Prediction of Spatial Self-Organization based on Statistical Moments

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Self-Organization in Engineering

Application

- Tissue Engineering. Repair part of or whole tissues, such as bone, blood vessels, skin and muscle.
- A framework for distributed multi-agent systems.
- The control of robotic swarms.
- Development of basic building elements for future systems that are capable of self-organization, self-assembly, self-healing and self-regeneration.

Advantages

- Advantages over traditional method: scalability, decentralization, adaptability.

Truly Local Algorithms

Benefits

- Benefit the system with scalability.
- Eliminate central points of failure by eliminating leaders.

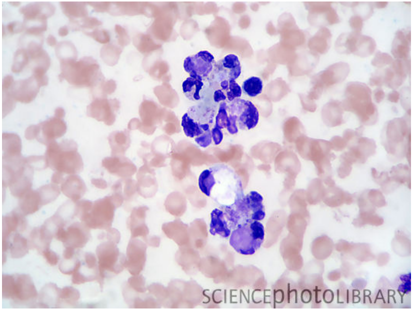
Problems

- How to convey a global goal to low level interactions?
- How to understand the emergent process of local interactions?
- What can we use paradigms for designing such algorithms?

What Can We Learn from Cell Biology?

Chemotaxis

- Cells emit accumulating chemicals into the environment.
- Neighboring cells detect the overall chemical concentration at their surfaces.
- Cells respond to the stimulus by moving in the direction of the gradient either towards or away from the source.

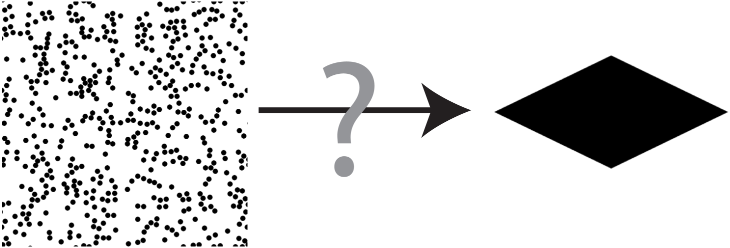


- Cell movements produce large-scale aggregation.
- The motions may lead to cell-cell aggregation, complex pattern formation or sorting of cells.

Introduction

Problem Description

- Given predefined shape and initially disorganized primitives, how to discover local interactions between the primitives that direct them to aggregate into the macroscopic target shape?



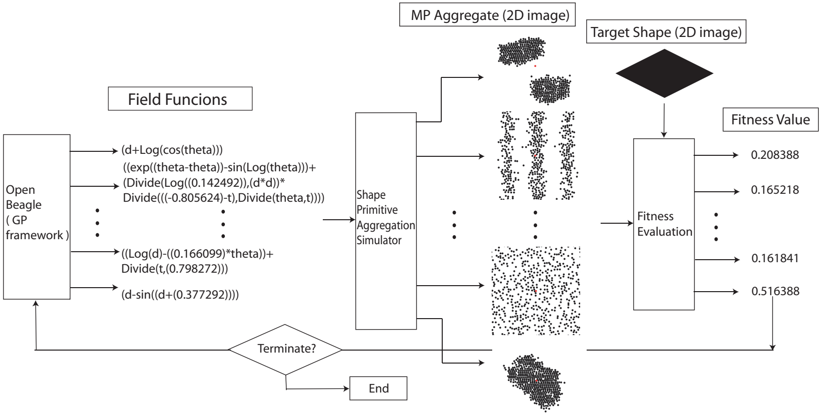
MP Design Principles

- Autonomous ‘agents’: there’s no ‘master designer’ that directs the actions/motions of the MPs.
- Actions are based on local information: each MP emits a *finite* field that can be sensed only by other primitives within a certain range.
- MPs respond to information with identical prescribed behaviors based on information received from the environment.
- MPs have no representation of the final, macroscopic shape to be produced.
- The shape emerges from the aggregation of local interactions and behaviors, rather than from following a plan to produce the shape.

General Approach

- Develop MP aggregation model, based on a previous chemotaxis-driven cell aggregation model.
- Define chemical field around individual cells with arbitrary mathematical functions
  -Instead of the physical 1/r function.
- Discover local interaction rules (chemical field function) that cause cells to form into specific shape by following cumulative field.
- Genetic Programming is used to evolve chemical field functions.

