Image credit: Ingo Arndt

Evolutionary models of collective behaviour in animal groups

Vishwesha Guttal

Centre for Ecological Sciences

Indian Institute of Science, Bengaluru, India

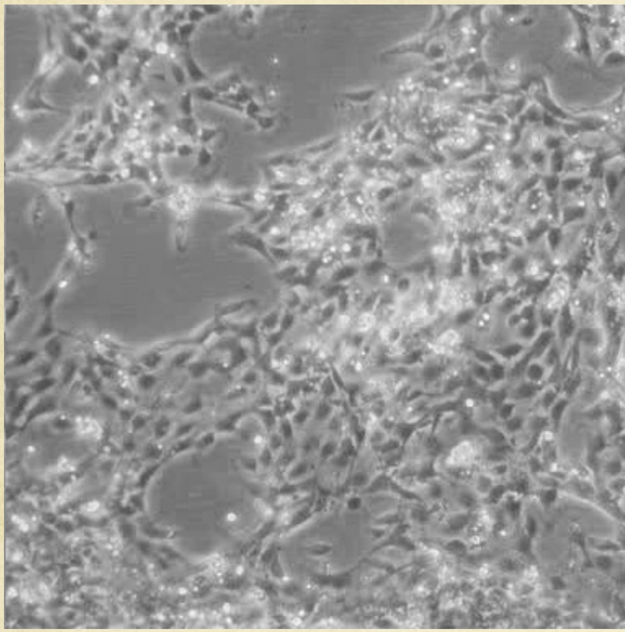
International Conference on Mathematical Modeling and Applications

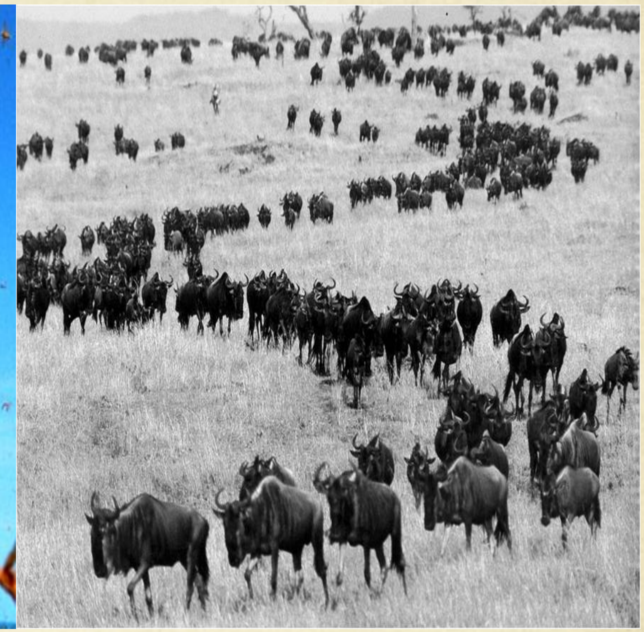
Meiji University, 26th Nov 2013

Collaborators

- Iain Couzin, Princeton University
- Christos Ioannou, Bristol
- Pawel Romanczuk, Max Planck Institute for Complex Systems
- Stephen Simpson, The Univ. of Sydney
- Gregory Sword, TAMU
- Debasish Chowdhury, IIT Kanpur
- Jaideep Joshi, IISc, Bangalore
- Many others!

Broad relevance of collective behavior



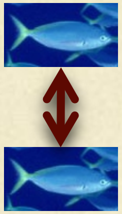


- Various disciplines:
  - Physics; Robotics; Computer Scientists;
  - Traffic organization; Human crowds; etc.

Physicists' s approach: Individuals (micro) to collectives (macro)

How do individual level interactions scale to collective patterns

Individual level interactions



Self-ordered collective motion

- System of self-driven interacting particles
  - **Agent/CA based models**: *follow average direction of particles in their neighborhood with some error/noise* (Vicsek, et al, 1995, PRL; Chowdhury et al, Phys Rep, etc).
  - **Biologically more realistic interactions:** Repulsion, attraction, alignment, information about environment (Chate et al, Couzin et al, Parrish, et al).
  - **Continuum hydrodynamic description:** universal macroscopic features (Ramaswamy, Toner, Tu, etc).

