\sum_{k=1}^{n-1} \omega_{ik,t}}$$

Example: A well-mixed population

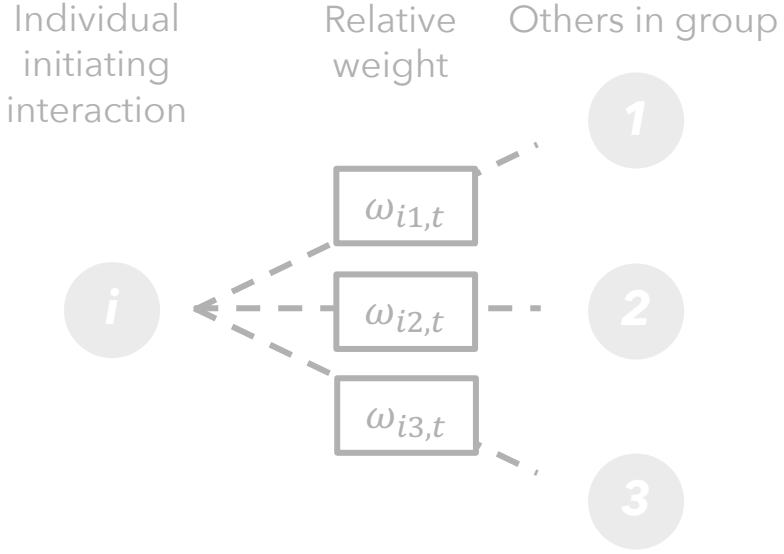


$$\Omega_{ik,t} = \frac{1}{n-1}$$

Model description: Interaction mechanics

1. Every individual initiates an interaction with exactly one other individual every time step *t*

Weighted random sample
(Efraimidis & Spirakis 2006)

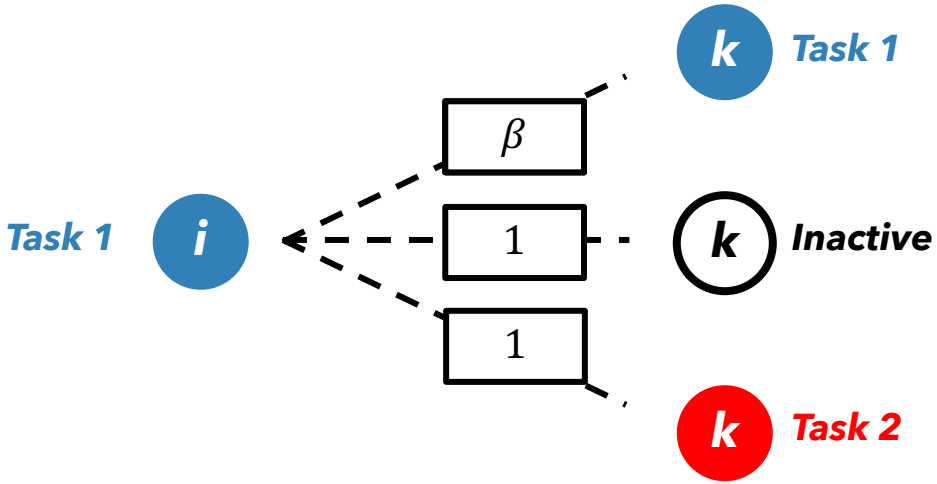


Probability individual *k* is interacted with by individual *i:*

$$\Omega_{ik,t} = \frac{\omega_{ik,t}}{\sum \omega_{ik,t}}$$

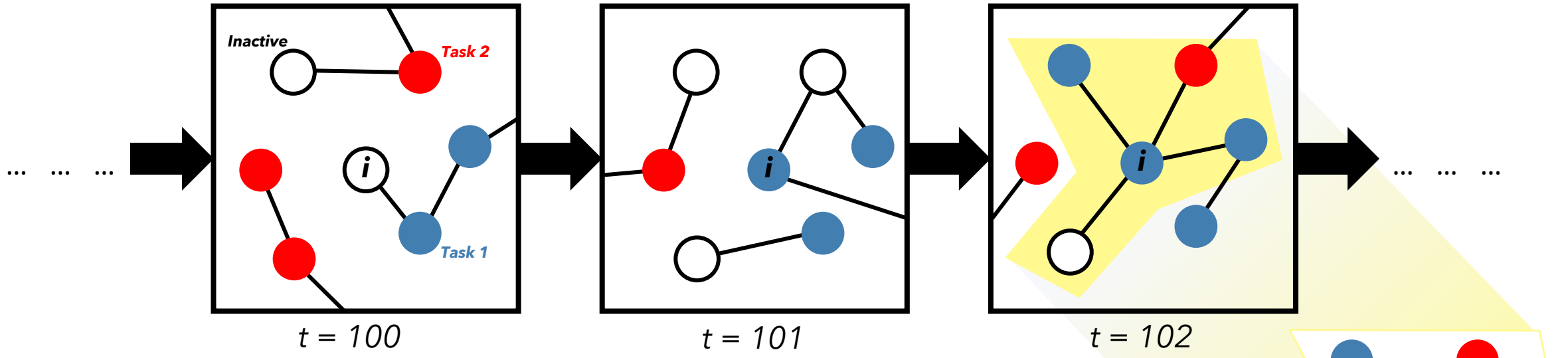
2. Accounting for non-well-mixed conditions: ***homophily*** or ***heterophily***

Same task:	$\omega_{ik,t} = \boldsymbol{\beta}$
Otherwise:	$\omega_{ik,t} = 1$



$\boldsymbol{\beta > 1}$**:**	Bias towards same behavioral type
$\beta = 1$:	No bias (well-mixed)
$0 < \beta < 1$:	Bias towards *other* behavioral types

Model description: Interactions & socially-modulated thresholds



$\varepsilon > 0$ **: positive social influence**

$\varepsilon < 0$: negative social influence

$$\theta_{ij,t+1} = \theta_{ij,t} + \varepsilon\left(\sum_{k\in N(i),l\neq j} x_{kl,t} - \sum_{k\in N(i)} x_{kj,t}\right)$$

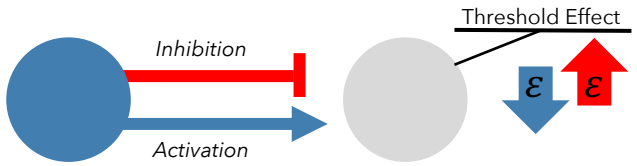
Current threshold

Social influence effect

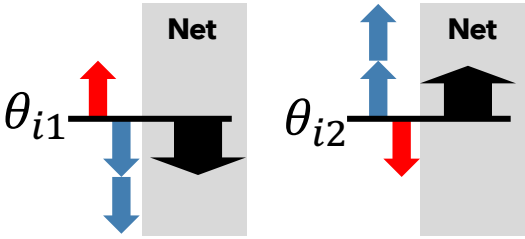
neighbors performing *other* tasks

neighbors performing task *j*

Active individuals change thresholds of other individuals

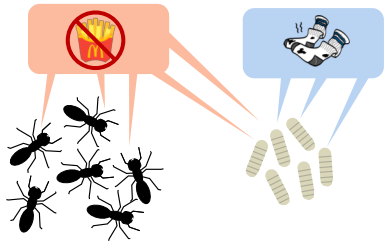


Positive social influence: make others *more likely* to perform *same* behavior in future

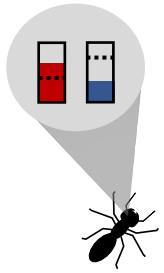


Model summary

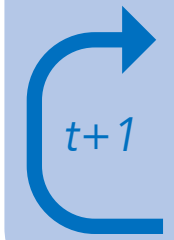
1 $$s_{j,t+1} = s_{j,t} + \delta_j - m\frac{\sum_i x_{ij,t}}{n}$$



2 $$x_{ij,t} = \begin{cases} 1, & s_{j,t} > \theta_{ij} \\ 0, & s_{j,t} \leq \theta_{ij} \end{cases}$$

