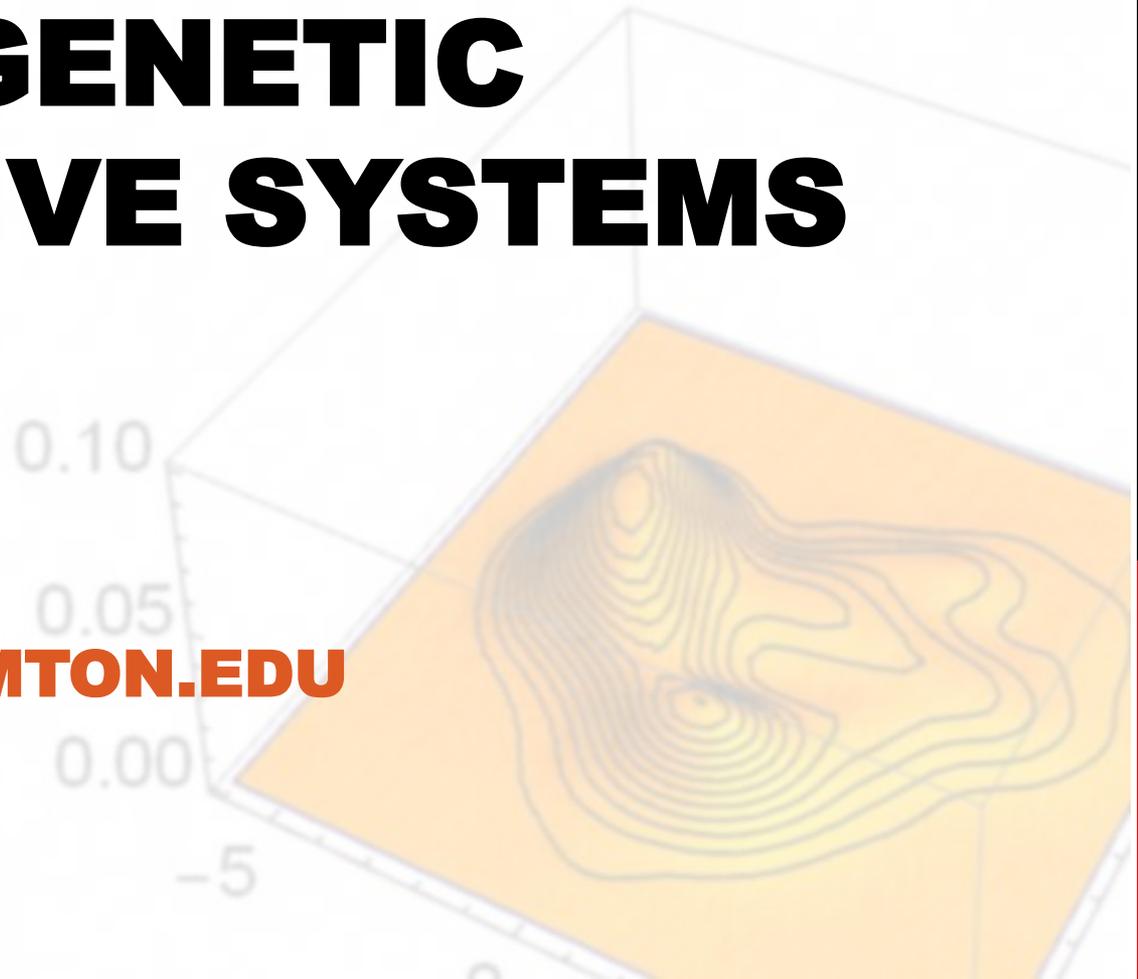


# **BEHAVIORAL DIVERSITIES OF MORPHOGENETIC COLLECTIVE SYSTEMS**

**HIROKI SAYAMA**

**SAYAMA@BINGHMTON.EDU**



# PREVIOUSLY, AT ALIFE 14...

A



Heterogeneity

B



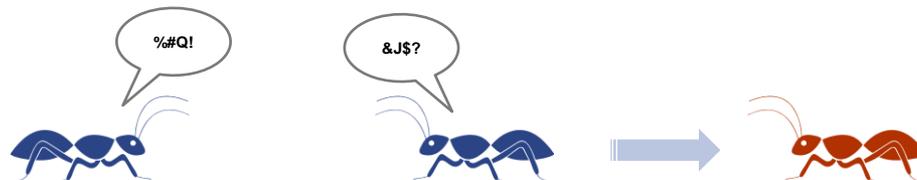
Dynamic (re-)differentiation

C



Local information sharing

D



# MODEL: “MORPHOGENETIC” SWARM CHEMISTRY

Heterogeneity

B



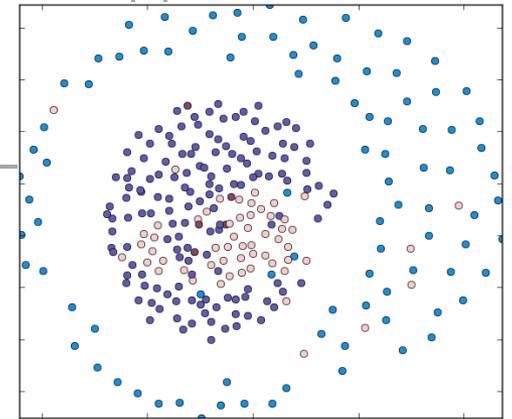
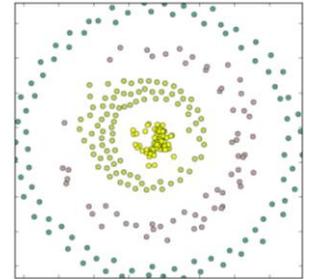
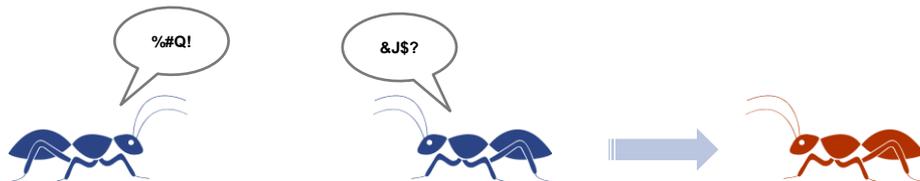
Dynamic (re-)differentiation