Image Credit: http://richardschwartz.files.wordpress.com/2010/07/fish-school.jpg

Why do organisms show collective movement?

Living in groups

- Why do animals live in groups?
- Tempting to say:
  - They benefit as a group.
  - Their chances of survival increases as a group.
- In evolution, all that matters is relative individual fitness but not whether the individuals/groups are optimal.

Run ***fastes***t, tiger will eat us!!!

No, I just need to run faster than you!

Image credit:
(Running) http://2.bp.blogspot.com/-Lwokg-XmBa0/TjRL-OmPn0I/AAAAAAAAAUg/F8esVnphX5Y/s1600/running%2Bcartoon.jpg
(Tiger) http://www.clker.com/cliparts/b/9/7/8/12096724699050529S2Telemachos_tiger_4x_b_w_2.svg.hi.png

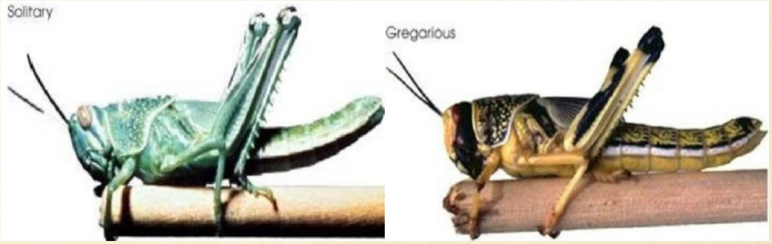
Evolution of collective behaviour

Migration and evolutionary branching of leaders and social followers

- Guttal & Couzin, 2010, PNAS
- Guttal & Couzin, 2011, Comm Integrative Biol.

Cannibalism and collective migration in insects

- Guttal et al, 2012, Ecology Letters



Predation and coordinated collective movement

- Ioannou, Guttal and Couzin, 2012, Science

Altruism and collective movement

- Joshi and Guttal, In prep.

A fusion of simulations and real animals

- Fact: *Bluegill sunfish* responds to, and tries to attack, moving dots on side of a tank.

