Cell Shapes Emerge from Confined Motion

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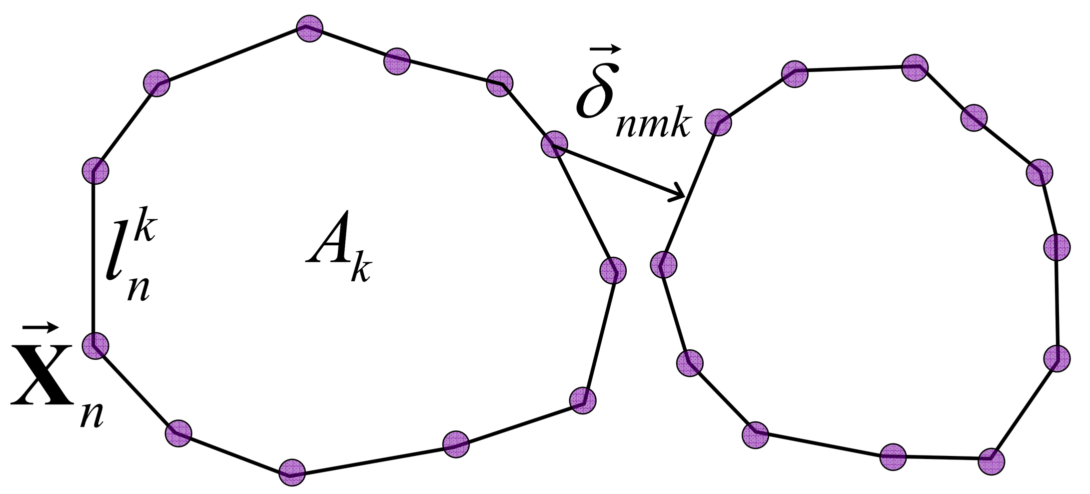
Funding: NSF-CMMI, NIH

Abstract: We use agent-based modeling of cells as deformable particles, to explore the distribution of cell shapes in active-driven systems. The deformable cells move using an active Brownian force model in a quasi-two-dimensional geometry. We characterize the cell shape using $S=P^2/4\pi A$, the non-dimensional ratio of perimeter P to area A. S=1 for a circle and is larger for any other shape. We compare systems containing cells with fixed (elastic) shape parameter to those with dynamic (plastic) shape parameter. The shape parameter must be greater than 1.15 for the cells to completely cover space. In these dense states, the cells must deform to move. In the fixed S_0 systems, the area of the cell is fixed and the perimeter is an elastic spring with rest-length $P_0=\sqrt{4\pi A S_0}$. In the dynamic system, the rest-length of the perimeter can relax based on the local stress. For fixed S_0 systems, a critical shape parameter S*=1.34 emerges. For $S_0<S^*$, the cells tend to stretch their perimeter, increasing S. For $S_0>S^*$, the cells tend to compress their perimeter. In the dynamic systems, a broad universal distribution of shape parameters emerges regardless of the initial distribution of shapes. This broad distribution is peaked near S=1.15, but has very long high S tails extending above S=3. The broad distribution matches that found in high mobility MDCK cell mono-layers.

Cell Model



$$\alpha = \frac{P_0^2}{4\pi A_0}$$

Shape Parameter

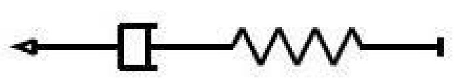
Area spring — Edge spring

$$U(\vec{\mathbf{X}}_n, l_0^k) = \frac{1}{2}K_A\sum_k (A_k(\vec{\mathbf{X}}_n) - A_0)^2 + \frac{1}{2}K_l\sum_k\sum_m (l_m^k(\vec{\mathbf{X}}_n) - l_0^k)^2$$

$$\vec{\mathbf{F}}_n = -\frac{\partial U}{\partial \vec{\mathbf{X}}_n} - \sum_{m,k} K_\delta(\delta_{nmk} - \delta_0)\hat{\delta}_{nmk} + F^D\hat{\boldsymbol{\theta}}_n - B\dot{\vec{\mathbf{X}}}_n$$

