Morphologies of Self-Organizing Swarms in 3D Swarm Chemistry

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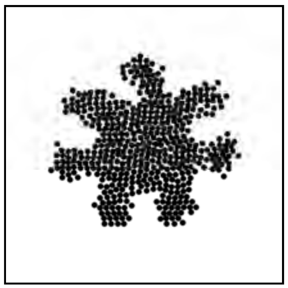
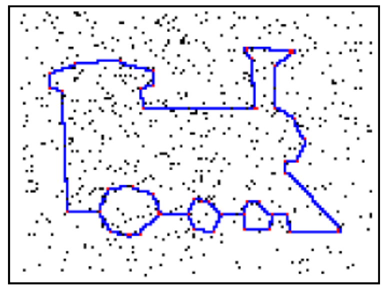
Self-Organization, Development and Morphogenesis in Biological Systems Are Inherently Spatial.

Similar Processes Realized in Engineered Systems

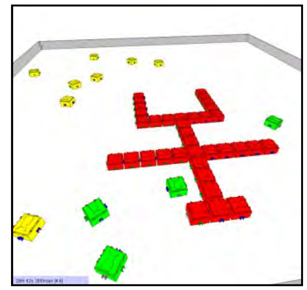


Bai, Eyiyurekli, Breen 2008

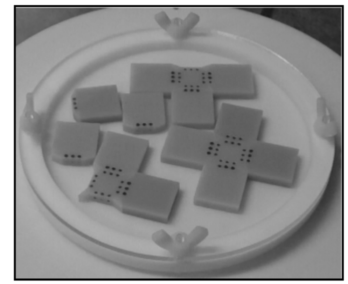
O'Grady, Christensen, Dorigo 2009



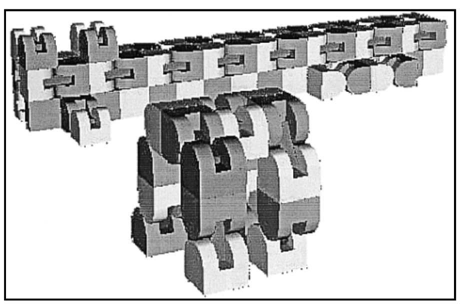
Arbuckle, Requicha 2010



Liu, Winfield 2010

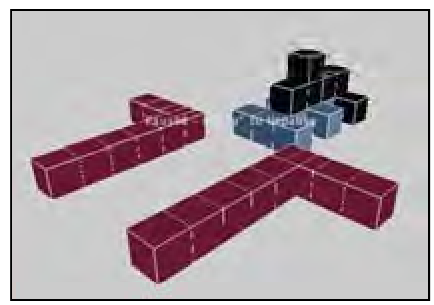


Bhalla, Bentley, Jacob 2010



Murata et al. 2002

Werfel, Nagpal 2008



Meng, Zhang, Jin 2011

How Robust Are Those Engineered Morphogenetic Systems Against Changes in Spatial Dimensions?

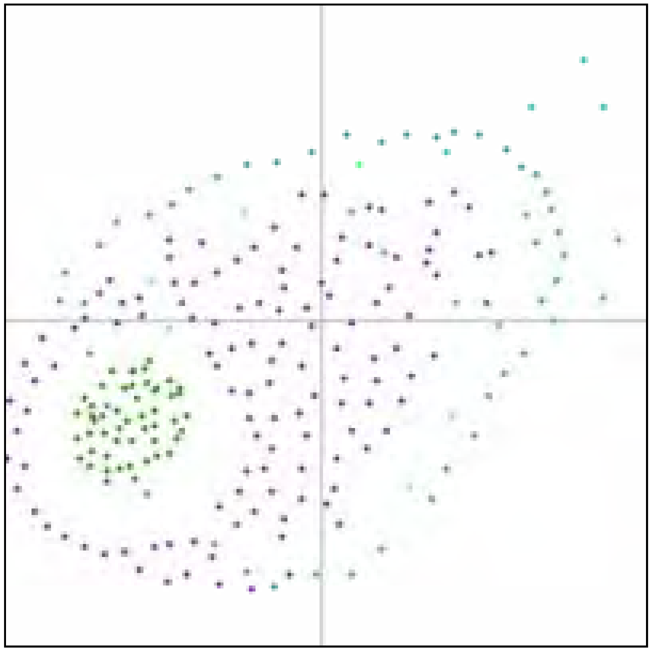
Objective

- **To study the effects of changes in spatial dimensions (2D vs. 3D) on morphologies of self-organizing swarms**