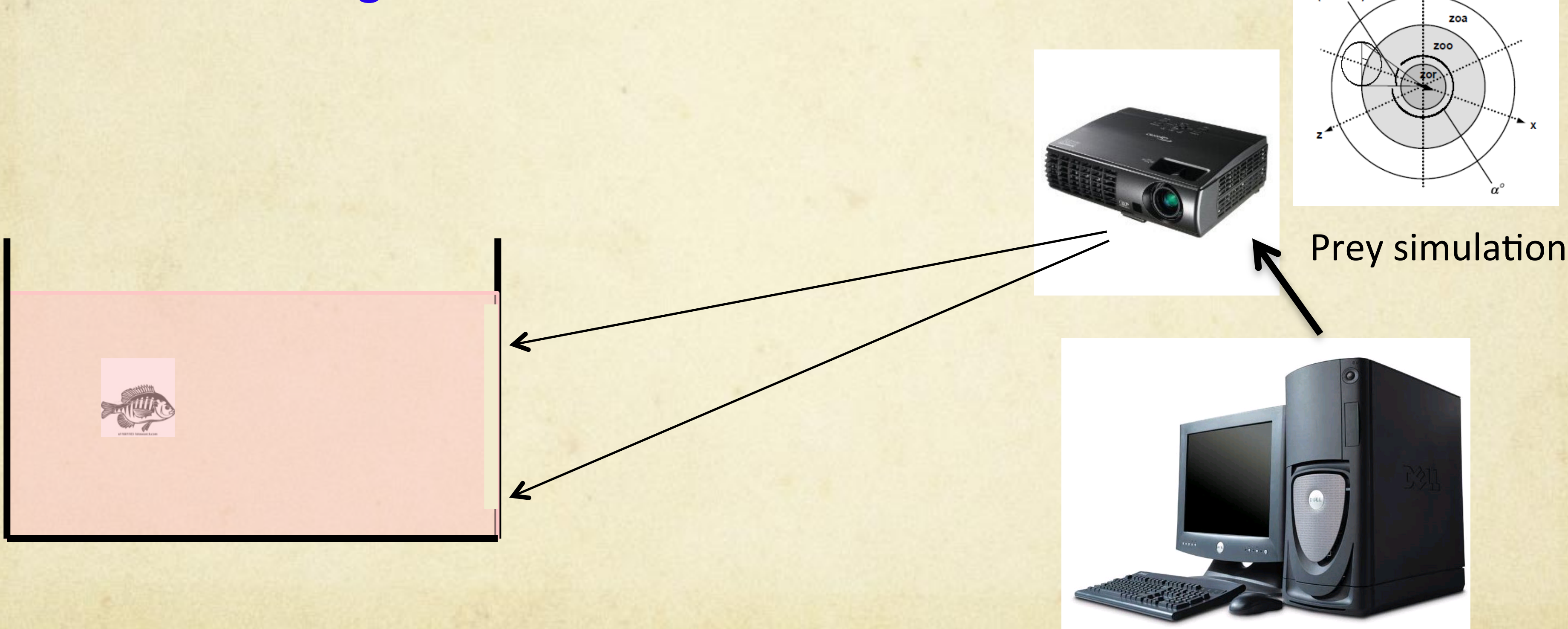


Image courtesy: Christos Ioannou and http://bplteensofwa.files.wordpress.com/2009/07/computer.jpg

Simulated prey

- Traits
  - ω_{ip} : *Persistence (lack of sociality)*
  - ω_{ia} : *Attraction*
  - ω_{io} : *Orientation/Alignment*

- Motion
  - $d_i(t+\Delta t) = \omega_{ip} * d_i(t) + \omega_{ia} * d_{ia}(t) + \omega_{io} * d_{io}(t)$

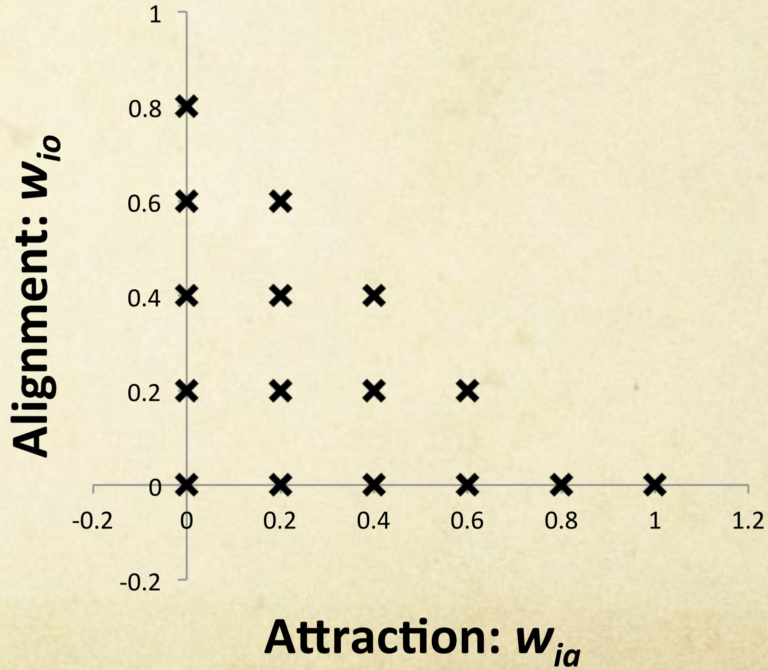
$$\sum_{j \neq i} \frac{c_j(t) - c_i(t)}{|c_j(t) - c_i(t)|} \qquad \sum_{j \neq i} \frac{v_j(t)}{|v_j(t)|}$$