Adaptive Perimeter — Interaction — Driving — Drag

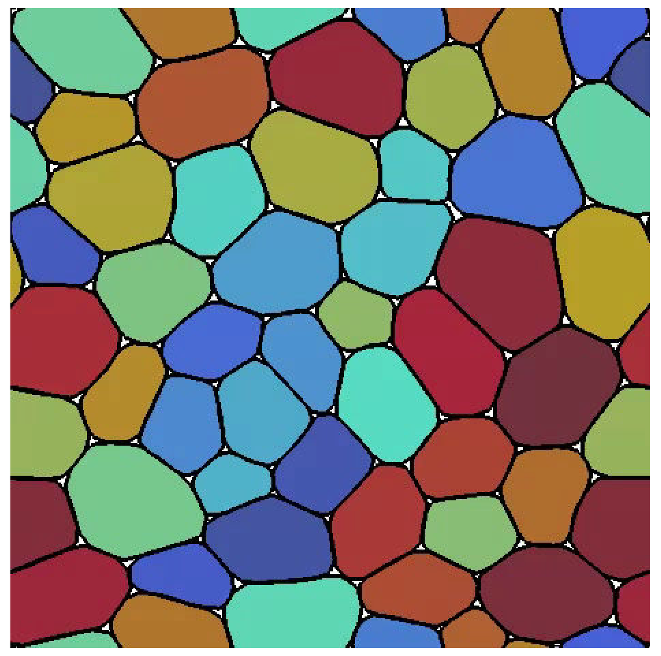
$$\ddot{l}_0^k = -\frac{1}{\mu}\frac{\partial U}{\partial l_0^k} - \frac{1}{\tau}\dot{l}_0^k$$