Model: Swarm Chemistry

Swarm Chemistry

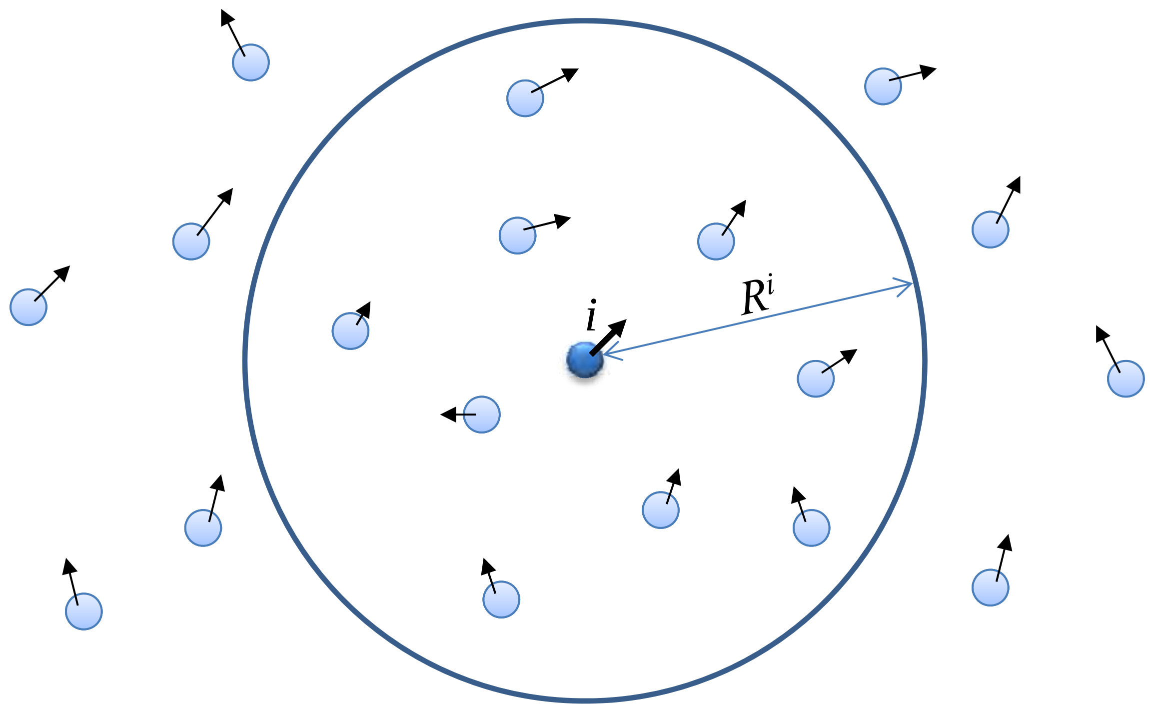
- **An artificial chemistry model that shows self-organization of kinetically interacting heterogeneous particles**



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

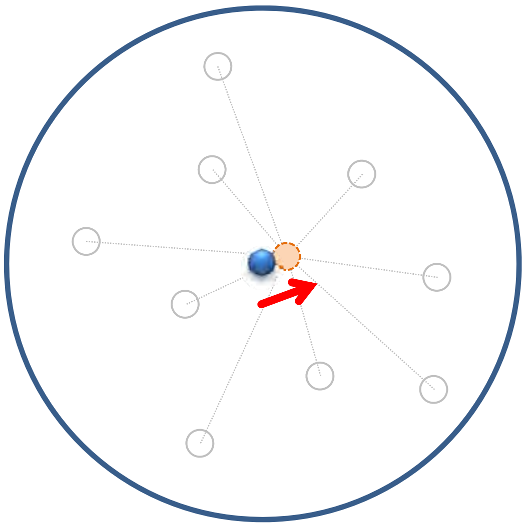
Model Assumptions

- **Particles in a continuous open 2D space**
  - **Kinetic interactions with local neighbors**
  - **No capability to distinguish different types**