  - *Plus randomness in motion.*

Simulated prey

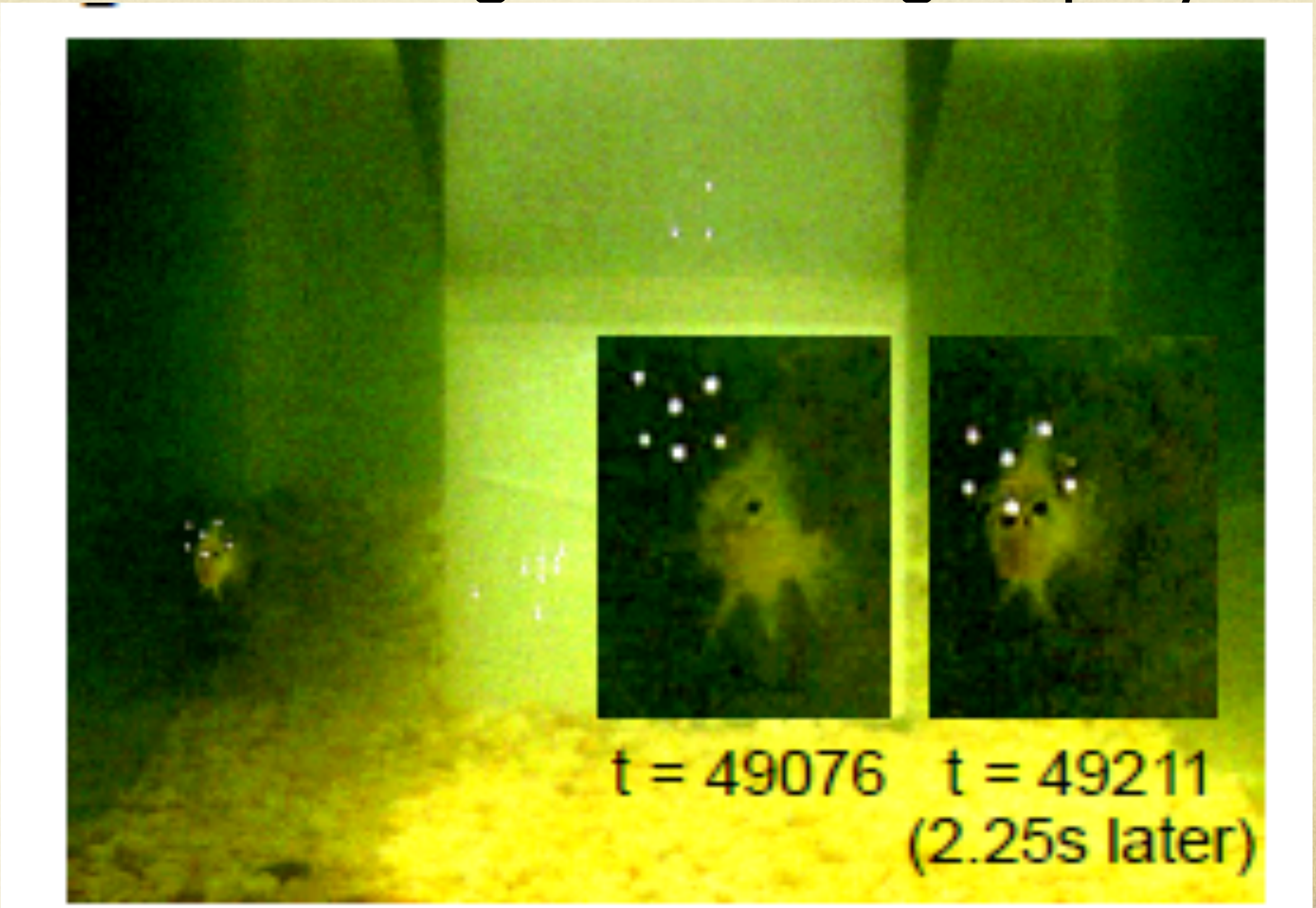
- A heterogeneous population (size 16)

- Having varying degrees of social interactions
  - Entirely solitary (random walk)
  - Strongly align with neighbors
  - Strongly attract towards neighbors
  - And a balance of the above