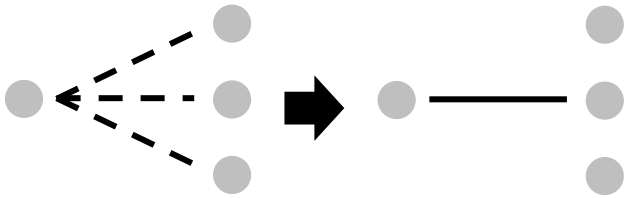


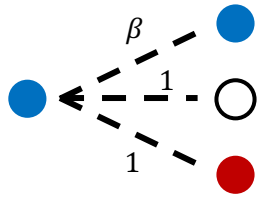
Simulation process



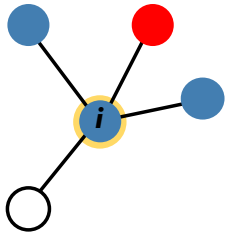
1. Update stimulus
2. Update behavior
3. Form interactions
4. Update thresholds

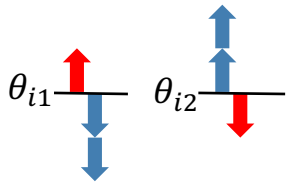
3 Each individual initiates interaction according to weighted random sample.
$\omega_{ik,t} = \beta$ if same task; $\omega_{ik,t} = 1$ otherwise





4 $$\theta_{ij,t+1} = \theta_{ij,t} + \varepsilon\left(\sum_{k\in N(i),l\neq j} x_{kl,t} - \sum_{k\in N(i)} x_{kj,t}\right)$$





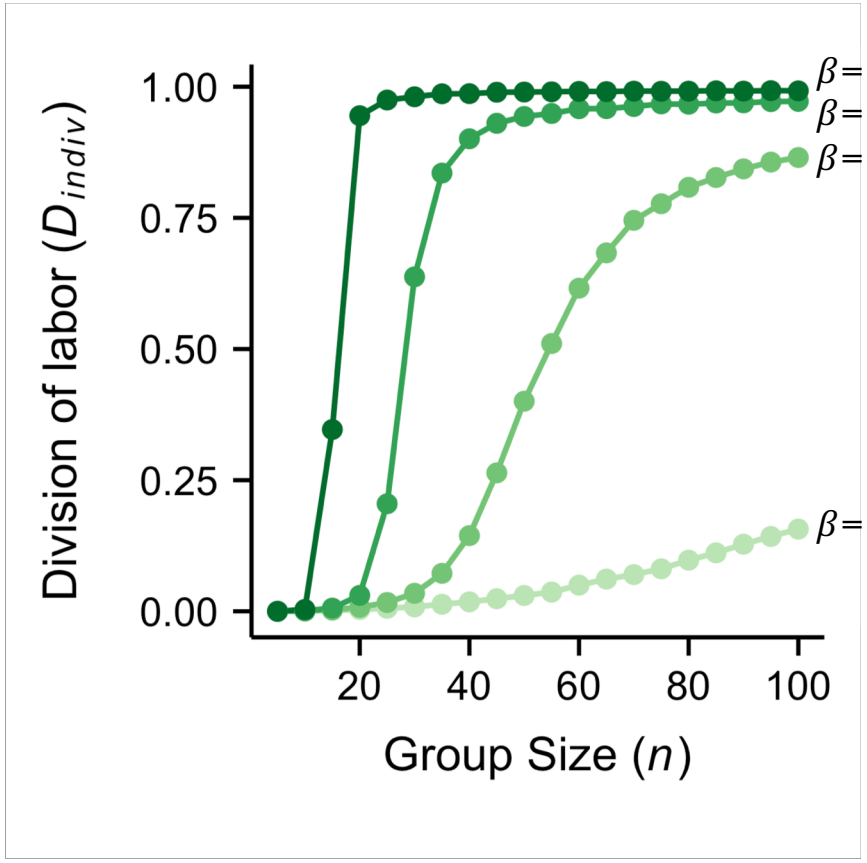
Parameter	Description	Value
n	Number of individuals.	5, 10, 15, 20, … 100
m	Number of tasks.	2
μ_j	Population mean for thresholds (θ_{ij}) for task j	50 , $\theta_{ij} \in [0, 100]$
σ_j	Population relative standard deviation for thresholds for task j	0 (social), 0.05 (fixed)
δ_j	Rate of stimulus increase for task j	0.8
τ	Probability of quitting task once active	0.2
$\boldsymbol{\varepsilon}$	**Social interaction effect**	**0.1 (social), 0 (fixed)**
$\boldsymbol{\beta}$	**Bias of interactions**	**1.1 (homophily)**

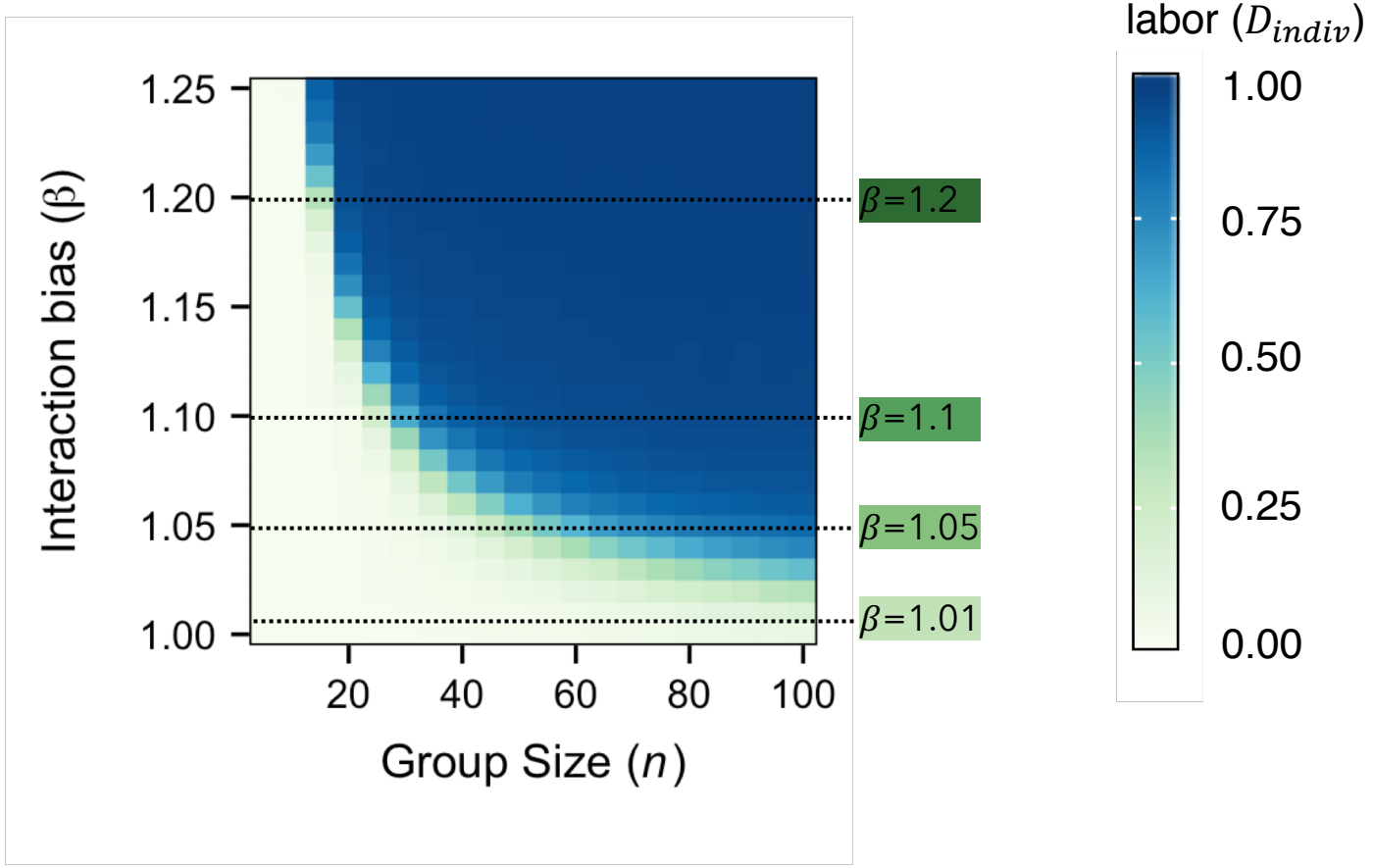
* 100 replicates per parameter combination (per group size)
* Simulations run for 50,000 time steps