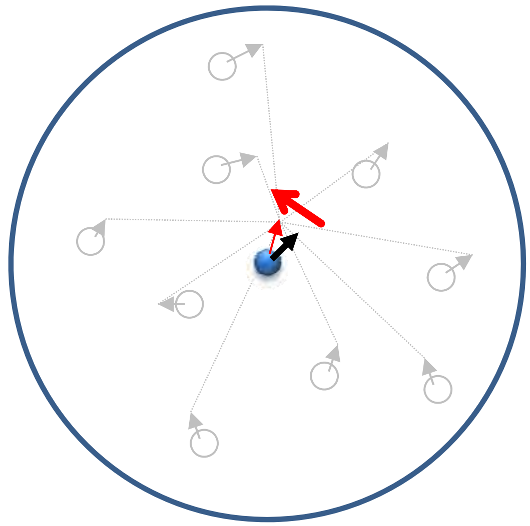


Behavioral Rules

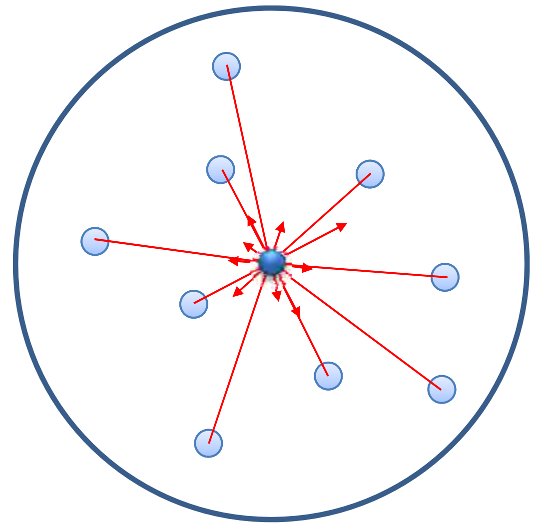
Cohesion



Alignment



Separation



Behavioral Rules (Details)

- If no particles are found within local perception range, steer randomly (**Straying**)
- Otherwise:
  - Steer to move toward the average position of local neighbors (**Cohesion**)
  - Steer towards the average velocity of local neighbors (**Alignment**)
  - Steer to avoid collision with neighbors (**Separation**)
  - Steer randomly with a given probability (**Randomness**)
- Approximate its speed to its normal speed (**Self-propulsion**)

Kinetic Parameters

(Assigned to each particle individually)

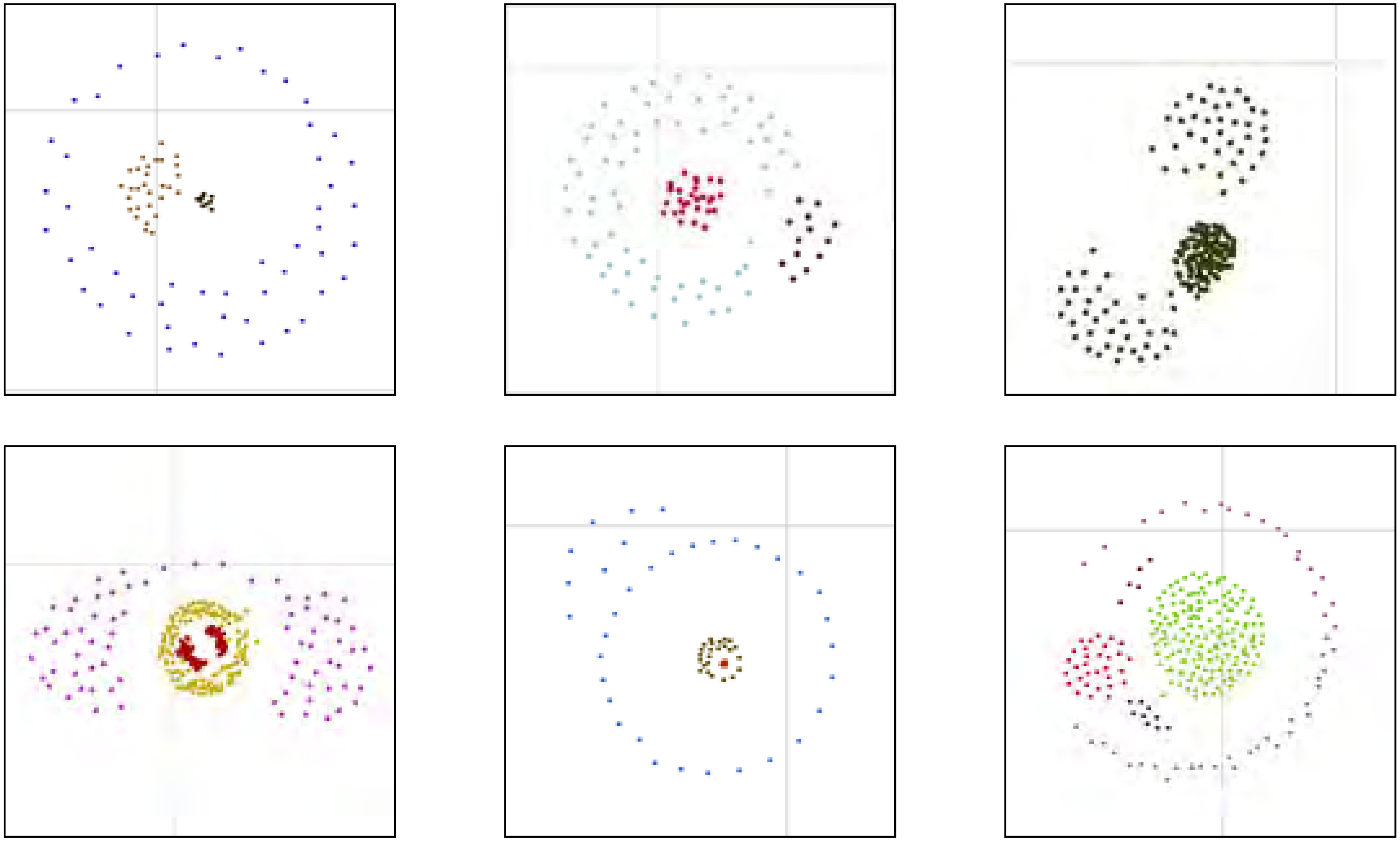
Name	Min	Max	Meaning	Unit
R^i	0	300	Radius of local perception range	pixel
V_n^i	0	20	Normal speed	pixel step^{-1}
V_m^i	0	40	Maximum speed	pixel step^{-1}
c_1^i	0	1	Strength of cohesive force	step^{-2}
c_2^i	0	1	Strength of aligning force	step^{-1}
c_3^i	0	100	Strength of separating force	pixel^2 step^{-2}
c_4^i	0	0.5	Probability of random steering	—
c_5^i	0	1	Tendency of pace keeping	—

