Physical modeling of collective motion in animal groups: carrying ants

Nir Gov
Groups of animals move collectively:

Inside a flock, everyone tries to imitate/follow the others’ motion
Other examples from nature:

In order to move together, or perform any collective task, some degree of conformism is needed.

But how much?
Conformism vs Individualism

What th-! Hey, wait a minute, fellows - don't push, punk! Whose idea was this? There's gotta be a better way...

Lemming second thoughts
Conformism vs Individualism

So too much conformism is dangerous!

But with pure individualism we can not cooperate to work together

What is the optimal balance between these opposing traits?
Ants carrying load to the nest
Collaboration with the group of Dr. Ofer Feinerman (Physics of Complex Systems, Weizman)

Ofer Feinerman  Aviram Gelblum  Ehud Fonio

And my group:

Itai Pinkoviezki (PhD)  Abhijit Ghosh (former Post-doc)
Analysis of the experiments:

Frame Number: 2273
Number of Carrying Ants in Frame: 12
Number of Free Ants in Frame: 8

2 cm
The model: pullers and lifters
The big puzzle:
How do they coordinate their pulling efforts?
Role switching

The ants can decide to switch their roles, with a rate that is dependent on the local force:

\[ R_{l \rightarrow p} = K_c \exp \left( \frac{\hat{P}_i \cdot \vec{f}_{loc}}{F_{ind}} \right) \]

\[ R_{p \rightarrow l} = K_c \exp \left( -\frac{\hat{P}_i \cdot \vec{f}_{loc}}{F_{ind}} \right) \]

\( F_{ind} \) is a measure for the individuality of the ant (similar to “effective temperature”).
Individuality vs Conformism

Perfect individualism:
The ant ignores the cue from the load, and assumes either one of the two roles with equal probability.

\[ F_{\text{ind}} \to \infty \]

Perfect conformism:
The ant perfectly “obeys” the cue from the load (group forces).

\[ F_{\text{ind}} = 0 \]
This model fits well the observed dynamics (clean sheet):

We find a fitted individuality parameter
Fitted individuality parameter:

\[ F_{\text{ind}} = 10 \text{ant force} \]

Ants are not perfect conformists!

But why?

What is special about this value of \( F_{\text{ind}} \)?
Ants lose their way to the nest

Along the path, there are transient “leaders” that correct the path to the nest.
Optimal response to a single “informed” ant:

\[ \text{Response} = \langle x \rangle (\text{over the mean forgetting time 10 sec}) \]

⇒ Why is there such a peak in the response?
Equivalent 1D Ising-like model: magnetic spins

\[ \sigma_i = \begin{cases} 
-1; & \text{lifter} \\
1; & \text{puller} 
\end{cases} \]

Ferromagnetic w.r.t. own side
Anti-ferromagnetic w.r.t. opposite side
Equivalent 1D Ising-like model

\[ \sigma_i = \begin{cases} 
-1; & \text{lifter} \\
1; & \text{puller} 
\end{cases} \]

The rate of a puller becoming a lifter is \( r_{p \rightarrow l} = \exp \left( -\frac{pFf_{tot}}{F} \right) \)

The rate of a lifter becoming a puller is \( r_{l \rightarrow p} = \exp \left( +\frac{pFf_{tot}}{F} \right) \)

\( p = \pm 1 \) for back/front
Equivalent 1D Ising-like model

⇒ the occupancy of pullers/lifters is given by:

\[ n_{p/l} = \frac{\pm \sigma_i + 1}{2} \]

the total force on the load:

\[ f_{tot} = f \sum_{\text{front}} \frac{\sigma_i + 1}{2} - f \sum_{\text{back}} \frac{\sigma_i + 1}{2} \]

Calculating the mean values:

\[
\frac{\langle \sigma_i \rangle + 1}{2} = \frac{\exp\left(\frac{f_{tot}}{F}\right)}{2 \cosh\left(\frac{f_{tot}}{F}\right)}
\]

Front

\[
\frac{\langle \sigma_i \rangle + 1}{2} = \frac{\exp\left(-\frac{f_{tot}}{F}\right)}{2 \cosh\left(\frac{f_{tot}}{F}\right)}
\]

Back
Equivalent 1D Ising-like model

⇒ Self-consistent equation for the mean $f_{tot}$:

$$ f_{tot} = f \frac{N}{2} \tanh \left( \frac{f_{tot}}{F} \right) $$

Second-order transition, expand for small $f_{tot}$:

$$ f_{tot} = F_c \left( \frac{f_{tot}}{F} - \frac{f_{tot}^3}{3F^3} \right) $$

With the critical value above which there is non-zero $f_{tot}$:

$$ F_c = f \frac{N}{2} $$

⇒ the critical “temperature” scales with the system size $N$. 
The MF solution for the transition:

Calculating $f_{tot}$ and the susceptibility when $F$ is close to $F_c$ we get,

$$f_{tot} = \pm \sqrt{3F_c} \sqrt{\frac{F_c - F}{F_c}}$$

Calculating the susceptibility:

$$f_{tot} = f \sum_{i=2}^{N} \frac{\langle \sigma_i \rangle + 1}{2} \hat{p}_i + f\hat{x} = f \sum_{i=2}^{N} \frac{\langle \sigma_i \rangle + 1}{2} \hat{p}_i + B\hat{x}$$

$$\chi = \frac{\partial f_{tot}^x}{\partial B}$$

for the susceptibility, $\chi$, we get:

$$\chi = \begin{cases} 
\frac{F_c}{F_c - F} ; & F > F_c \\
\frac{F_c}{2(F_c - F)} ; & F < F_c
\end{cases}$$

Our results give the expected exponents of Landau mean field theory: $\beta = 1/2, \gamma = \gamma' = 1$. 
Fully-connected 1D Ising-like model: inherently "mean-field".