Results

Increasing homophily results in prominent and more rapid emergence of DOL with increasing group size

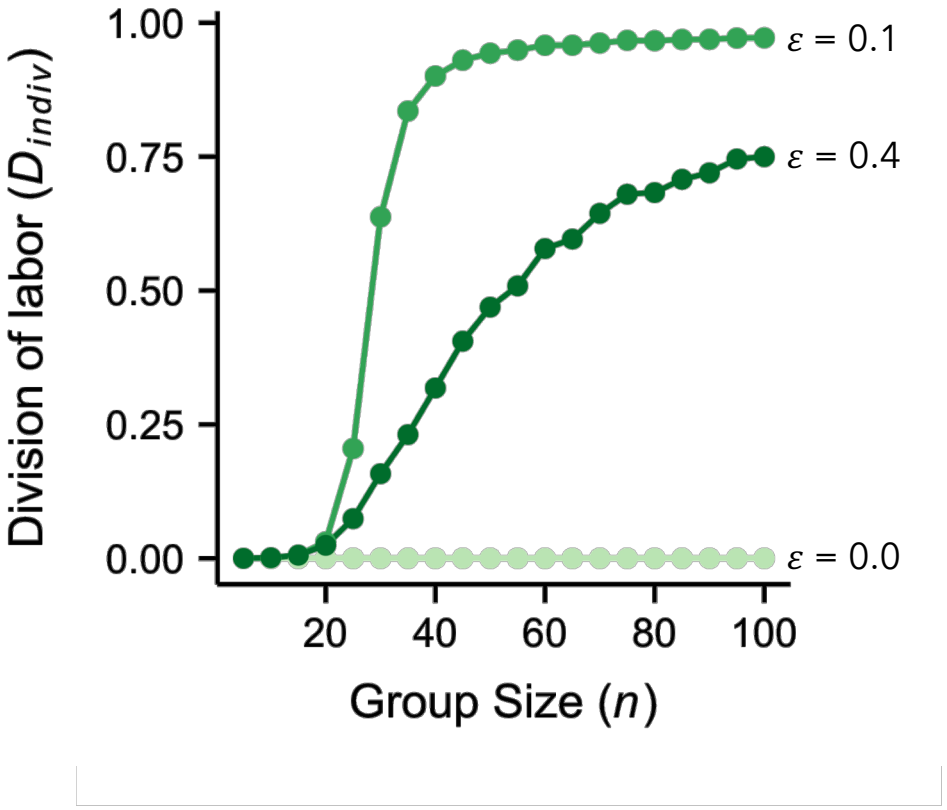
$\varepsilon = 0.1$, β varied

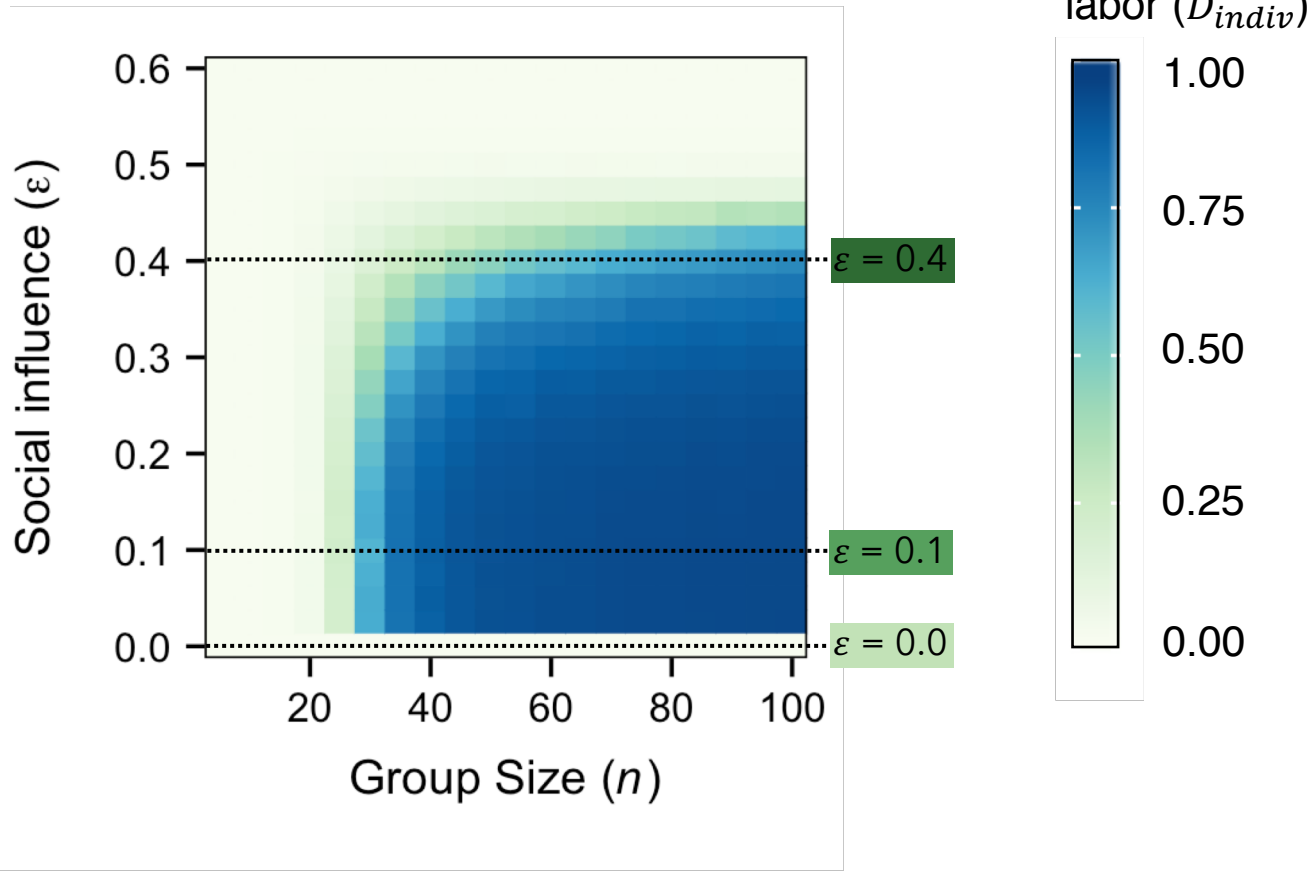




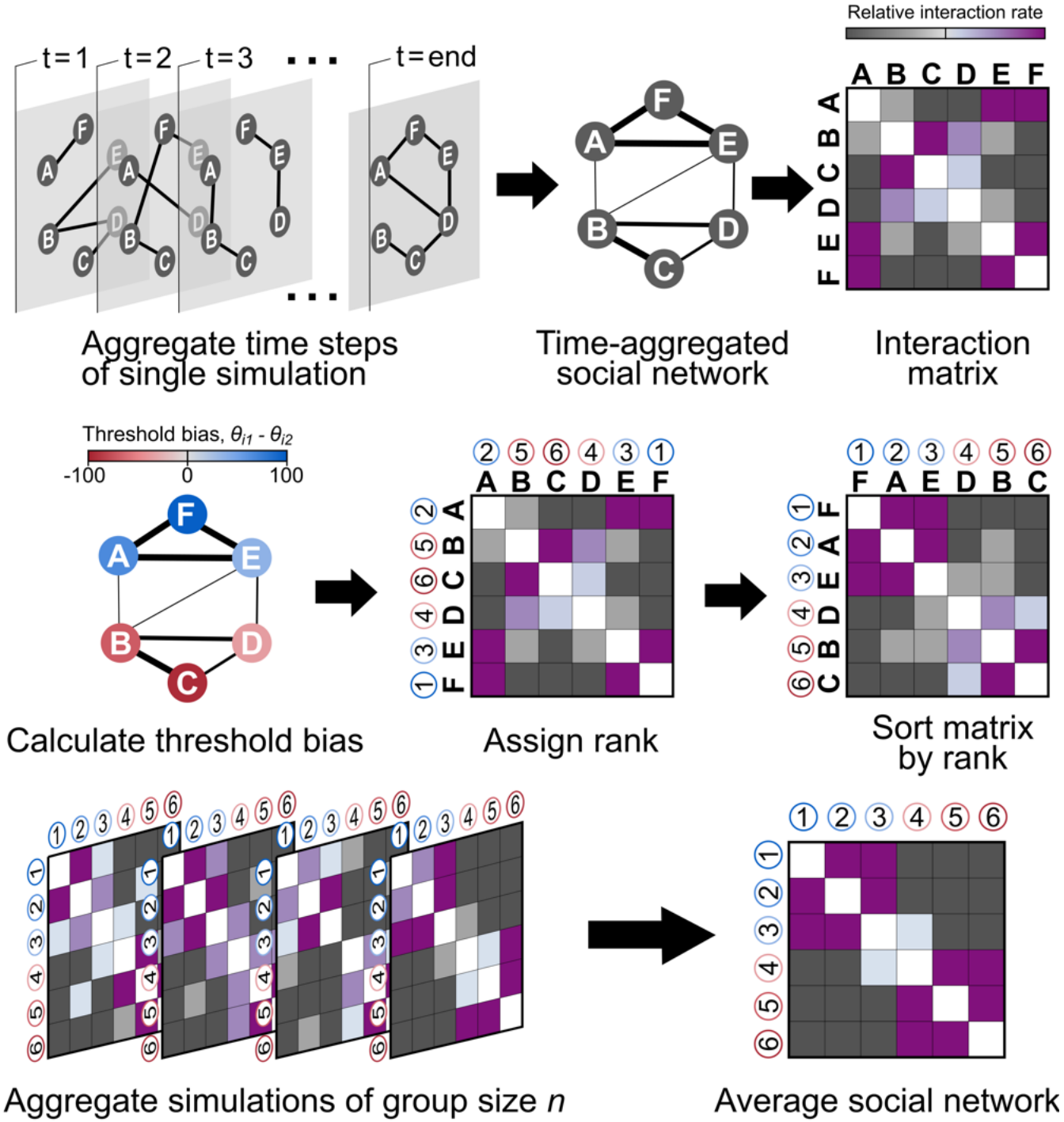
Positive social influence parameter generally results in same pattern of emergent DOL, but high social influence decreases DOL