C

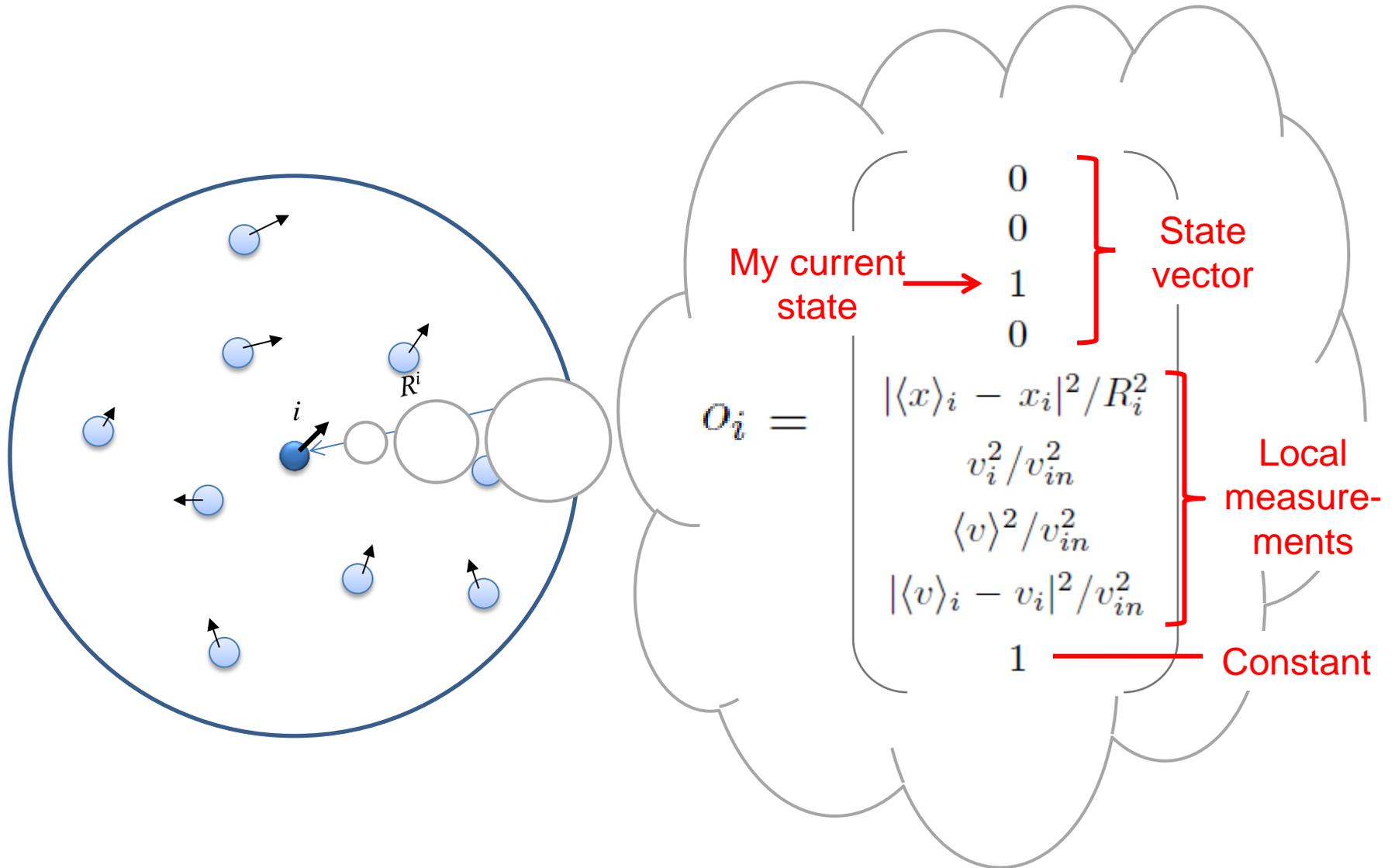


Local information sharing

D



# OBSERVATION VECTOR $O$



# PREFERENCE WEIGHT MATRIX $U$

$U$


$$\begin{pmatrix} 0.15 & 0.035 & -0.041 & 0.077 & 0.08 & 0.079 & 0.005 & 0.05 & 0.064 \\ -0.049 & -0.112 & -0.042 & -0.082 & 0.083 & 0.073 & 0.035 & -0.261 & -0.259 \\ -0.127 & -0.124 & -0.073 & 0.105 & 0.023 & 0.121 & 0.028 & -0.092 & -0.166 \\ 0.036 & 0.024 & 0. & 0.179 & 0.078 & 0.086 & 0.058 & 0.03 & -0.057 \end{pmatrix}$$