Framework


MP Aggregate (2D image)
Target Shape (2D image)
Field Funcions
Fitness Value
Open Beagle (GP framework)
(d+Log(cos(theta)))
((exp((theta-theta))-sin(Log(theta)))+
(Divide(Log((0.142492)),(d*d))*
Divide(((-0.805624)-t),Divide(theta,t))))
((Log(d)-((0.166099)*theta))+
Divide(t,(0.798272)))
(d-sin((d+(0.377292))))
Shape Primitive Aggregation Simulator
Fitness Evaluation
0.208388
0.165218
0.161841
0.516388
Terminate?
End

MPs Form into A Gear Shape

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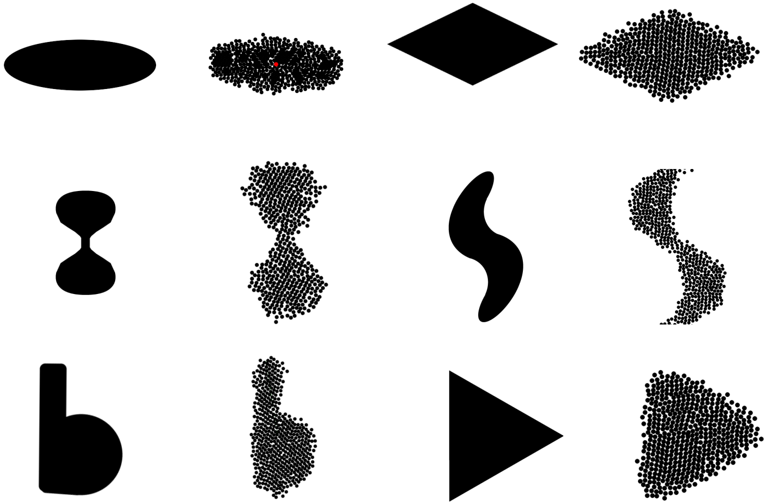
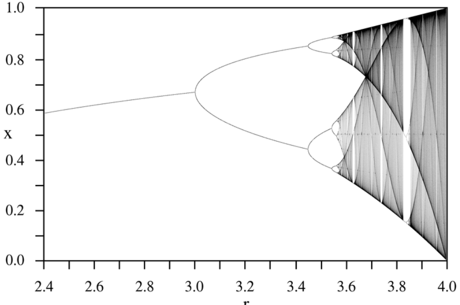
Results



Bifurcation

- In dynamical systems, a bifurcation is a qualitative change in its behavior produced by varying parameters.
- It is a period-doubling, a change from an n-point attractor to a $2n$-point attractor.
- A bifurcation diagram shows the possible long-term values of a system as a function of a bifurcation parameter.



Bifurcation in our system

Due to Randomness

- Every simulation begins with a different uniform random initial configuration.
- Primitives stochastically follow the gradient of the cumulative field.

Statistical Moments

Mean, Variance, Skewness and Kurtosis

$$M_1 = \frac{1}{n}\sum_{i=1}^{n} X_i, \tag{1}$$

$$M_2 = \frac{1}{n}\sum_{i=1}^{n} (X_i - \mu)^2, \; where\; \mu = \frac{1}{n}\sum_{i=1}^{n} X_i, \tag{2}$$

$$M_3 = [\frac{1}{n}\sum_{i=1}^{n} (X_i - \mu)^3]/(M_2)^{3/2}, \tag{3}$$

$$M_4 = [\frac{1}{n}\sum_{i=1}^{n} (X_i - \mu)^4]/(M_2)^2. \tag{4}$$

for all X_i, where ($i = 1, 2, ...n$) and $X_i =< x_i, y_i >$.

Feature Vector

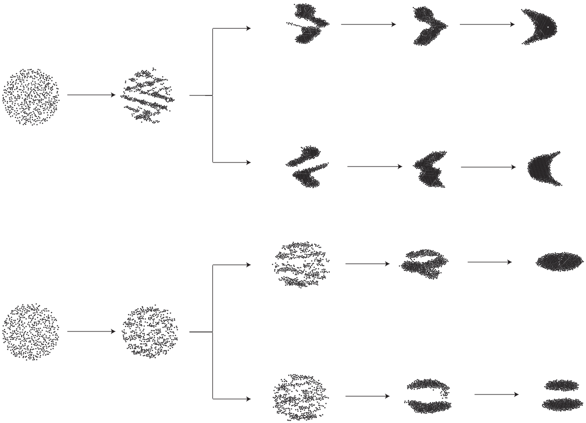
- Our shape simulation evolves over time, at each simulation time t, we obtain four moments associate with the time $M_i(t)$, where $i = 1, 2, 3, 4$.
- Consider an interval of 5τ, that is, $M_i(t-2\tau)$, $M_i(t-\tau)$, $M_i(t)$, $M_i(t+\tau)$ and $M_i(t+2\tau)$, we fit a straight line to these five points, and we obtain the slope of the line k_i.
- Feature vector is:

$$\begin{aligned}[& M_{x_1}(t), M_{y_1}(t), M_{x_2}(t), M_{y_2}(t), \\ & M_{x_3}(t), M_{y_3}(t), M_{x_4}(t), M_{y_4}(t) \\ & k_{x_1}(t), k_{y_1}(t), k_{x_2}(t), k_{y_2}(t), \\ & k_{x_3}(t), k_{y_3}(t), k_{x_4}(t), k_{y_4}(t)] \end{aligned} \quad (5)$$