ε varied, β = 1.1



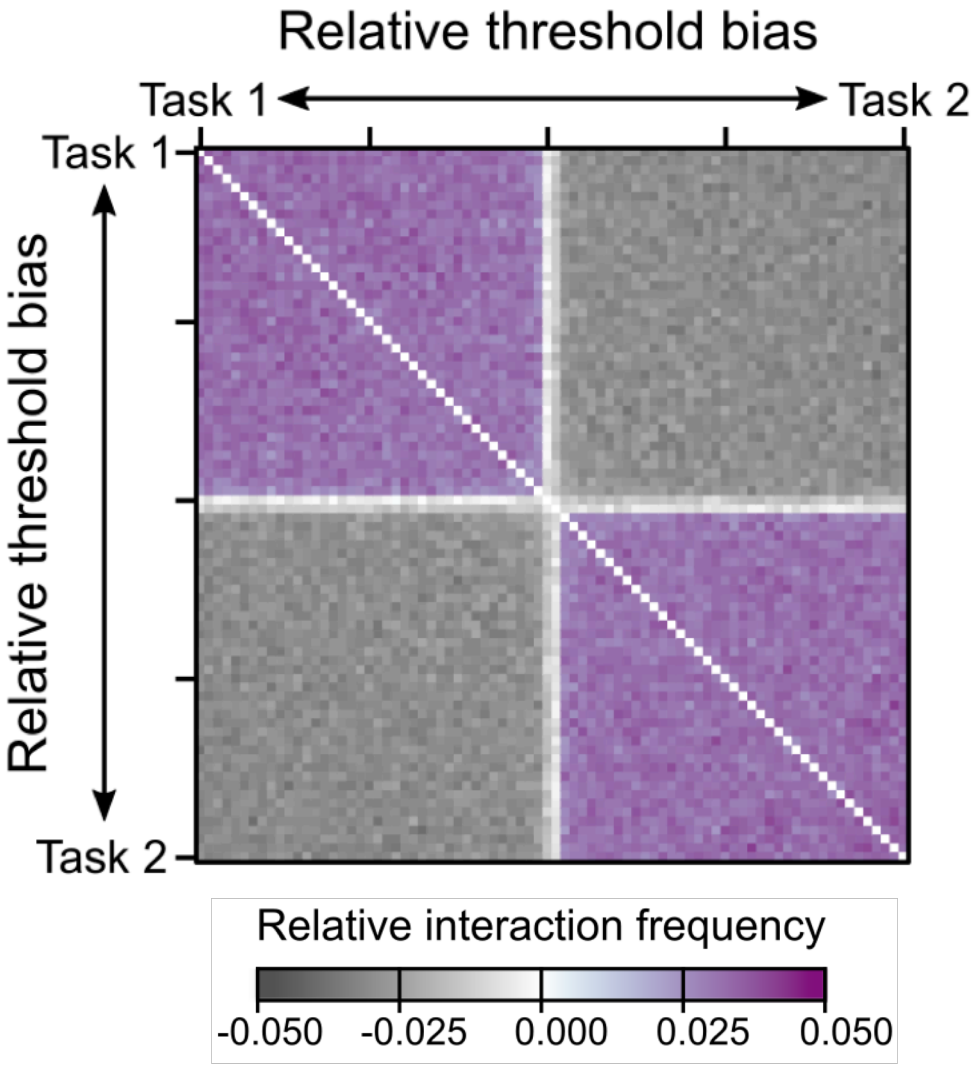


Analyzing social networks

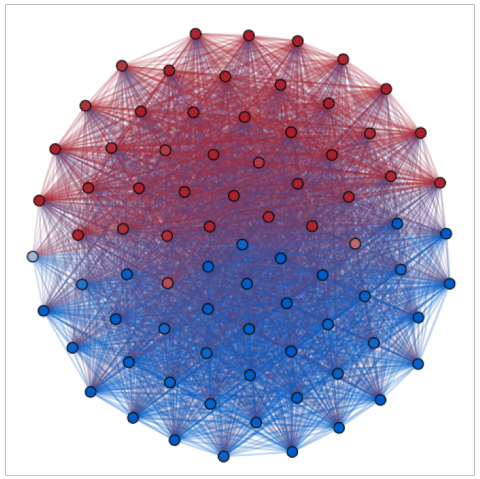


Analyzing social network structure: **group size 80**

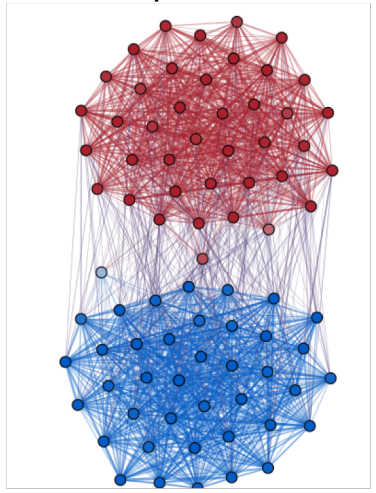
$\varepsilon = 0.1, \beta = 1.1$



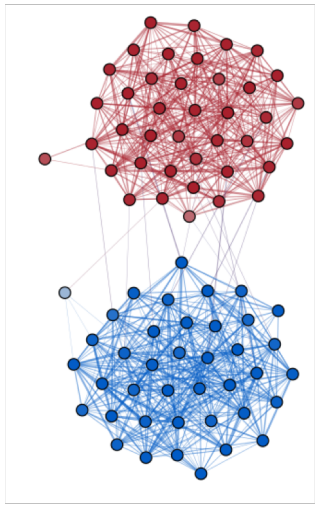
All interactions