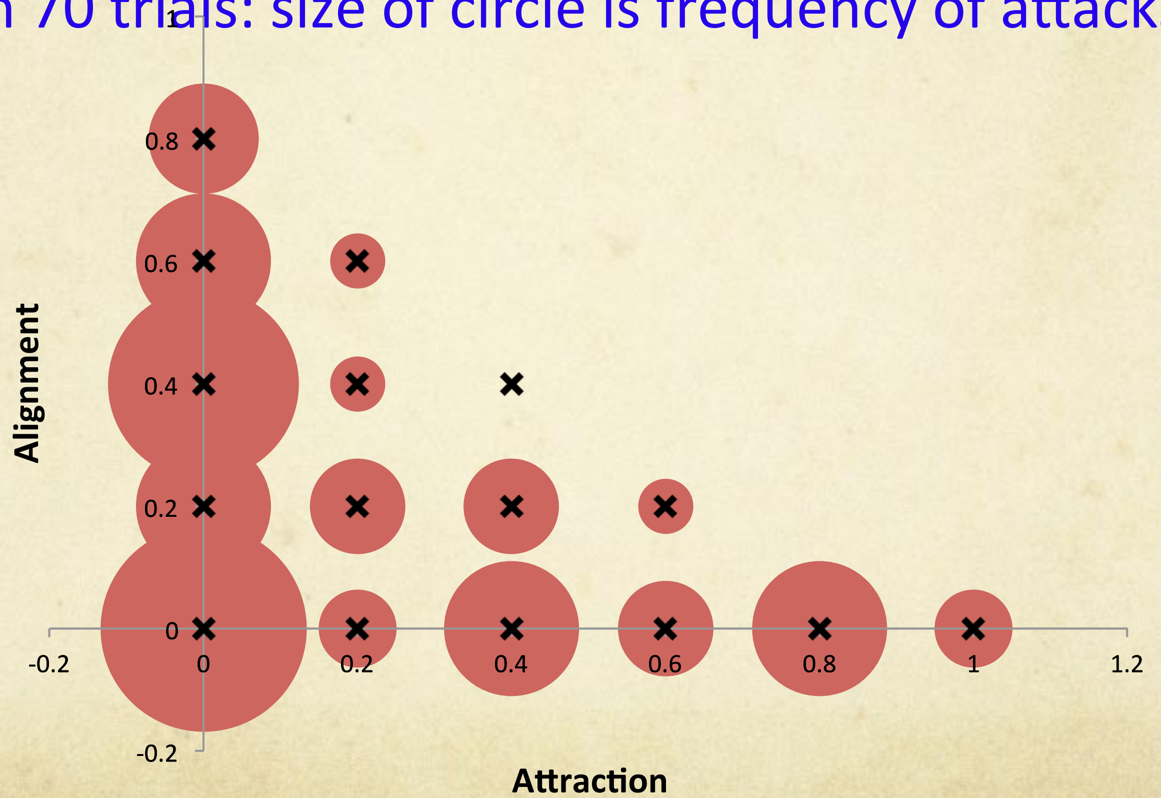
C C Ioannou, ***V Guttal*** and I D Couzin, ***Science***, 2012

Let the Bluegills attack digital prey



Analyze the data

- Identify the trait of the individual who got attacked (attraction and alignment coefficients).
- Based on 70 trials: size of circle is frequency of attacks.



C C Ioannou, ***V Guttal*** and I D Couzin, ***Science***, 2012

What causes large scale locust swarms?

- A very local phenomenon:
  - Density-dependent phase-change in locusts
  - **Solitary @ low densities**
    - Locusts are shy, solitary insects
  - **Gregarious @ at high densities**
    - Switch to gregarious behavior
    - Are attracted towards other individuals
  - **Locusts are cannibalistic**

Simpson et al, Biol. Rev., (1999);
Bouaichi and Simpson, Phys. Ent. (2003).;
Bazazi, et al, Current Biology (2008)