$$\dot{\hat{\boldsymbol{\theta}}}_n = \frac{1}{\tau_p}N(0,1)$$

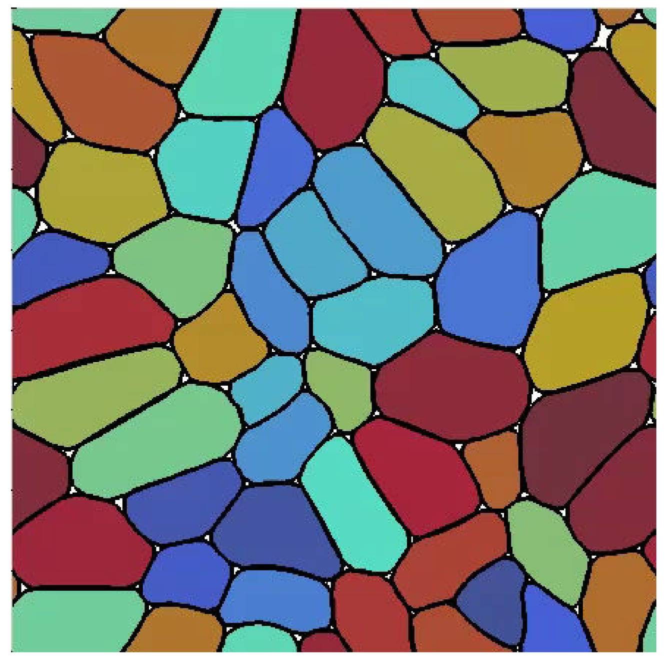
Cell Shape and Activity

Stretched



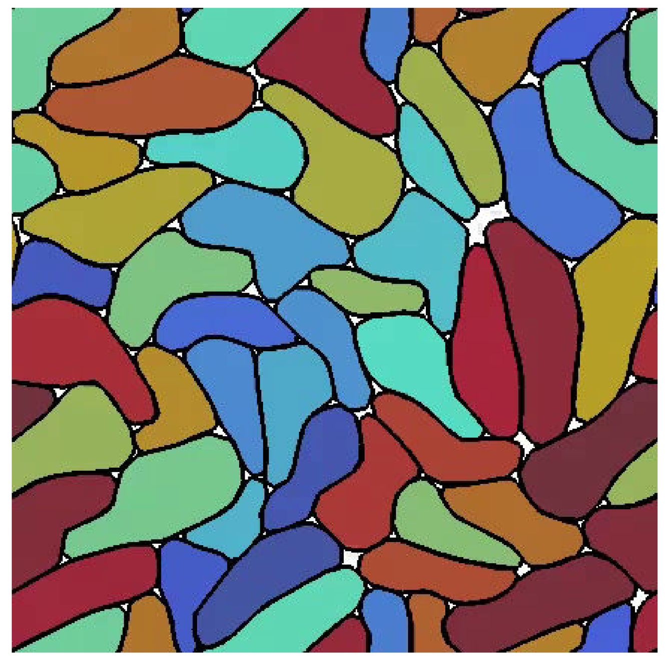
Shape Parameter:1.15

Just Right

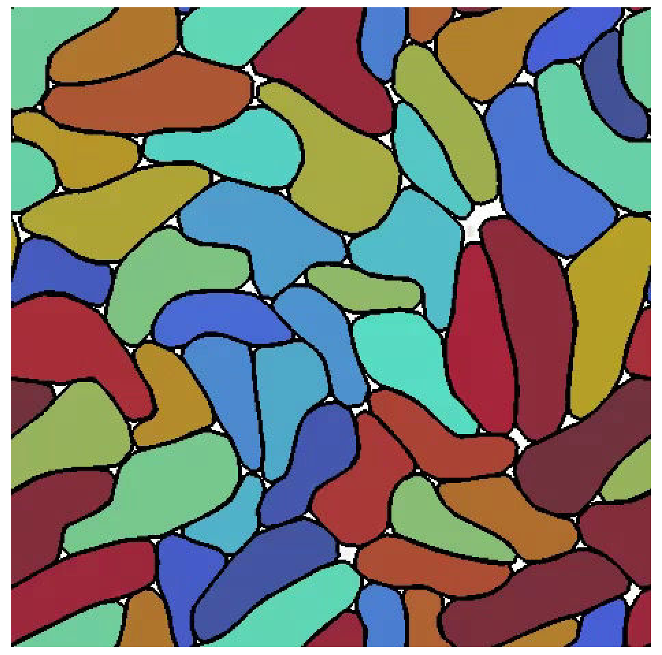


Shape Parameter:1.34

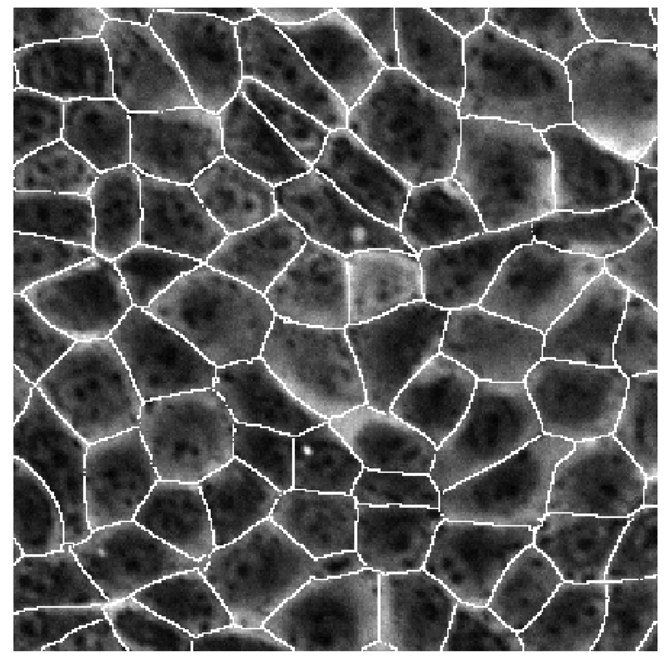
Compressed



Shape Parameter:2.00



Adaptive Shape: Broad



MDCK Cells