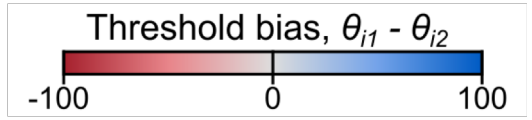


Interactions >50th percentile



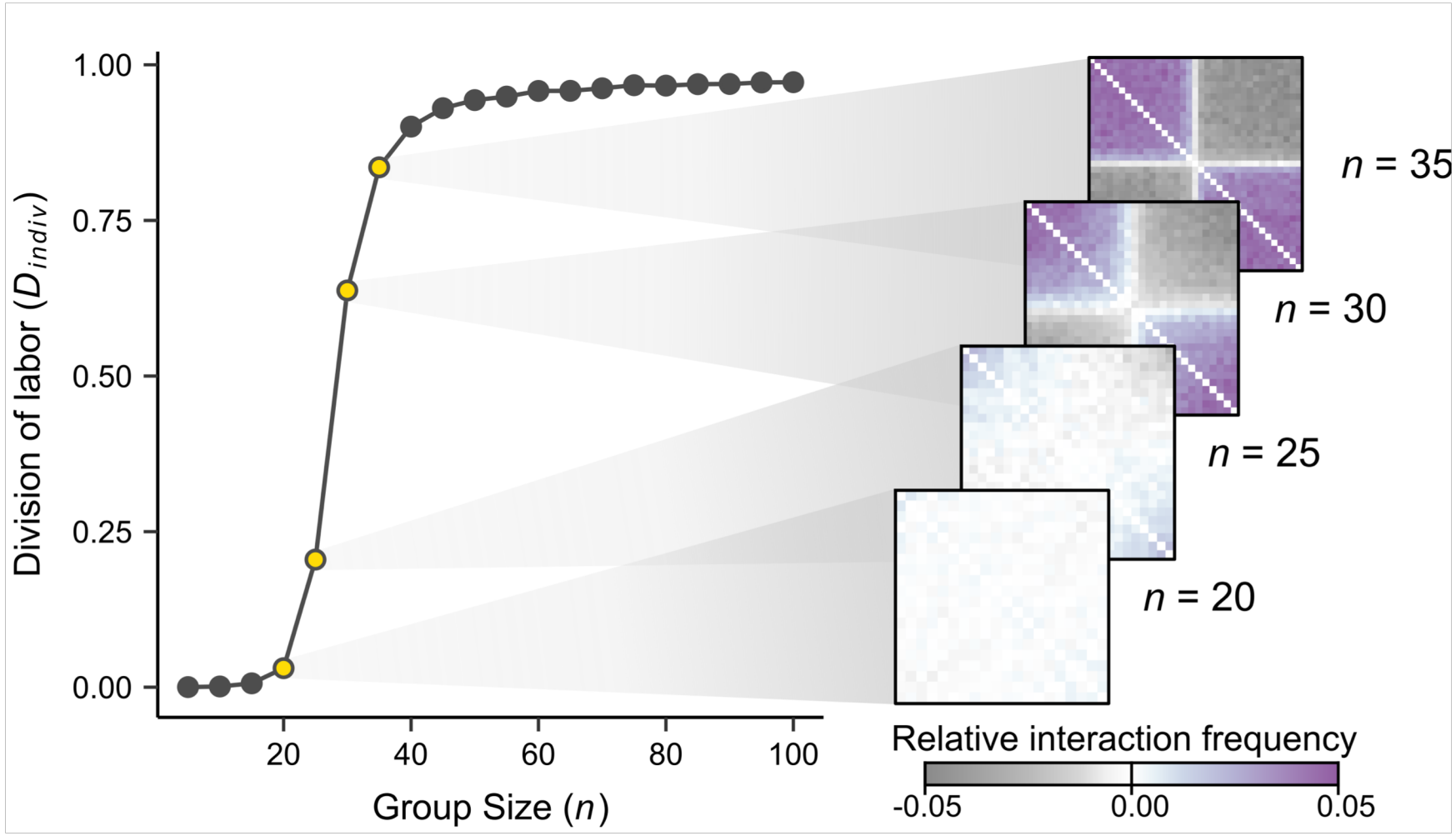
Interactions >25th percentile



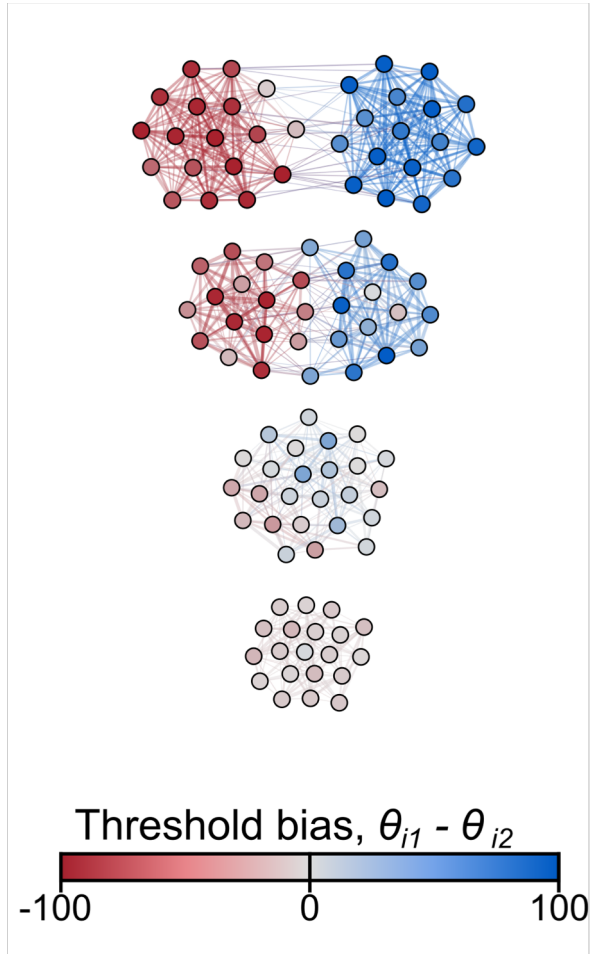


Co-emergence of DOL and polarized social networks

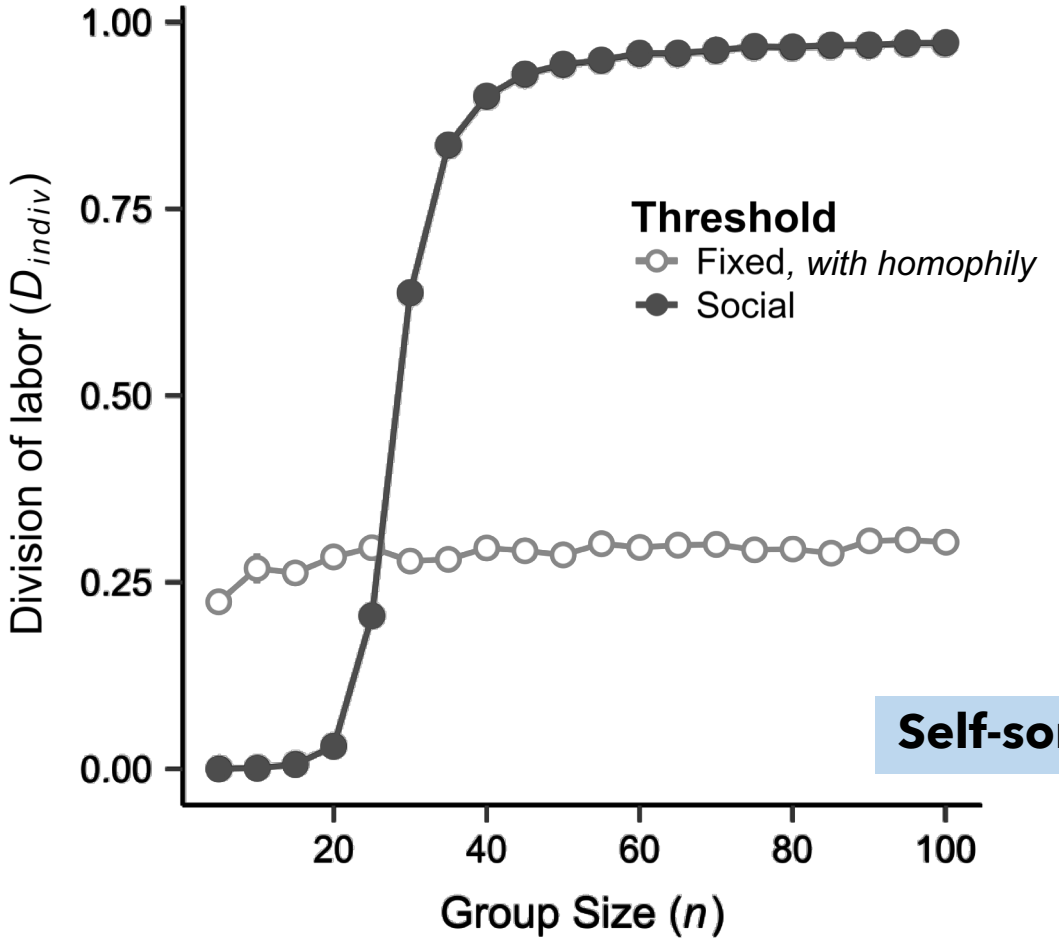
$\varepsilon = 0.1, \beta = 1.1$



Example social networks at each group size