0  
0  
1  
0

$|\langle x \rangle_i - x_i|^2 / R_i^2$

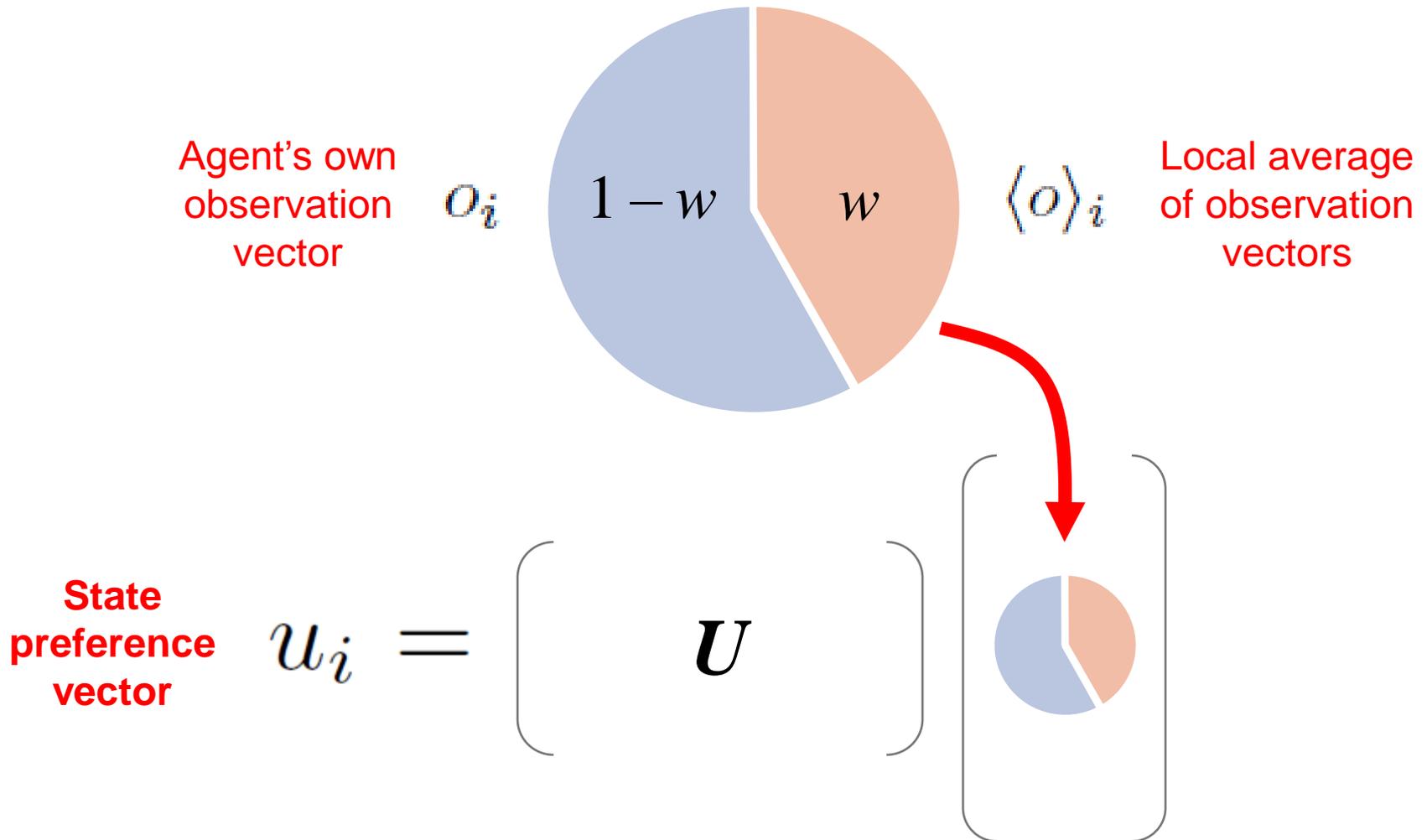
$v_i^2 / v_{in}^2$

$\langle v \rangle^2 / v_{in}^2$

$|\langle v \rangle_i - v_i|^2 / v_{in}^2$

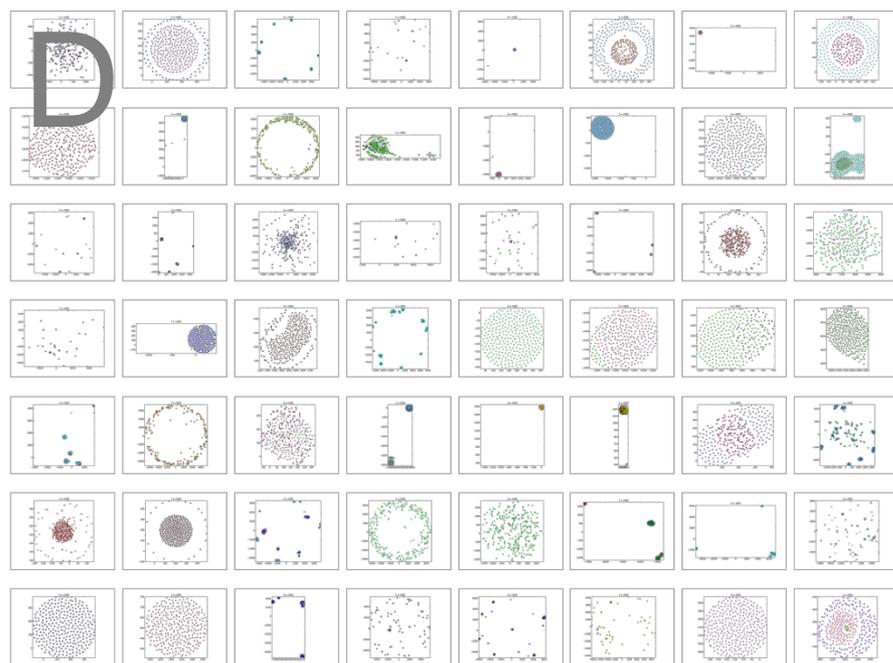
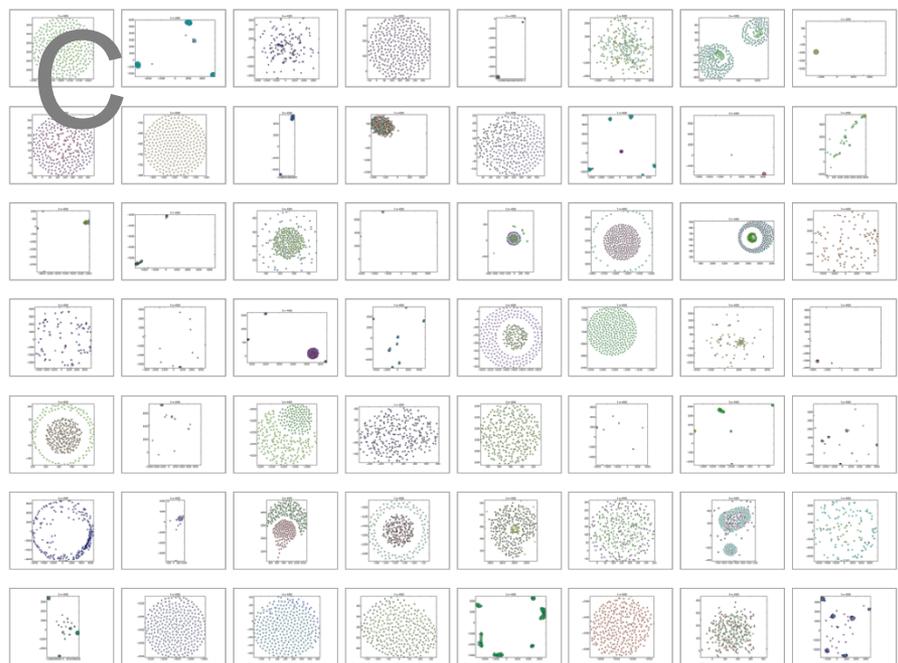
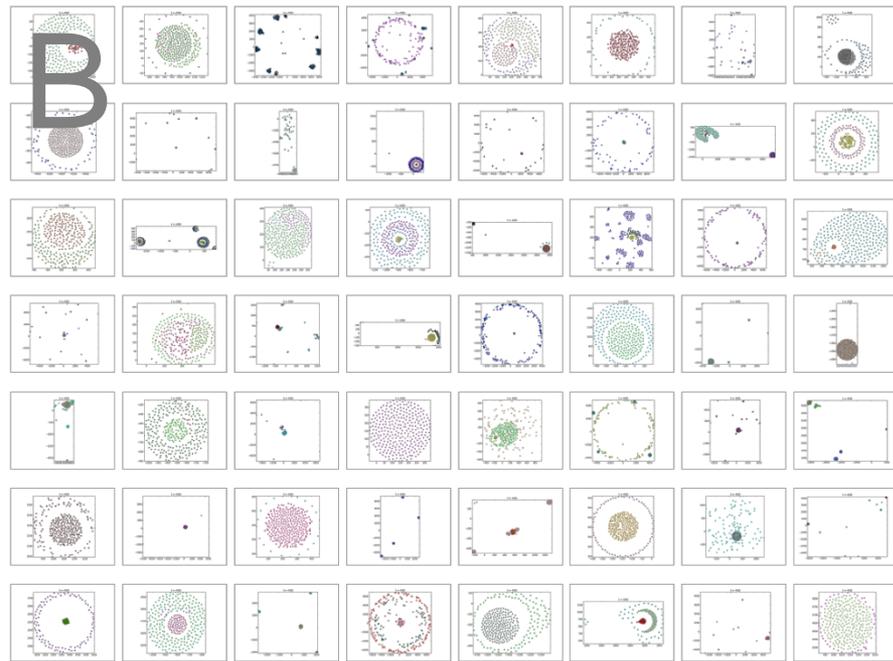
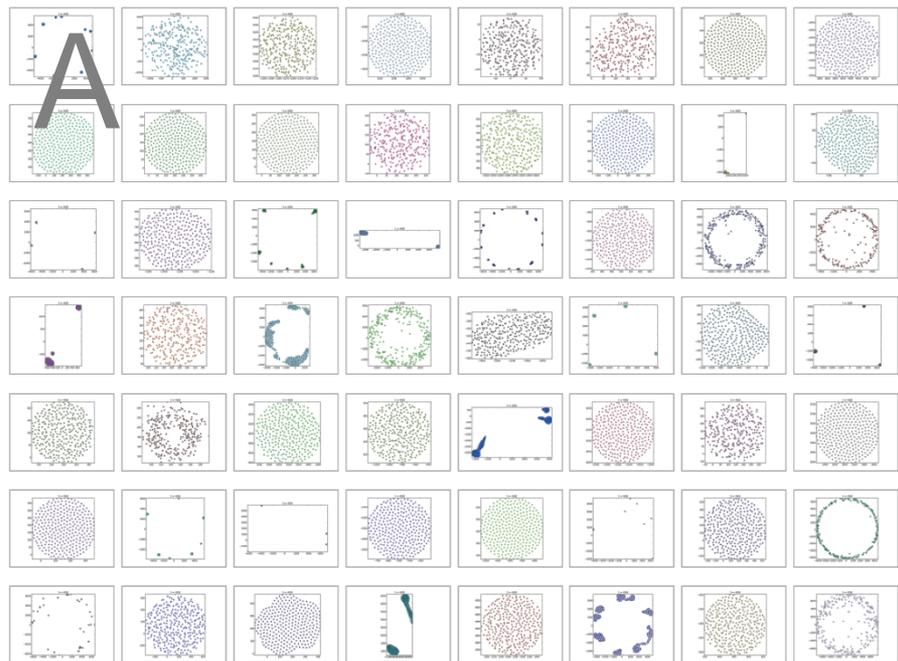
1

# LOCAL INFORMATION SHARING COEFFICIENT $w$



# FOUR CLASSES PARAMETERIZED

Class	$\mathcal{R}$	$U$	$w$
A	One type	0	0
B	Multiple types	0	0
C	Multiple types	$\neq 0$	0
D	Multiple types	$\neq 0$	$\neq 0$



		Class A median	Class B median	Class C median	Class D median	K-W test <i>p</i> -value	
Temporal Mean	Kinetic outcomes	average speed of swarm	2.46921	3.63557	3.71434	4.0491	0.00006***
		average absolute speed of agents	7.93488	9.14903	9.15137	9.86948	0.00024**
		average angular velocity of swarm	0.000381388	0.00135723	0.000879347	0.000775047	0.00000***
		average distance from center	144.646	375.673	215.245	206.946	0.00000***
		average pairwise distance	197.277	521.194	302.728	284.57	0.00000***
	Topological outcomes	number of connected components	1.54	11.65	9.91	7.8175	0.00000***
		average size of connected components	234.013	27.7284	32.4974	41.5561	0.00000***
		homogeneity of connected component sizes	0.957634	0.647418	0.669637	0.670815	0.00000***
		size of largest connected component	298.633	177.26	199.48	212.645	0.00000***
		average size of smaller connected components	1.00075	6.93472	5.18955	5.0891	0.00000***
		average clustering coefficient	0.43364	0.434347	0.433522	0.431574	0.18211
		link density	0.0164127	0.0131673	0.0137475	0.0136435	0.00000***
Temporal Standard Deviation	Kinetic outcomes	average speed of swarm	0.109343	0.318225	0.28713	0.262987	0.00000***
		average absolute speed of agents	0.0285353	0.0849336	0.0910742	0.0853709	0.00000***
		average angular velocity of swarm	0.00185723	0.00357737	0.00376014	0.00401965	0.00000***
		average distance from center	0.353314	45.9475	11.2173	4.87346	0.00000***
		average pairwise distance	1.11209	62.249	15.4285	6.60913	0.00000***
	Topological outcomes	number of connected components	0.156125	2.17945	1.86601	1.79757	0.00000***
		average size of connected components	1.24983	4.90952	4.20666	4.12473	0.00000***
		homogeneity of connected component sizes	0.0176554	0.0424783	0.0458559	0.053207	0.00000***
		size of largest connected component	0.211601	5.37309	4.24246	4.94907	0.00000***
		average size of smaller connected components	0.297179	1.54578	1.03091	1.04183	0.00000***
		average clustering coefficient	0.00936916	0.0174722	0.0165864	0.0162297	0.00000***
		link density	0.000306748	0.000324602	0.000351948	0.000350871	0.00000***