Recipe

- **A list of kinetic parameter sets of different types within a swarm**
  - Format: # of particles * (R, V_n, V_m, c_1, c_2, c_3, c_4, c_5)
  - Each row represents one type

```
97 * (226.76, 3.11, 9.61, 0.15, 0.88, 43.35, 0.44, 1.0)
38 * (57.47, 9.99, 35.18, 0.15, 0.37, 30.96, 0.05, 0.31)
56 * (15.25, 13.58, 3.82, 0.3, 0.8, 39.51, 0.43, 0.65)
31 * (113.21, 18.25, 38.21, 0.62, 0.46, 15.78, 0.49, 0.61)
```

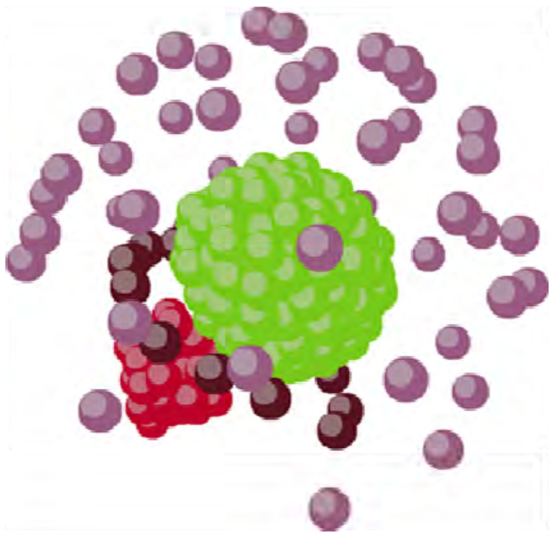
Complex Self-Organizing Patterns



Evolved using ***Hyperinteractive Evolutionary Computation***
For details, see Bush & Sayama, IEEE Trans. Evol. Comp. 15: 424-433 (2011)

Making It 3D

- Straightforward extension of position/velocity vectors from 2D to 3D
- 3D visualization realized in plain Java