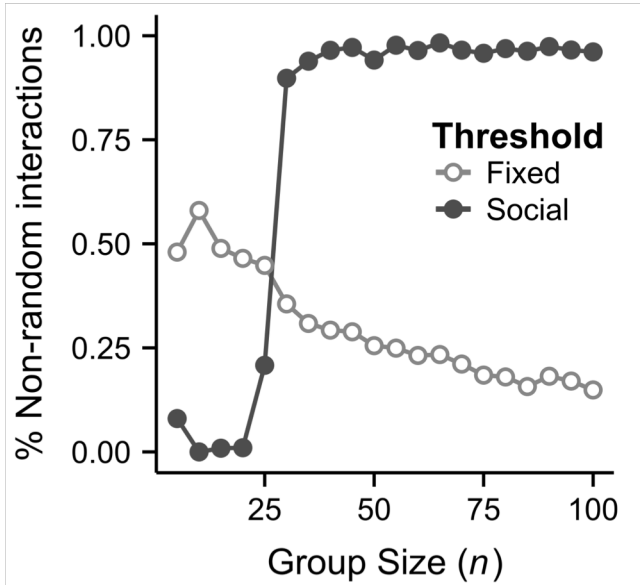


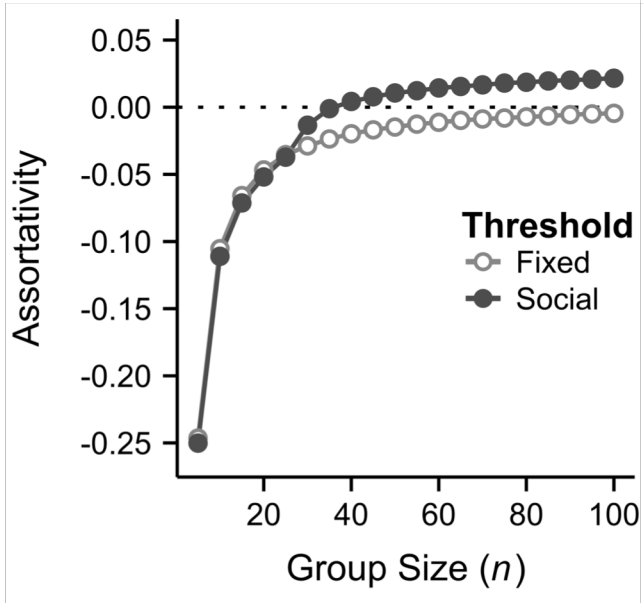
Co-emergence of DOL and polarized social networks: **network metrics**

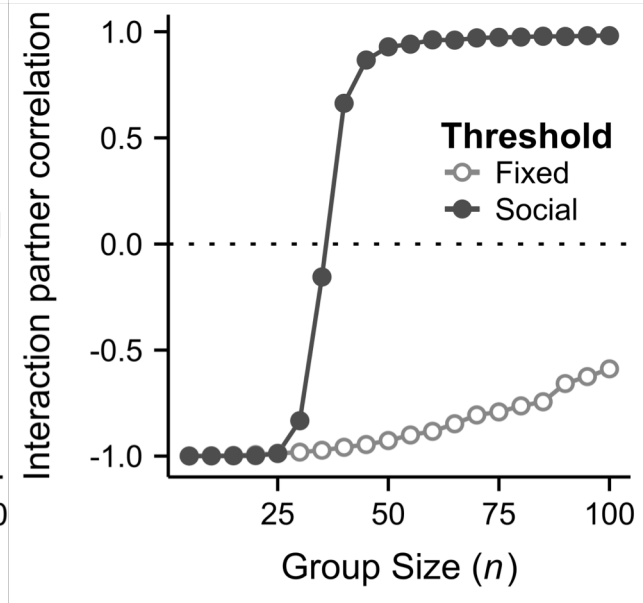


Self-sorting

Clusters







Parallels in social systems generally? The importance of **social interactions** on divergent behavior and structure.