# FINDINGS (4)

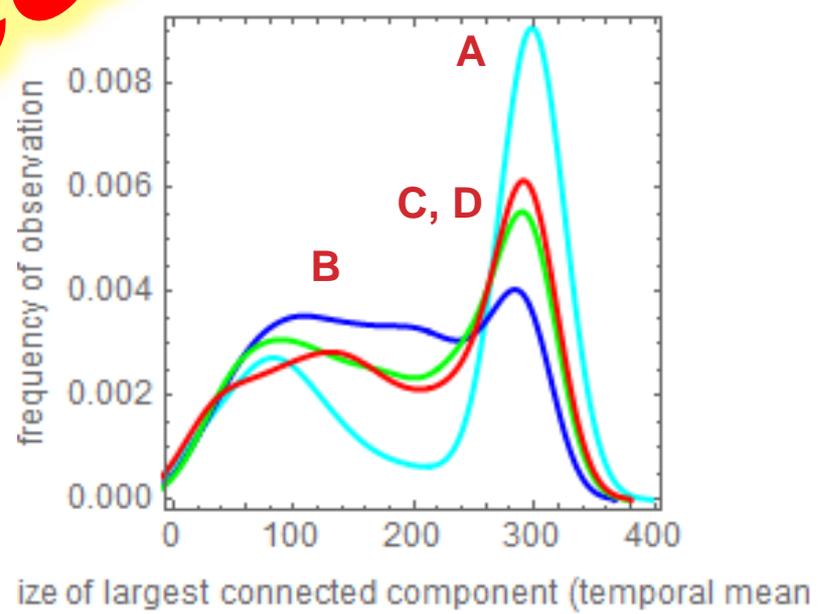
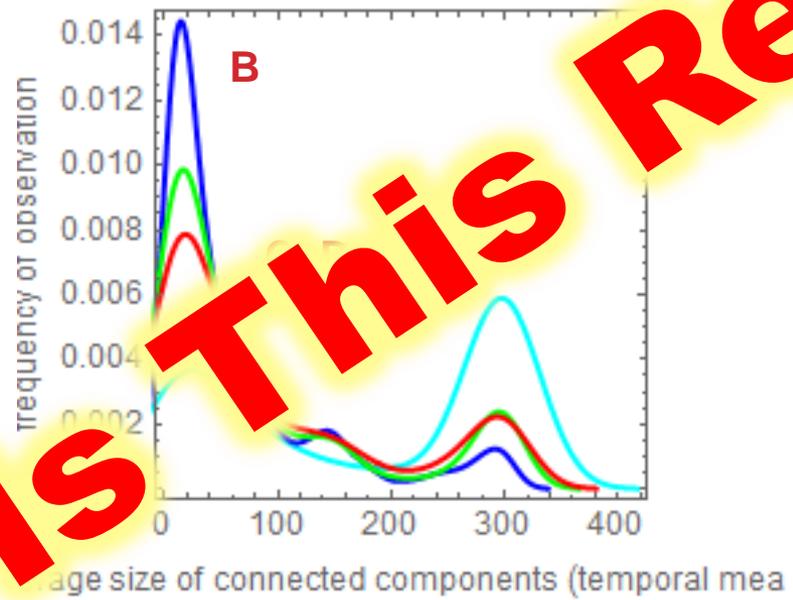
	Class A median	Class B median	Class C median	Class D median	K-W test p-value
average speed of swarm	2.46921	3.63557	3.71434	4.0491	0.0000
average ...				6948	0
average ...				00775047	**
average ...				6.946	**
average ...					0.0000***
number ...					0.00000***
average ...				5501	0.00000***
homogen ...				70815	0.00000***
size of la ...				2.645	0.00000***
average ...					0.00000***
componen ...				891	0.00000***
average ...				31574	0.18211

Many variables showed a trend

**"A → C&D → B"**

Morphogenetic principles may have helped collectives maintain spatially adjacent, coherent motion

**Is This Really True!?**



# HERE IS THE NEW STUFF

**More detailed comparative analysis of the same experimental data among four classes**

**Focusing on *behavioral diversity* within each class**

# INPUT DATA

Average speed of swarm as a whole  
Average of absolute speed of agents  
Average angular velocity of swarm  
Average distance of agents from center  
Average pairwise distance  
Number of connected components  
Average size of connected components  
Homogeneity of sizes of connected components  
Size of largest connected component  
Average size of CCs except for the largest one  
Average clustering coefficient  
Link density

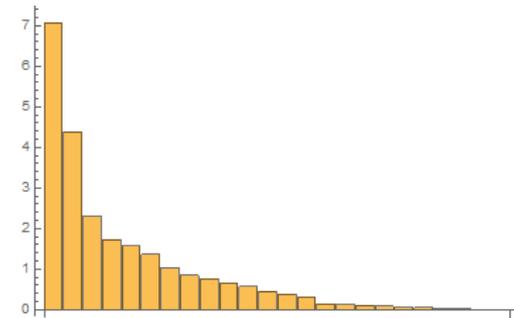
**Standardized &  
transformed by  
PCA**

**24-D  
behavioral  
feature  
space**

**Temporal  
means  
&  
Temporal  
standard  
deviations**



# PRINCIPAL COMPONENTS



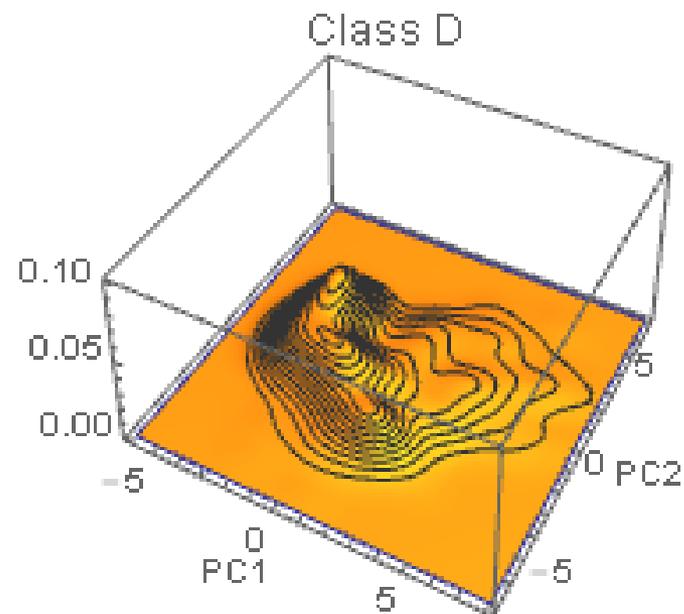
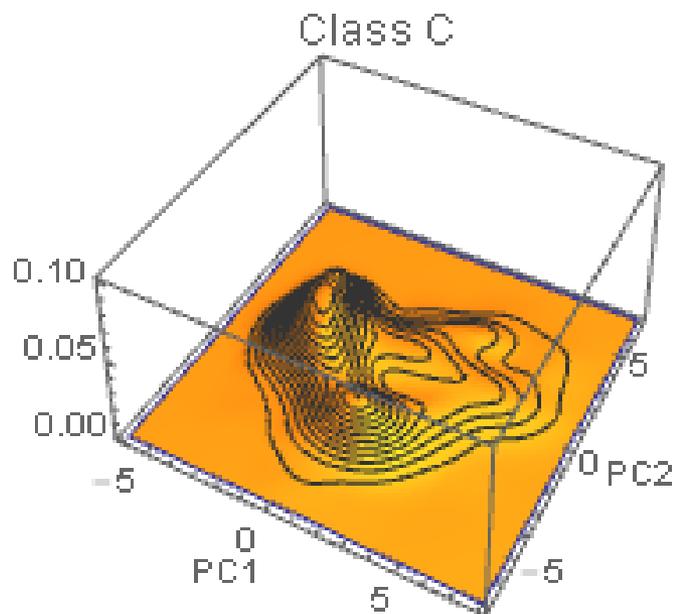
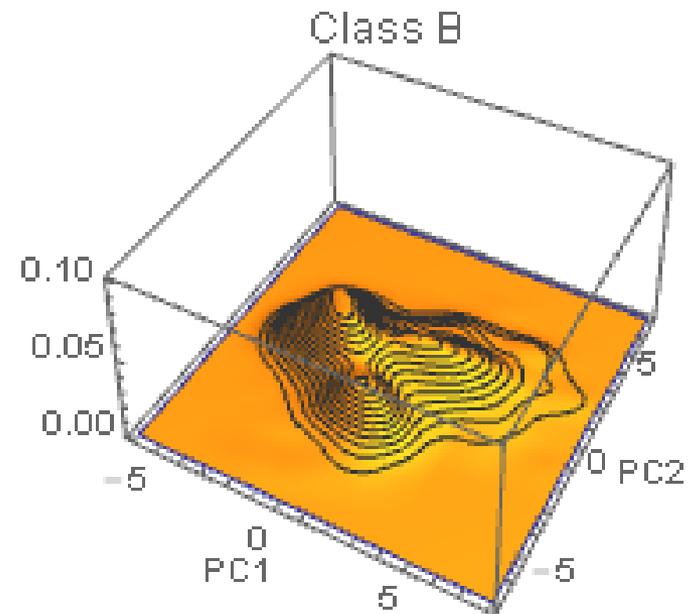
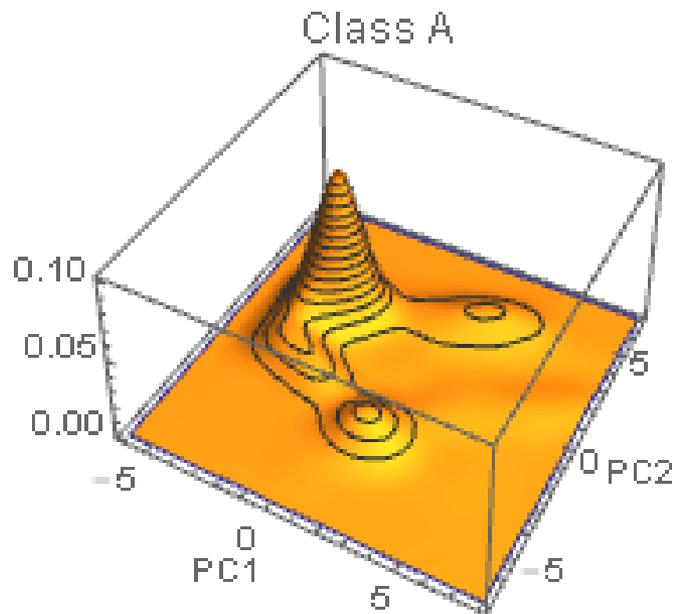
measurement