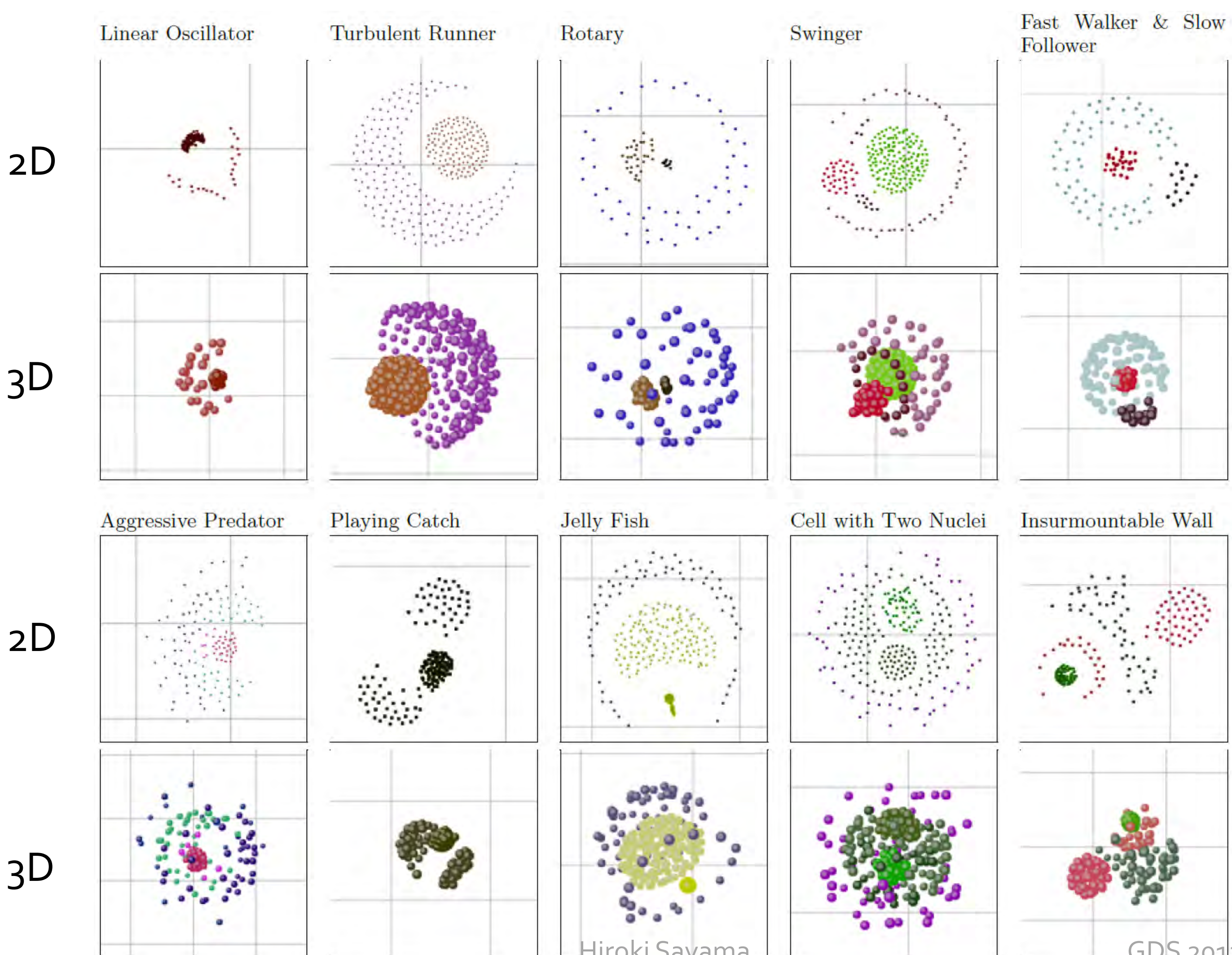
Demo…

Experiment I: Comparison between 2D and 3D

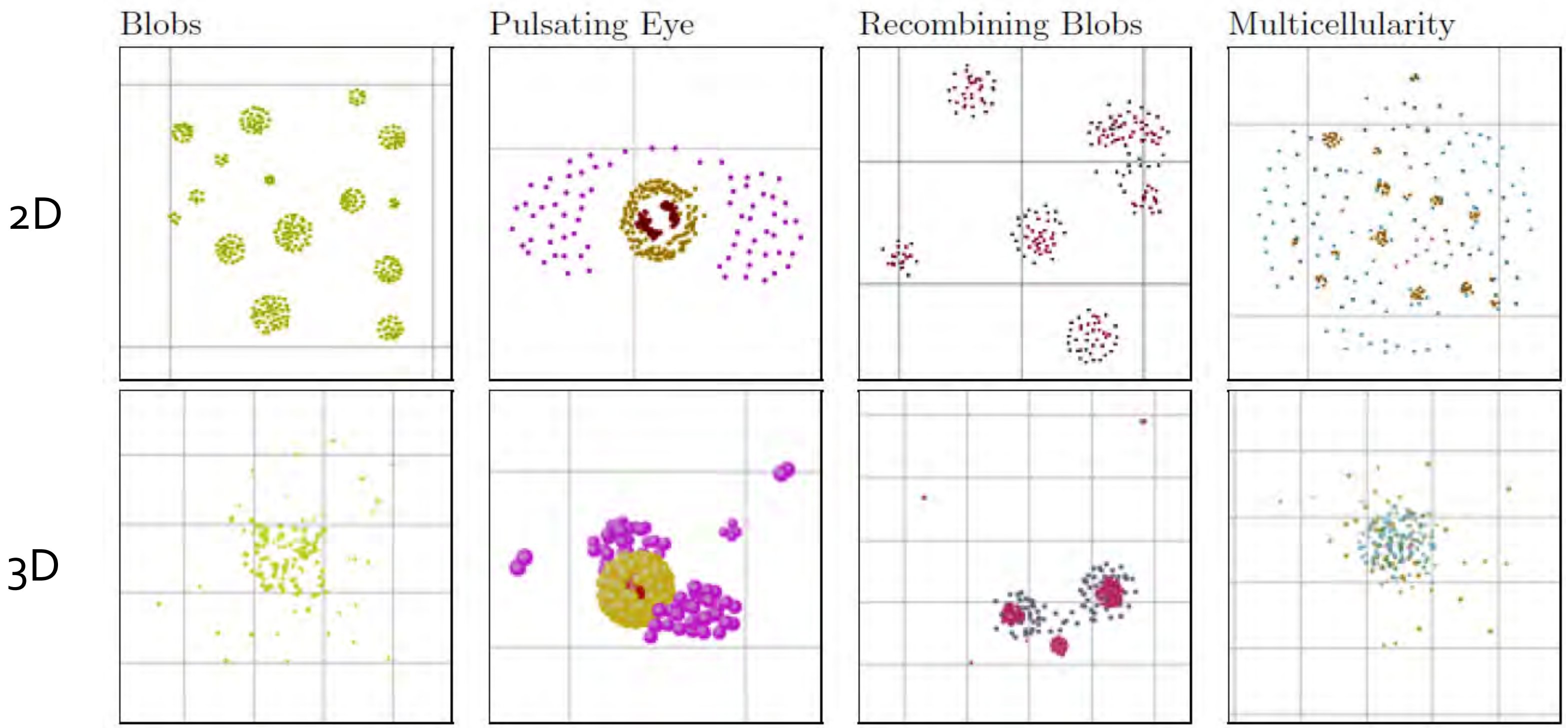
Experimental Settings

- **Initial conditions**: 17 recipes available on the Swarm Chemistry website
- **Experimental variable**: 2D or 3D
- **Output**: Similarity of self-organizing patterns
  - Topology and behavior
  - By visual inspection (so far…)