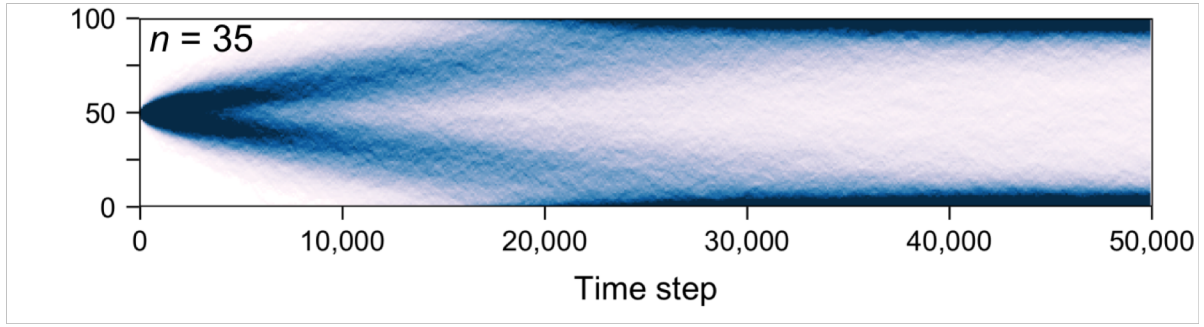
Divergent internal traits

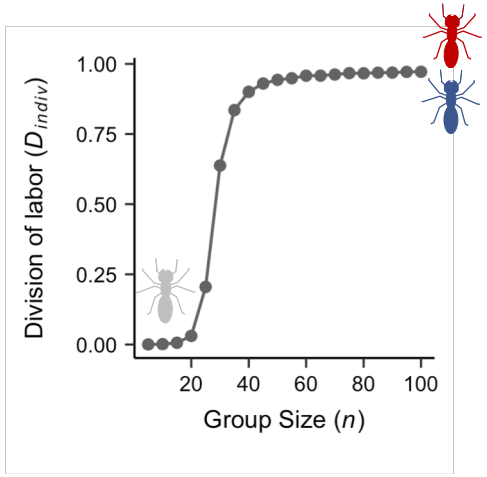
Divergent behavior

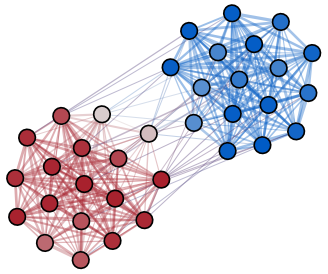
Divergent social networks

Division of labor

Threshold values over time

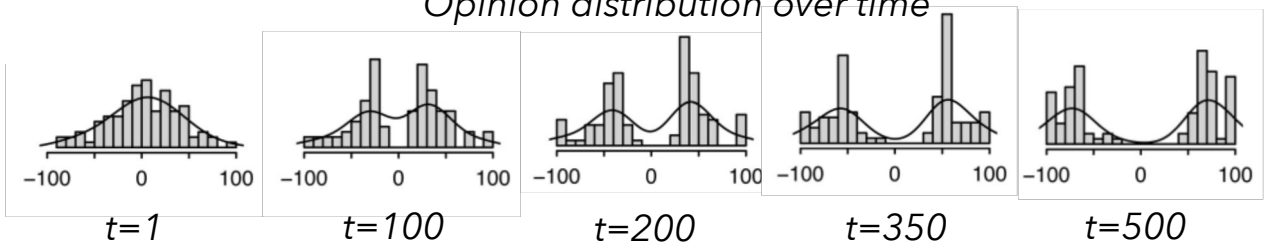






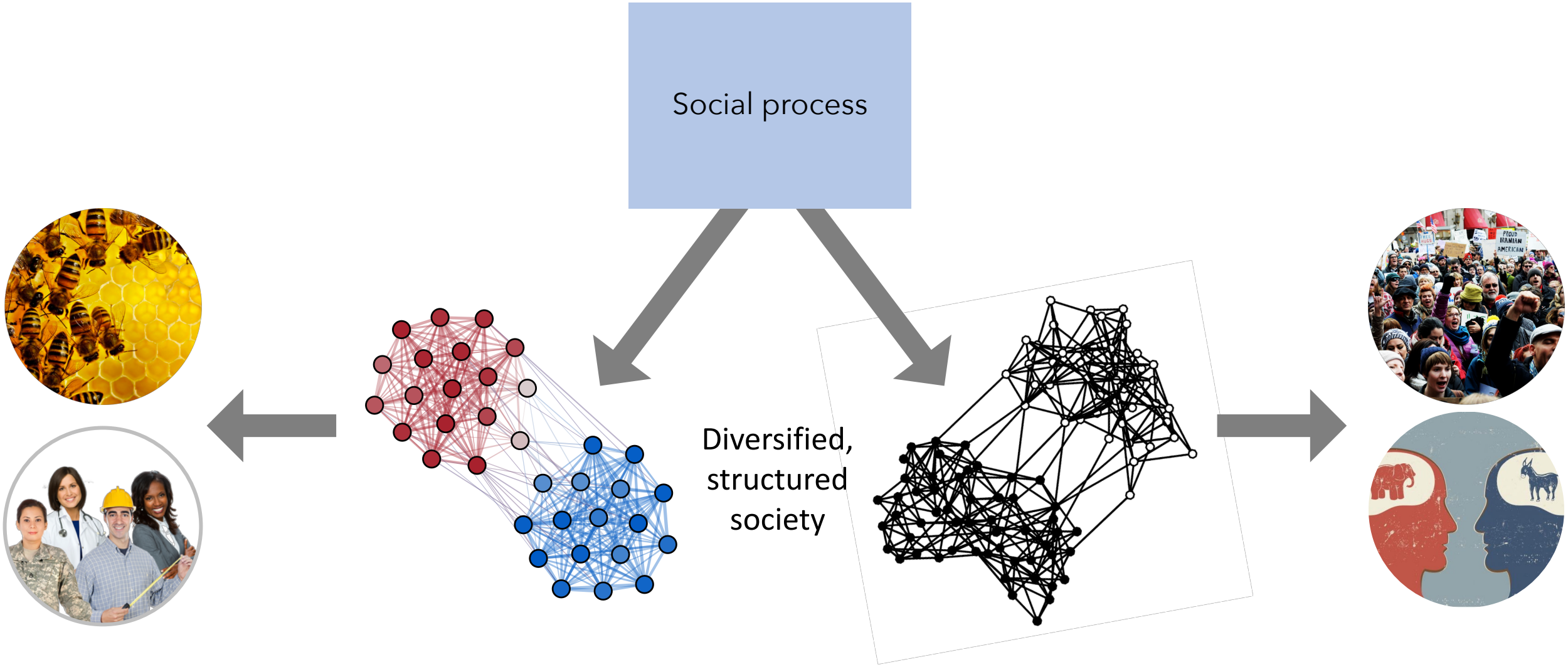
Political polarization

Opinion distribution over time



Baldassarri & Bearman 2007 *Am. Sociol. Rev.*

Parallels in social systems generally? The importance of **social interactions** on divergent behavior and structure.



Thank you!

Department of Ecology & Evolutionary Biology

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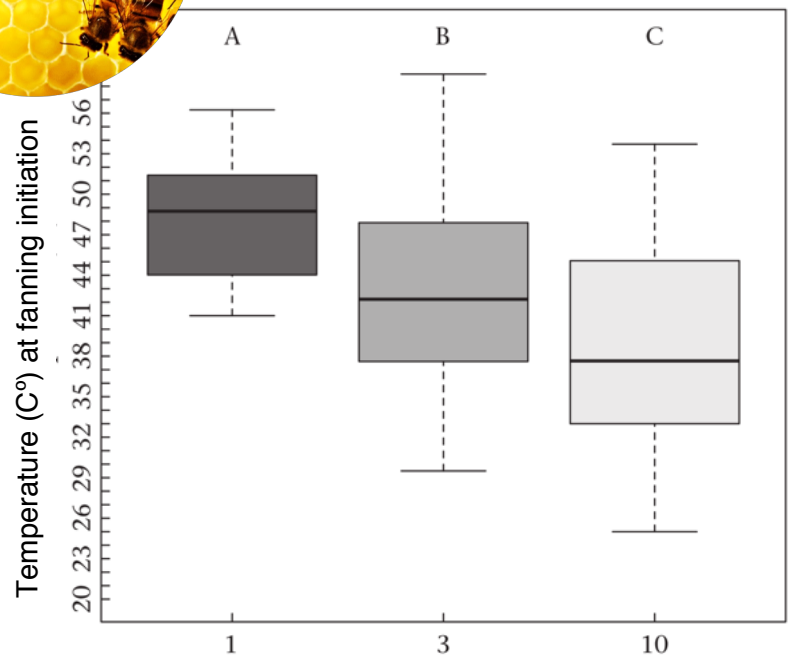
Jonathan Saragosti

Workshop Organizers & Help
Eitan Tadmor
Javier Morales
Anil Zenginoglu

Backup slides

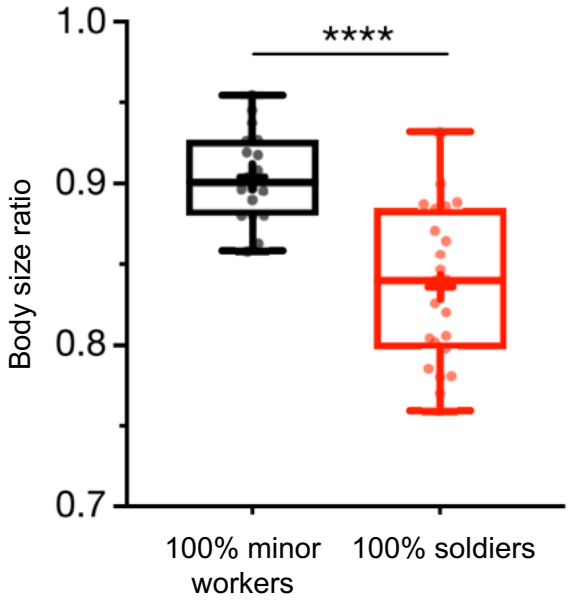
What about **social interactions**?: evidence for influence on individual traits