	PC1	PC2	PC3	PC4
average speed of swarm (temporal mean)	0.126188	-0.0117046	-0.343913	-0.461731
average speed of swarm (temporal s.d.)	-0.0848143	0.191242	-0.274709	-0.0018571
average absolute speed of agents (temporal mean)	-0.168803	-0.0174855	-0.353387	-0.375001
average absolute speed of agents (temporal s.d.)	-0.0144692	0.207744	-0.214091	-0.0199408
average angular velocity of swarm (temporal mean)	0.0352469	0.126252	-0.17559	-0.333102
average angular velocity of swarm (temporal s.d.)	0.0231763	0.185107	-0.0634259	-0.363481
average distance from center (temporal mean)	-0.302103	-0.224319	-0.16295	0.0829295
average distance from center (temporal s.d.)	-0.302199	-0.216265	-0.178495	0.0728311
average pairwise distance (temporal mean)	-0.308231	-0.21665	-0.143017	0.0814428
average pairwise distance (temporal s.d.)	-0.309568	-0.207969	-0.155069	0.0719618
number of connected components (temporal mean)	-0.300046	0.117956	0.184435	-0.00990775
number of connected components (temporal s.d.)	-0.232185	0.316555	0.157694	-0.0144359
average size of connected components (temporal mean)	0.281699	-0.203519	0.0617303	0.0123429
average size of connected components (temporal s.d.)	0.194613	0.116325	-0.250346	0.37388
homogeneity of connected component sizes (temporal mean)	-0.0693812	-0.254539	0.107558	0.0169742
homogeneity of connected component sizes (temporal s.d.)	0.160712	0.17535	-0.186174	0.350526
size of largest connected component (temporal mean)	0.348582	-0.0231079	0.00648618	-0.0407336
size of largest connected component (temporal s.d.)	-0.0778615	0.347487	0.00623167	0.0275512
average size of smaller connected components (temporal mean)	-0.0373044	-0.118318	-0.341501	0.16111
average size of smaller connected components (temporal s.d.)	0.0471745	0.0566901	-0.361369	0.253611
average clustering coefficient (temporal mean)	-0.189347	-0.0782191	0.0950544	-0.0284318
average clustering coefficient (temporal s.d.)	-0.221418	0.339613	0.0950589	0.0546026
link density (temporal mean)	0.253324	-0.303562	-0.0826841	-0.0601691
link density (temporal s.d.)	0.0303761	0.256193	-0.23233	0.123305

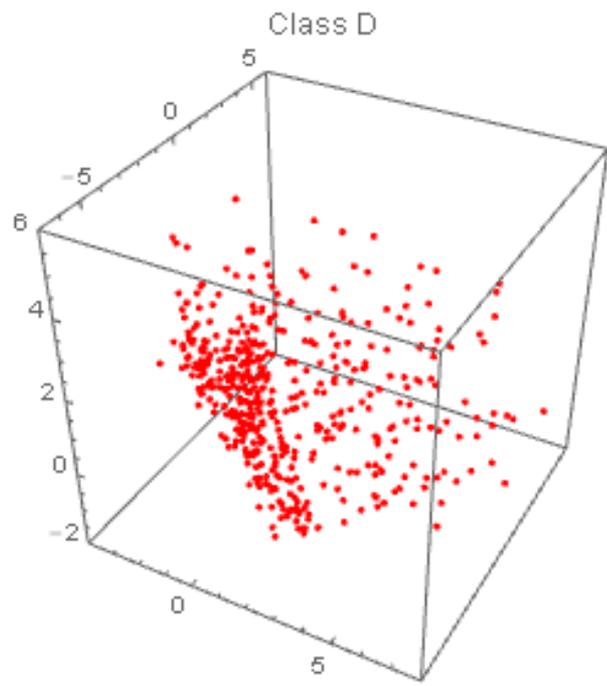
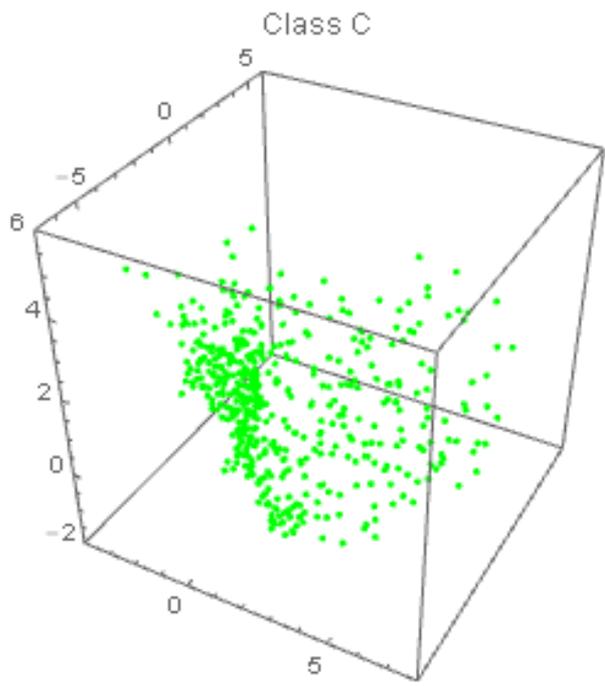
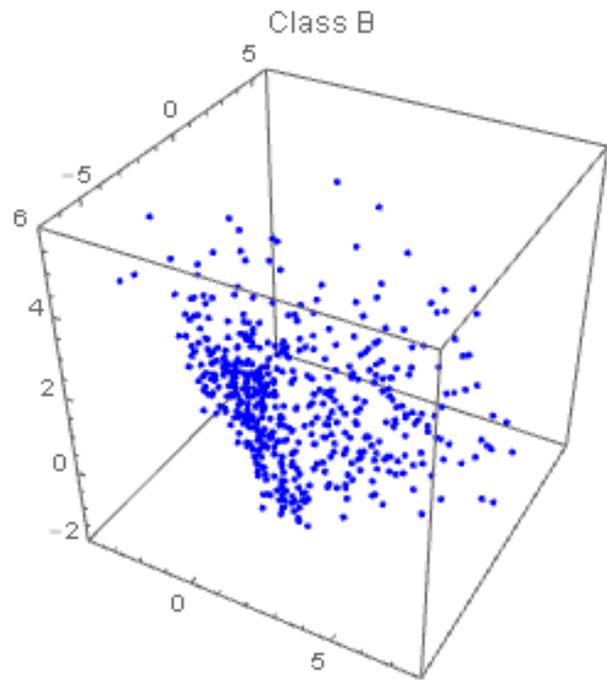
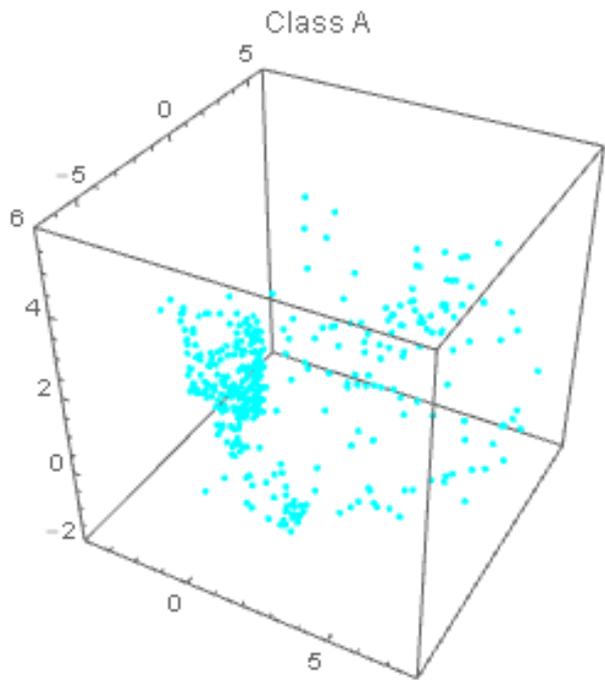
**Cohesion (+) vs.  
dispersal (-)**