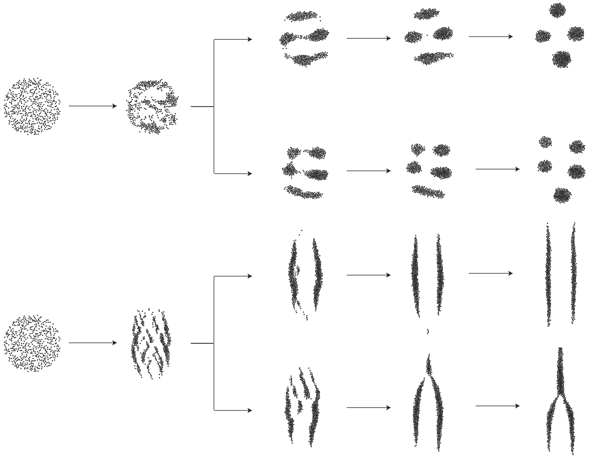
Using Support Vector Machines

- We consider predicting bifurcating outcomes a classification problem.
- We use the LIBSVM library with the RBF kernel and use grid search to find optimal SVM parameters, i.e., C and γ.
- The size of the training set is 200, with 100 in each category.

Examples - quarter-moon and ellipse



Examples - blobs and line segments



Cross Validation Results

Quarter-moon			
	Accuracy	Sensitivity	Specificity
10-fold	$(90.65 \pm 1.21)\%$	$(89.45 \pm 1.36)\%$	$(91.85 \pm 1.68)\%$

Ellipse			
	Accuracy	Sensitivity	Specificity
10-fold	$(86.30 \pm 0.93)\%$	$(89.31 \pm 1.46)\%$	$(83.23 \pm 1.12)\%$

Four Blobs			
	Accuracy	Sensitivity	Specificity
10-fold	$(81.58 \pm 1.00)\%$	$(83.60 \pm 1.43)\%$	$(79.55 \pm 1.07)\%$

Parallel Line Segments			
	Accuracy	Sensitivity	Specificity
10-fold	$(80.53 \pm 2.28)\%$	$(78.06 \pm 3.59)\%$	$(82.99 \pm 2.25)\%$

Future Work

- We are able to predict the outcome of the shape formation evolution at 10% of the simulation time steps.
- The next step is to control or influence the shape evolution path so that the primitives consistently form into one stable configuration.

Related Publications

- L. Bai, M. Eyiyurekli, P.I. Lelkes and D.E. Breen, "Self-Organized Sorting of Heterotypic Agents Via a Chemotaxis Paradigm," *Science of Computer Programming*, Vol. 78, No. 5, pp. 594 – 611, May 2013.
- L. Bai and D. Breen, "Chemotaxis-Inspired Cellular Primitives for Self-Organizing Shape Formation," R. Doursat, H. Sayama, O. Michel (eds.), *Morphogenetic Engineering: Toward Programmable Complex Systems*, Springer, Berlin, Chapter 9, 2012, pp. 209 – 237.
- M. Eyiyurekli, L. Bai, P. Lelkes, D. Breen, "Chemotaxis-based Sorting of Self-Organizing Heterotypic Agents," *Proceedings of the 2010 ACM Symposium on Applied Computing*, pp. 1315 – 1322, Sierre, Switzerland, March 2010.

Related Publications

- L. Bai, D. Breen, “Calculating Center of Mass in a Toroidal Environment,” *Journal of Graphics Tools*, Vol. 13, No. 4, 2008, pp. 53 – 60.
- L. Bai, M. Eyiyurekli, D. Breen, “An Emergent System for Self-Aligning and Self-Organizing Shape Primitives,” *Proceedings of 2nd IEEE International Conference on Self-Adaptive and Self-Organizing Systems (SASO)*, pp. 445 – 454, Venice, Italy, October 2008.
- L. Bai, “Self-Organizing Primitives for Automated 2D Shape Composition,” M.S. Thesis, Drexel University, Philadelphia, PA, August 2008.

Related Publications

- L. Bai, M. Eyiyurekli, D. Breen, "Automated Shape Composition Based on Cell Biology and Distributed Genetic Programming," *Proceedings of Genetics and Evolutionary Computation Conference (GECCO)*, pp. 1179 – 1186, Atlanta, GA, July 2008.
- L. Bai, M. Eyiyurekli, D. Breen, "Self-Organizing Primitives for Automated Shape Composition," *Proceedings of IEEE International Conference on Shape Modeling and Applications (SMI)*, Stony Brook, NY, pp. 147 – 154, June 2008.

Other Publications

- L. Bai, T. Widmann, F. Jülicher, C. Dahmann and D.E. Breen, "3D Surface Reconstruction and Visualization of the Drosophila Wing Imaginal Disc at Cellular Resolution," *Proceedings of SPIE-IS&T Conference on Electronic Imaging*, Volume 8654, Article 86540D, February 2013.
- D.E. Breen, T. Widmann, L. Bai, F. Jülicher and C. Dahmann, "Epithelial Cell Reconstruction and Visualization of the Developing Drosophila Wing Imaginal Disc," *Proceedings of IEEE Symposium on Biological Data Visualization*, pp. 77 – 84, Seattle, WA, October 2012.