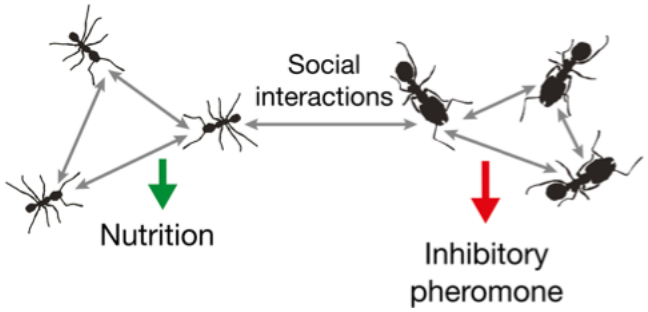
Response thresholds
in honey bees



Cook & Breed 2013 *Animal Behav*

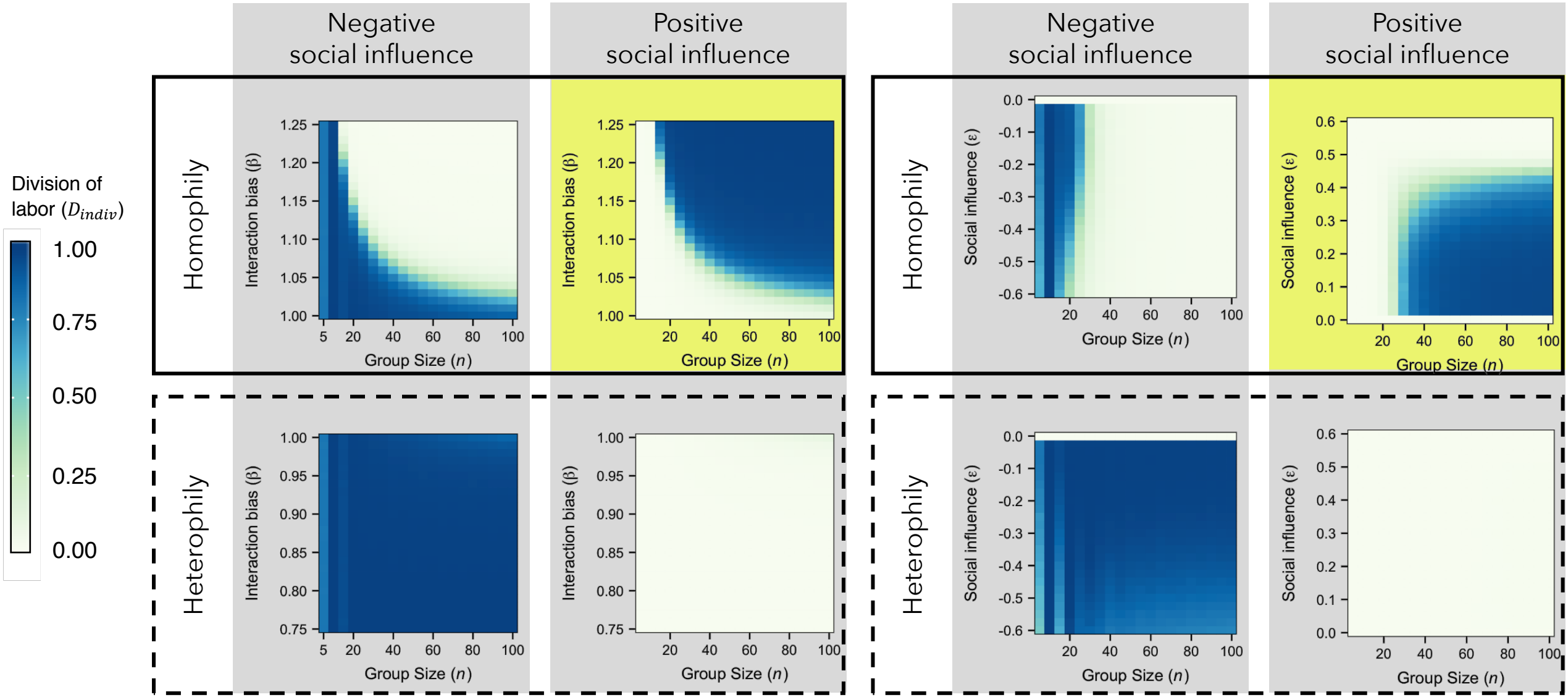
Body size/Caste
in *Pheidole* ants



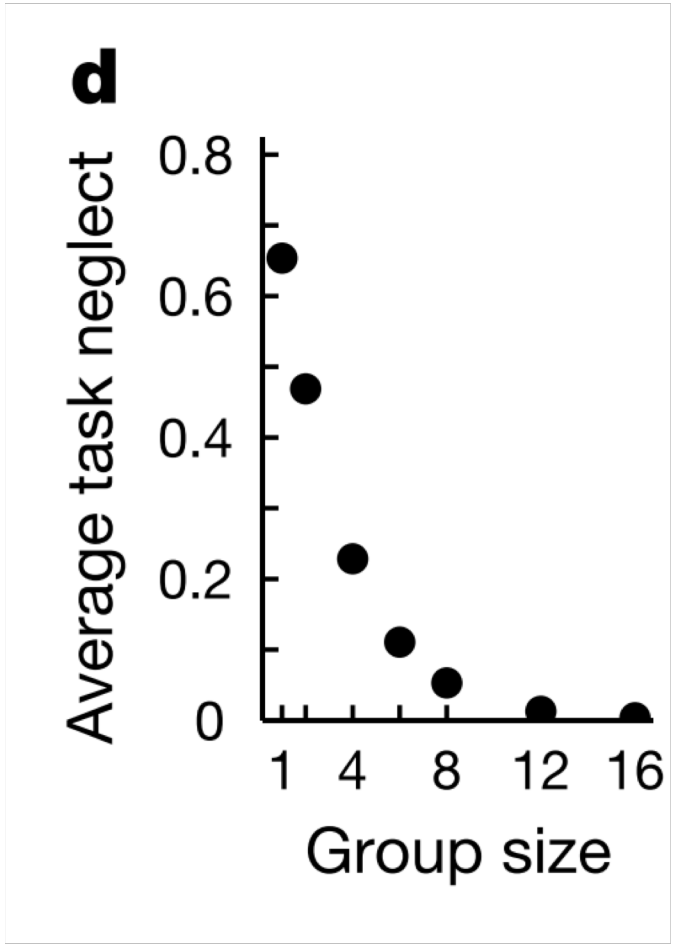


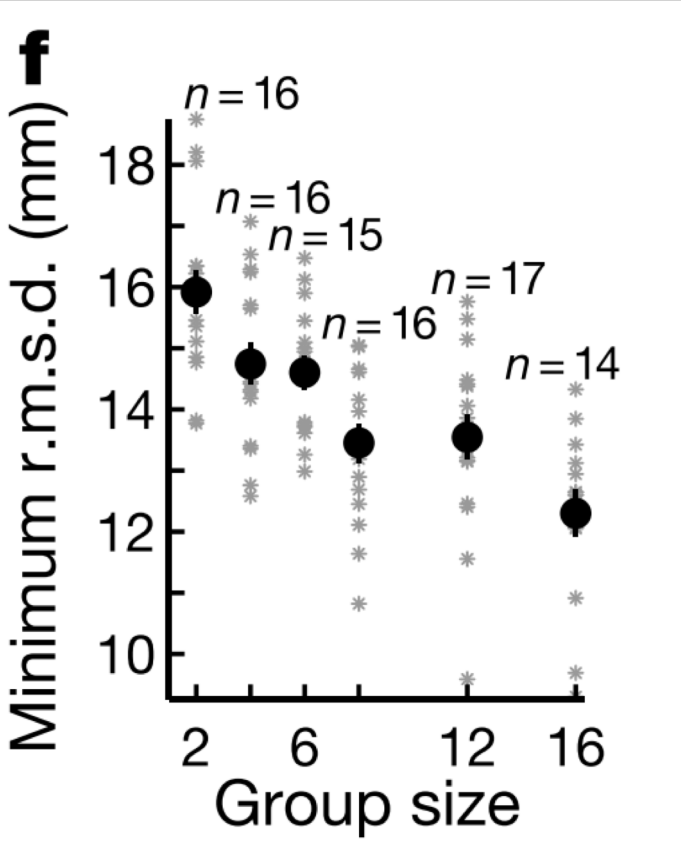
Adapted from Rajakumar, et al. 2018 *Nature*

Parameter space for all social interaction and social influence types



Fitness


d
Average task neglect
0.8
0.6
0.4
0.2
0
1
4
8
12
16
Group size


f
Minimum r.m.s.d. (mm)
n = 16
n = 16
n = 15
n = 16
n = 17
n = 14
18
16
14
12
10
2
6
12
16
Group size

Stimulus