**Temporally changing (+)  
vs. static (-)**

# DISTRIBUTIONS (2 PCS)



# DISTRIBUTIONS (3 PCS)



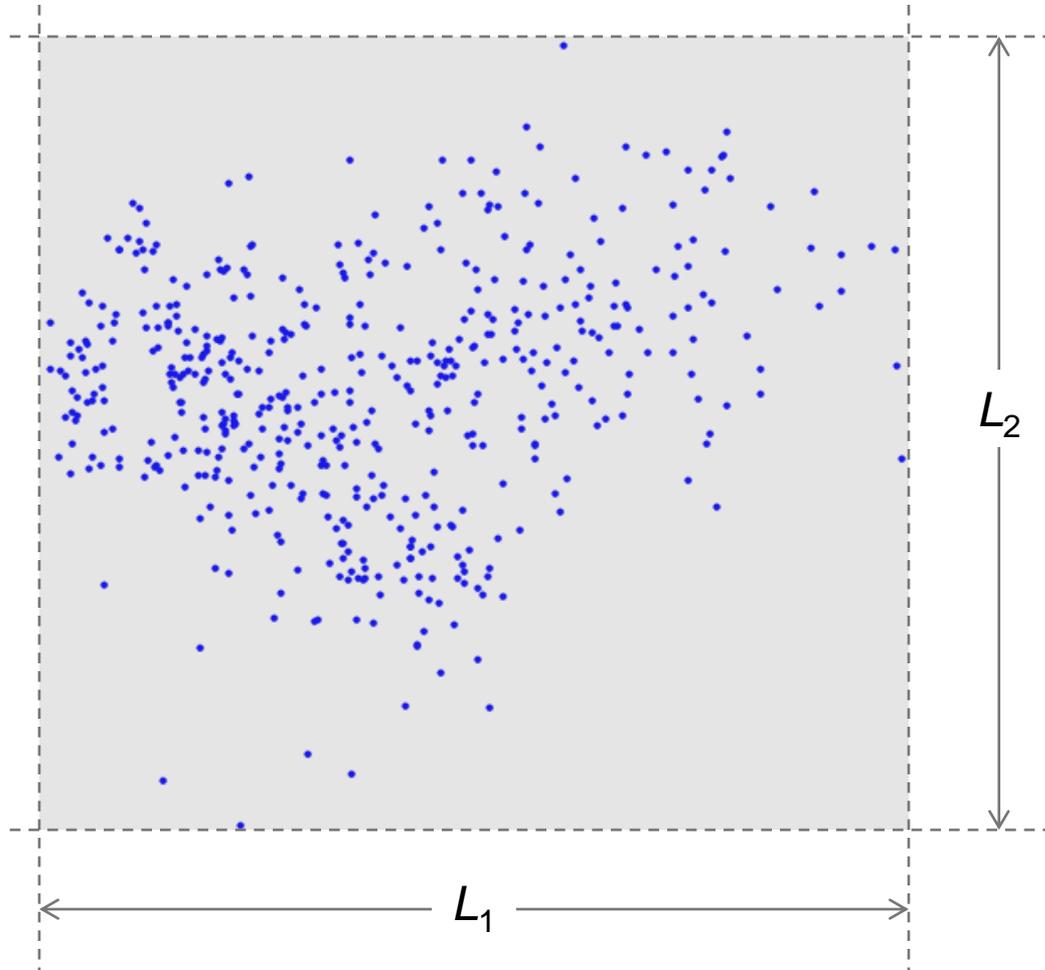
# **HOW TO MEASURE BEHAVIORAL DIVERSITY**

**Approximate volume of behavior coverage**

**Average pairwise distance of behaviors**

**Differential entropy of behaviors**

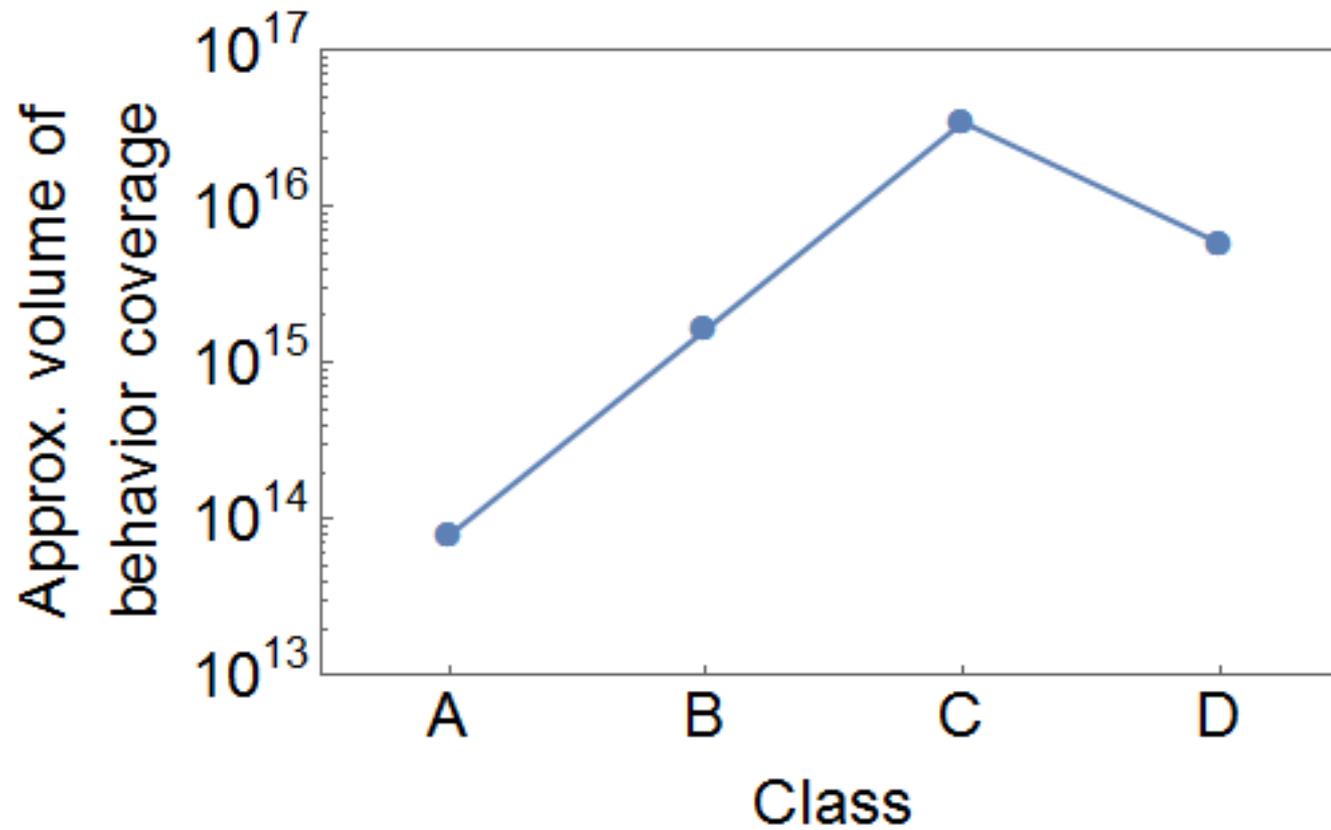
# APPROXIMATE VOLUME OF BEHAVIOR COVERAGE