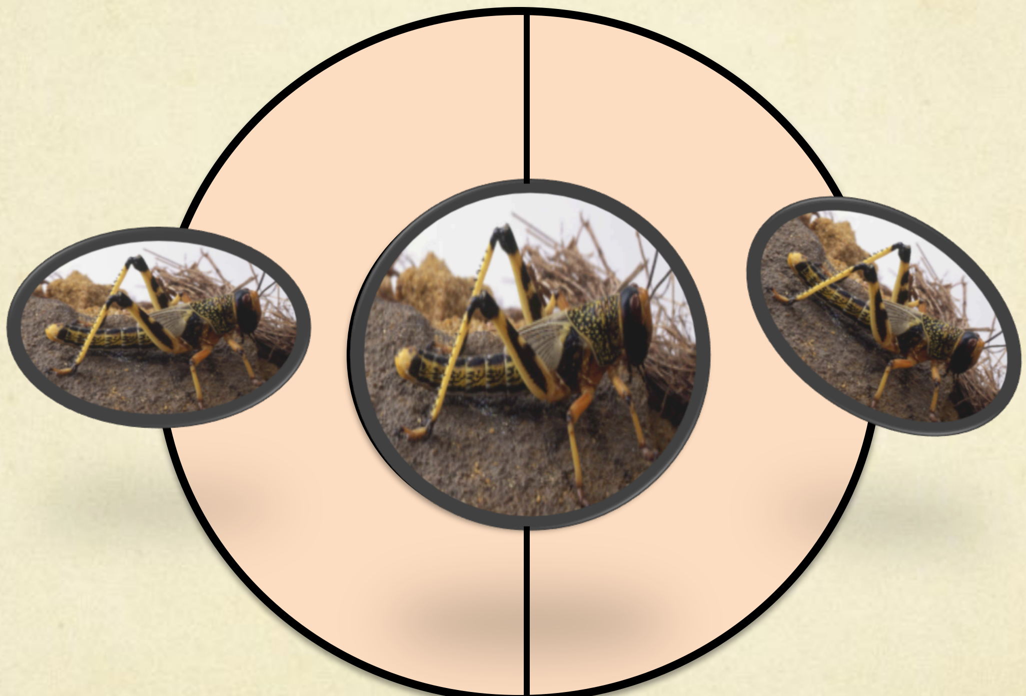
Why do locusts show phase-change and collective movement?

- **Hypothesis:** Density-dependent phase-change in locusts reduces risks of cannibalism in locusts.

Local interactions (response to neighbors movement)

ω_{ai} Response to individuals approaching

ω_{mi} Response to those moving away from you

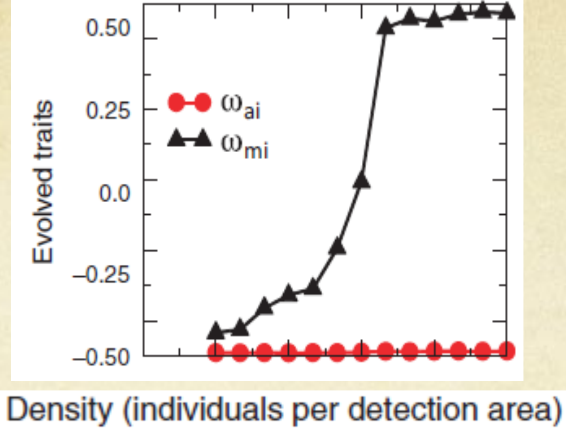


$$\mathbf{f}_{ai} = \frac{\omega_{ai}}{n_{ai}} \sum_{j \neq i} |v_{ji}| \hat{\mathbf{r}}_{ji} \quad \text{if} \quad v_{ji} < 0 \quad \text{and} \quad r_{ji} < l_s,$$