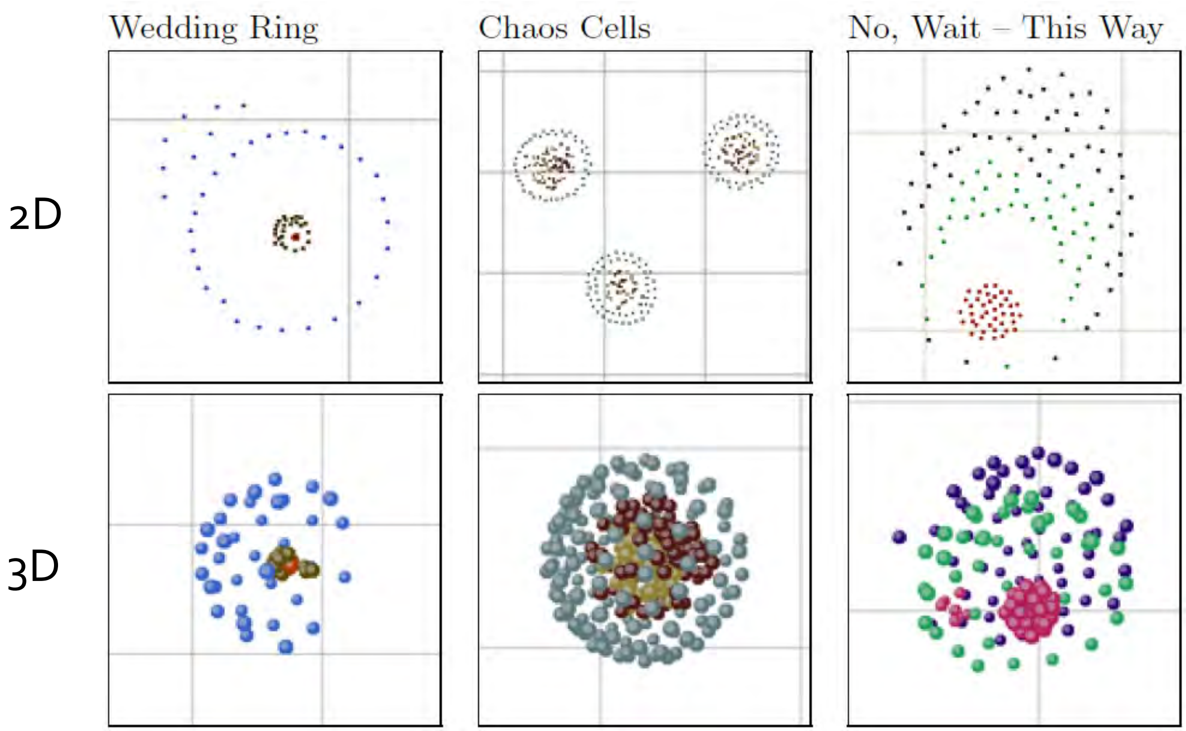
Results (1): Robust Patterns



Results (2): More Dispersed in 3D



Results (3): More Aggregated in 3D



Results (4): Statisitical Comparison of Average Parameter Values

Parameter	n	R	V_n	V_m	c_1	c_2	c_3	c_4	c_5
Overall mean	63.85	179.03	10.03	21.65	0.58	0.42	40.06	0.2	0.51
Results (1) mean	55.47	$\boxed{199.61}$	10.35	22.79	0.56	0.39	37.87	0.21	0.52
Results (2) mean	$\boxed{95.45}$	143.42	10.19	15.55	0.72	0.55	47.25	0.16	0.59
Results (3) mean	56.89	144.79	8.63	24.81	0.5	0.39	39.58	0.2	0.38
ANOVA p-value	*0.082*†	*0.073*†	0.726	0.141	0.181	0.325	0.692	0.63	0.313

Experiment II: Adjusting Parameters

Which Parameters Should Be Varied?

- **Particles have ~12 nearest neighbors in 3D (c.f. ~6 in 2D)**
  -> Halve separation strength c_3
  - No effects on cohesion or alignment

- **Average distance b/w nearby particles is 1.5~3x longer in 3D than 2D**
  -> Double interaction range R
  -> Halve initial particle distribution range L

Experimental Settings

- **Initial conditions**: 7 recipes that were not robust against 2D/3D changes
- **Experimental variable**:
  - Separation strength c_3 -> halved
  - Interaction range R -> doubled
  - Initial particle distribution range L -> halved
    - And their combinations
- **Output**: Similarity of self-organizing patterns

Results (5): Recovery of Original Morphologies

Easily recovered

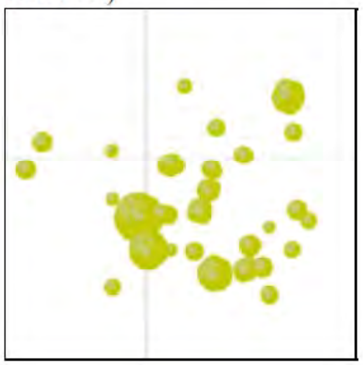
Parameter Setting										
c_3 halved	R doubled	L halved	Blobs	Pulsating Eye	Recombining Blobs	Recipe Multi-cellularity	Wedding Ring	Chaos Cells	No, Wait – This Way
✓			.	.	.	.	.	.	◯
	✓		○	◯	.	○	.	.	◯
		✓	○	◯	○	○	.	.	.
✓	✓		○	◯	.	.	.	.	.
✓		✓	◯	◯	.	○	.	.	◯
	✓	✓	.	◯	.	◯	.	.	◯
✓	✓	✓	.	◯	.	◯	.	.	.

Morphology recovered
- ◯: 4 or 5 times out of 5 trials
- o : 1~3 times out of 5 trials
- . : never

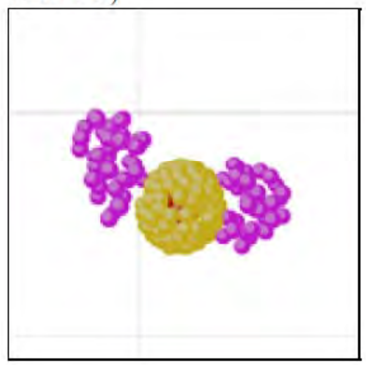
Successful parameter adjustments found through further manual exploration

Results (6): Recovered Patterns

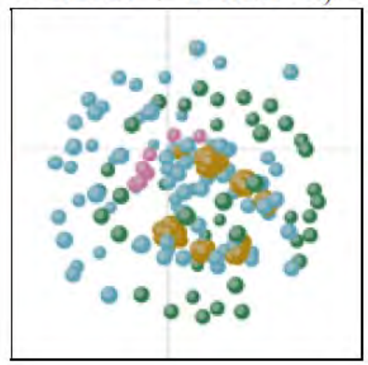
Blobs (c_3 halved + L halved)



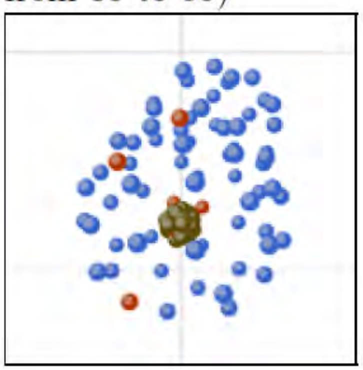
Pulsating Eye (L halved)