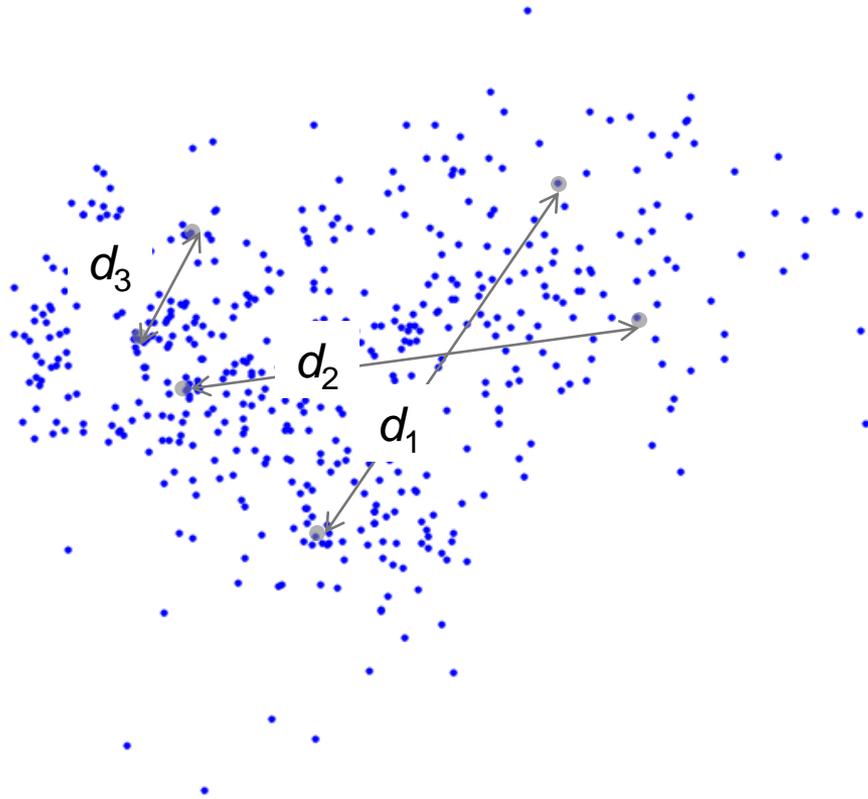
**Approximate  
volume  
 $= L_1 * L_2 * \dots$**