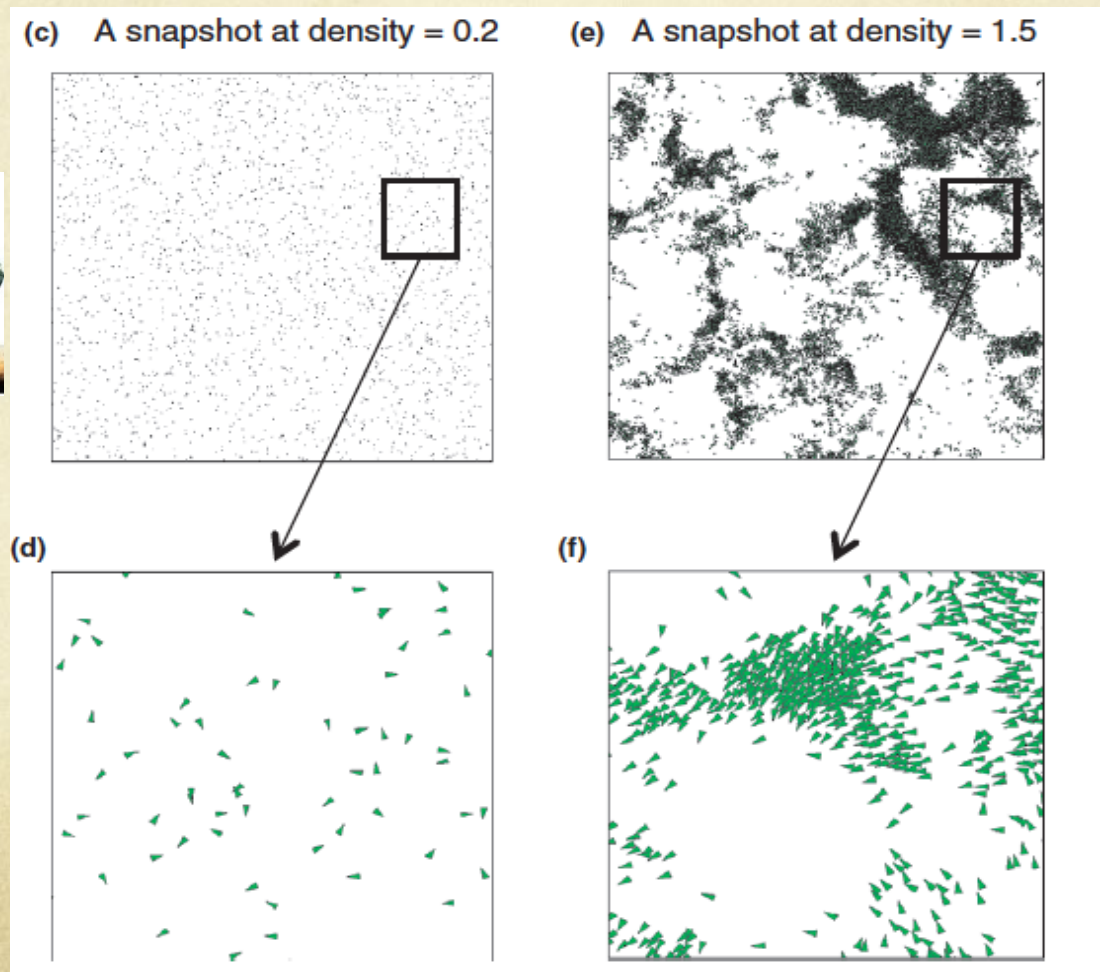
$$\mathbf{f}_{mi} = \frac{\omega_{mi}}{n_{mi}} \sum_{j \neq i} |v_{ji}| \hat{\mathbf{r}}_{ji} \quad \text{if} \quad v_{ji} > 0 \quad \text{and} \quad r_{ji} < l_s$$

Individual traits are determined by natural selection

- Recall that traits are:
  - Response to those moving away (ω_m)
  - Response to those approaching (ω_a)
- We do not predetermine what the individual traits in the population are.
- They are going to be determined by "natural selection".


0.50
0.25
0.0
−0.25
−0.50
Evolved traits
ω_{ai}
ω_{mi}
Density (individuals per detection area)


Solitary


(c) A snapshot at density = 0.2
(e) A snapshot at density = 1.5
(d)
(f)


Gregarious

Cost of cannibalism alone explain the phase change behavior in Locusts!

i.e., the phase change strategy minimizes the risk of being cannibalized for individuals.

***Guttal** et al, 2012, Ecology Letters*

Acknowledgements

- **Collaborators:**
  - Iain Couzin, Princeton Univ; Christos Ioannou, Bristol Univ. UK
  - Pawel Romanczuk, Max Planck, Germany
  - Stephen Simpson, The Univ. of Sydney
  - Gregory Sword, TAMU

- **Funding:**

  DBT, MoEF, IISc (India); DARPA, NSF (USA);

- **Thanks to all of you!**