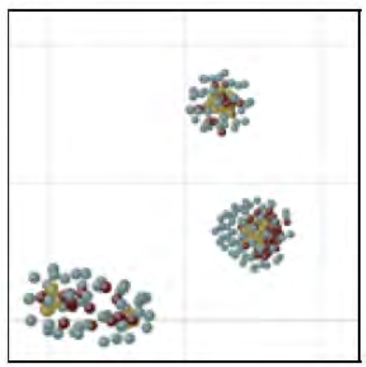
Multicellularity (R doubled + L halved)



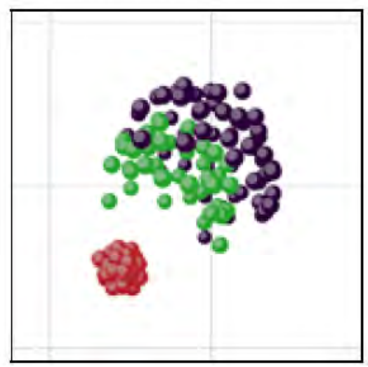
Wedding Ring (third ingredient increased from 35 to 65)



Chaos Cells (L halved + R reduced to 65%)



No, Wait – This Way (c_3 halved)



Proximity in Parameter Space

- Total parameters considered: 10
  - 9 parameters in recipes, plus *L*

- No parameters adjusted: **10** out of 17 recipes
- One parameter adjusted: **2** out of 17 recipes
- Two parameters adjusted: **4** out of 17 recipes

Conclusions

Summary of Findings

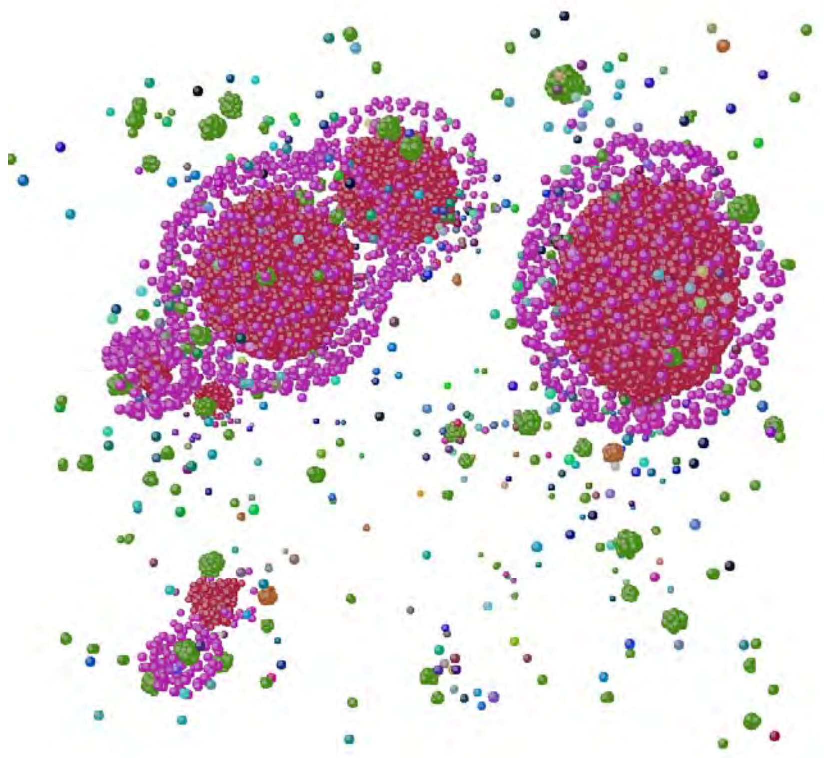
- **Swarm morphologies were robust against dimensional change from 2D to 3D ☺**
  - Mostly no adjustment needed, or just a few, if any
  - Advantage of swarm-based systems in general
- **Ways of parameter adjustments were quite recipe-specific ☹**
  - No generic parameter mapping found (yet) between 2D and 3D

Future Directions

- **Objective, quantitative measurement of topological/dynamical similarities**
  - Persistent homology analysis?
- **Mathematical analysis of parameter relationships b/w 2D and 3D**
  - Any unique patterns possible only in 3D?

Coming Soon…

- Sayama, H. (2012) **Evolutionary Swarm Chemistry in three-dimensions.** Proc. of *ALIFE 13*, MIT Press, in press.



Thank You!

For more info:
Google "Swarm Chemistry"