**(do this for  
all 24D)**

# RESULT



# AVERAGE PAIRWISE DISTANCE OF BEHAVIORS

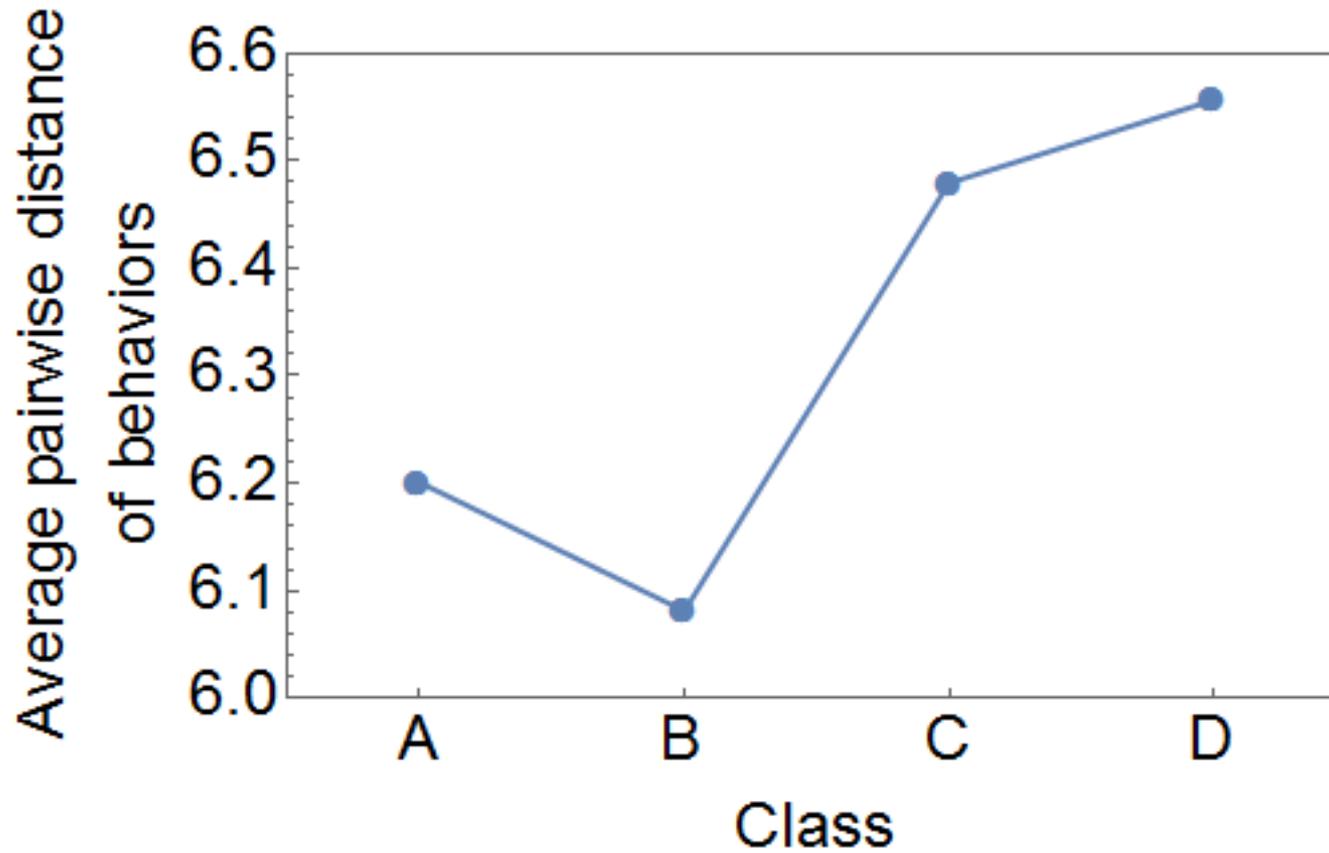


Average pairwise  
distance

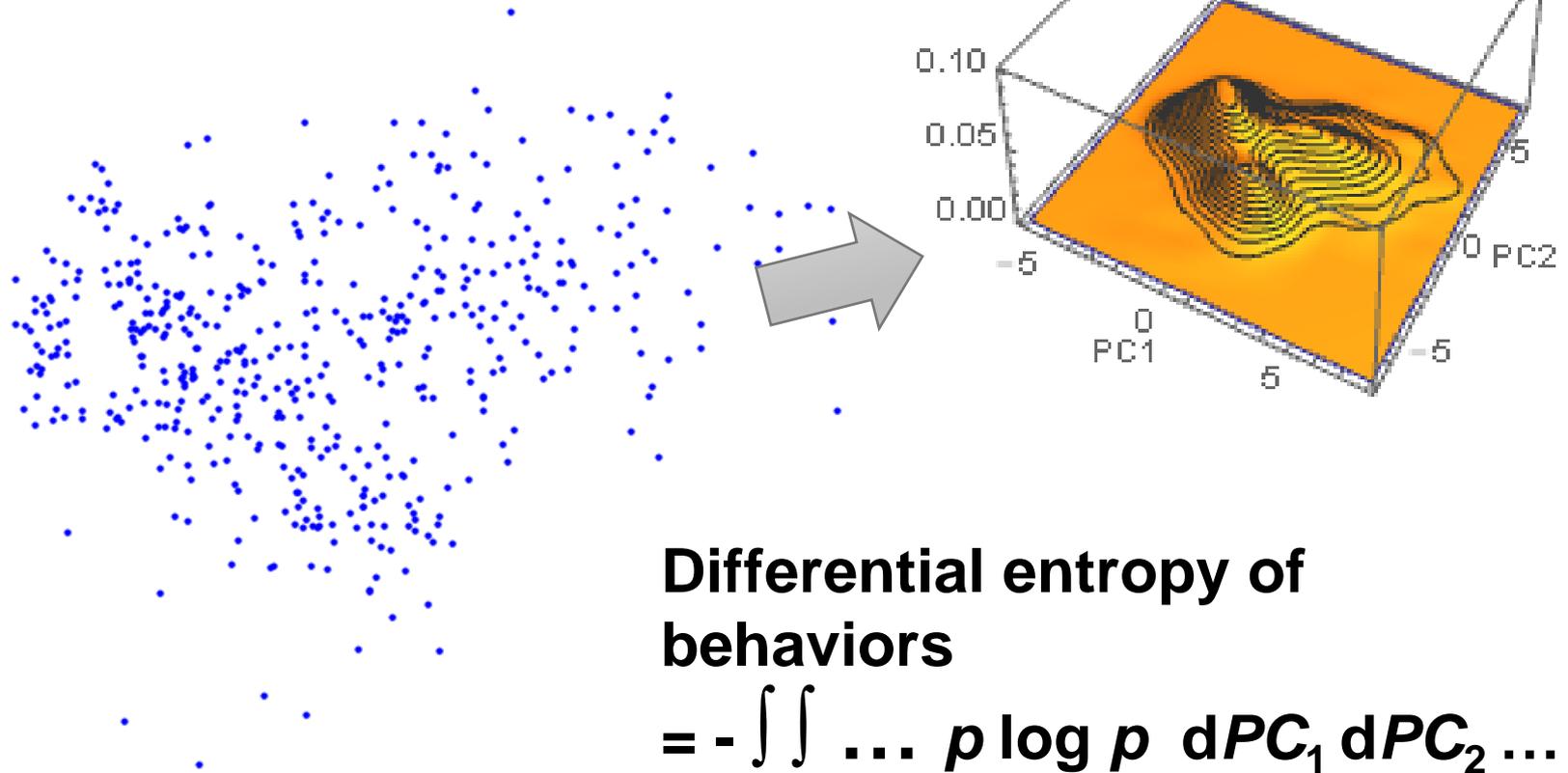
$$= \sum_{i=1 \sim n} d_i / n$$

(do this for  $n = 10^6$  )

# RESULT



# DIFFERENTIAL ENTROPY OF BEHAVIORS

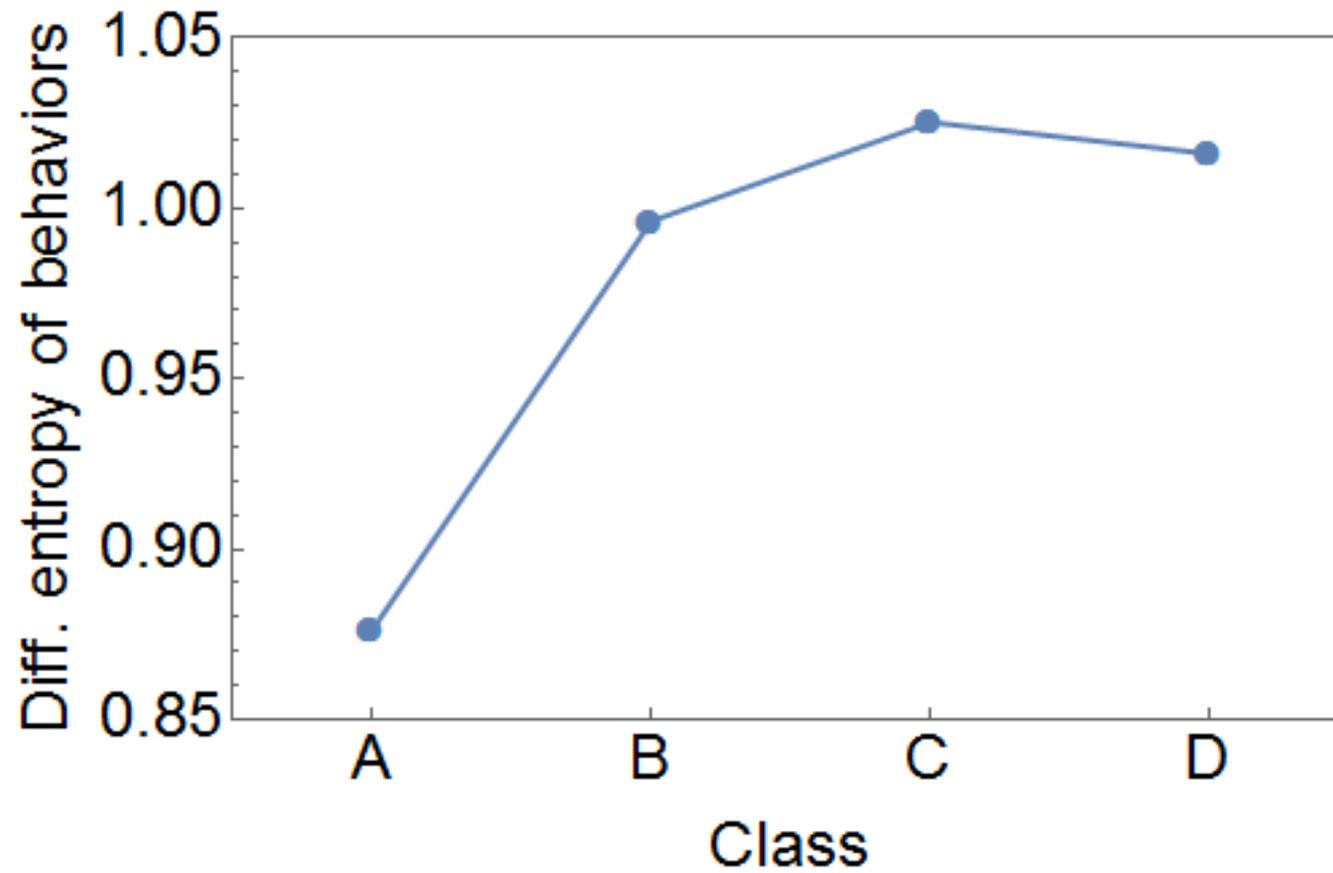


Differential entropy of behaviors

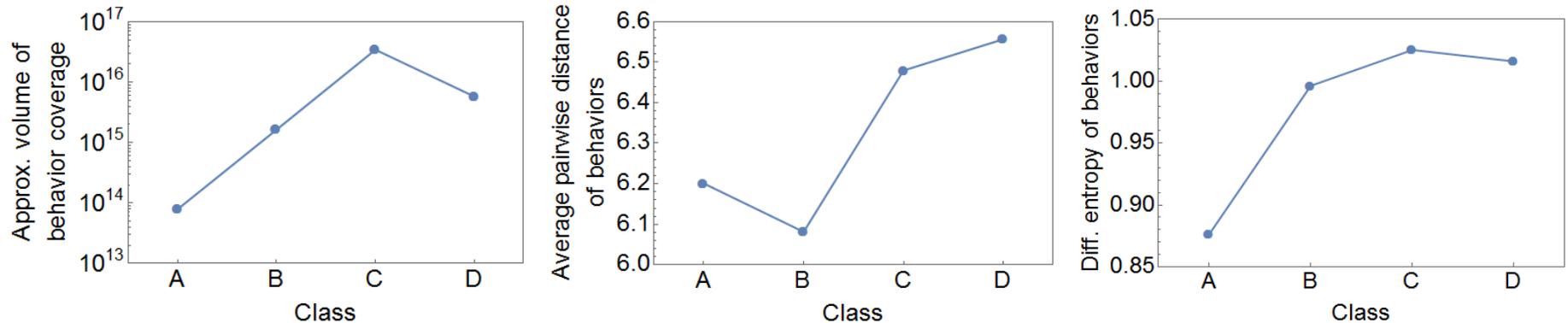
$$= - \int \int \dots p \log p \, dPC_1 \, dPC_2 \dots$$

(do this for top 4 PCs)

# RESULT



# INTERPRETATIONS



**In all of three measurements, Classes C & D showed greater values than A & B**

**I WAS WRONG;**

**Classes C & D were *NOT* in between A and B!!**

**Difference between B and C/D not so significant in differential entropy that used only 4D**

**→ *Behavioral diversity is truly high-dimensional***

# CONCLUSIONS

**Experimental data of “Four Classes of MCS” paper re-analyzed to characterize behavioral diversities in high-dimensional feature space**

**Classes C & D consistently showed greater behavioral diversities than A & B**

**Dynamic (re-)differentiation contributes to the production of more diverse behaviors in MCS**

**Still not clear: What role does local information sharing play (between C & D)?**

# **ACKNOWLEDGMENTS**



**Financial support by the US National Science  
Foundation (award #: 1319152)**

# FOR MORE INFO

**NSF RI “Robustness and Adaptation in Morphogenetic Collective Systems” website:**

<http://bingweb.binghamton.edu/~sayama/NSF-RI-MCS/>

**Swarm Chemistry website:**

<http://bingweb.binghamton.edu/~sayama/SwarmChemistry/>