The rate of a puller becoming a lifter is $r_{p\rightarrow l} = \exp\left(-\frac{p f_{\text{tot}}}{F}\right)$

The rate of a lifter becoming a puller is $r_{l\rightarrow p} = \exp\left(+\frac{p f_{\text{tot}}}{F}\right)$

These Boltzmann factors arise from the following Hamiltonian:

$$H_i = -f \sum_{j=1}^{N} \rho_i \rho_j \sigma_i \frac{\sigma_j + 1}{2}$$
Response of the 1D spin model for short times

We consider one ant replaced by an informed ant.

The change in the average force:

\[
\frac{\delta f_{tot}(0)}{\delta t} = \begin{cases} 
  f \frac{E_c}{F} & \text{if } F > F_c \\
  f \frac{E_c}{F} \frac{1}{\cosh \left( \frac{f_{tot}(0)}{F} \right)} & \text{if } F < F_c
\end{cases}
\]
However, we cannot change $F_{\text{ind}}$ in the experiment, it is an intrinsic ant property.

So how can we probe this (finite-size) order-disorder transition?
But there is an accessible control parameter:

We can keep $F_{ind}$ constant, and vary the system size $N$:

$$\frac{\delta f_{tot}(0)}{\delta t} = \begin{cases} 
\frac{f^2}{2F} N; & N < F/f_c \\
\frac{f^2}{2F} \cosh \left( \frac{N}{f_{tot}(t=0,N)} \right); & N > F/f_c 
\end{cases}$$
Experimental validation:

But the transition is not seen directly...
Why are the ants optimized to this size range?

Constraint of size of nest entrance:
What happens when there is an obstacle?
Appearance of large amplitude oscillations
“Antulum”

Direction of nest
Will our model give such oscillations?

This is a strong vindication of the model: The ants do indeed seem to be coordinated through the forces that they feel.
Further comparisons:
The model predicts a strong dependence on the size of the system: below a critical size there are **no** oscillations.

Blue: 0.15 cm radius, 1-3 ants, Red: 0.15 cm, 3-5 ants, Green: 0.5 cm, 10 ants, Black: 1 cm, 30 ants, Pink: 4 cm, 100 ants

As we saw before: larger systems are more persistent.
For a given object the transition can be seen when the number of ants increases beyond a threshold:

Self-organization: when the object is stuck the number of attached ants can increase, thereby crossing the threshold and releasing it.
Lets analyze a simpler (1D) version of the model:

- Motion along a fixed circle (replace the tether by a rigid rod).
- The number of attached ants is fixed, their roles on each side is replaced by the mean values.
- The pull by the informed ants is a fixed (gravity-like) pull $G$. 
Lets analyze a simpler (1D) version of the model:

The total force along the ring is due to the pullers and $G$:

$$f_{\text{tot}} = f_0 n_p^+ - f_0 n_p^- - f_0 G \sin (\theta)$$

Resulting equations of motion:

$$\frac{d\theta}{dt} = \frac{v}{L}$$

$$\frac{1}{K_c} \frac{dv}{dt} = -\frac{\tilde{G}}{K_c L} v \cos (\theta) + \tilde{N} \sinh \left( \frac{v}{\tilde{F}_{\text{ind}}} \right) - 2 \left( v + \tilde{G} \sin (\theta) \right) \cosh \left( \frac{v}{\tilde{F}_{\text{ind}}} \right)$$
Results from the 1D ("antulum") model:

The system has two bifurcations:
Results from the 1D ("antulum") model:

The oscillation period increases with rod length:
The model predicts several phase transitions (or dynamical bifurcations)
And indeed this was then observed:

The oscillation transitions are manifestations of the collective behavior.
In agreement with the model:

In both experiment and theory, the speed extrema appear at ±90° which are, indeed, the locations in which the effect of the informed ants is maximized.

The direction of cycles can change over time:
The large-amplitude oscillatory mode is a form of collective problem solving:
Some of this is already published:

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Ant groups optimally amplify the effect of transiently informed individuals

Aviram Gelblum1,*, Itai Pinkoviezky2,*, Ehud Fonio1,*, Abhijit Ghosh2, Nir Gov2 & Ofer Feinerman1
Why the excitement?

Emergent phenomena exhibiting the physics of order-disorder phase transition in the collective behavior of animal groups.
People have been looking for such critical behavior in animal groups: however, no current example of a collective behavior in an animal group that goes through the transition.

Swarms of flying midges
Conclusion

• Individual “noisy” decisions, based on local (mechanical) information.

• The result is an optimal ability of the group to change its decision about which direction to choose, according to new information.
Conclusion

• When there is a conflict between the information flow (informed ants) and external constraint (tether, obstacle), new collective modes can arise.

• Some of these modes can help the group to “solve” the problem, without any individual member of the group becoming aware of it.
What can all this tell us about human society?

- A mix of conformism and individuality is good.
- Extensive spread of the information allows for a “knowledgeable” minority to share its knowledge, convince and correct a detrimental policy.
- Transient leadership.
- These properties are best maintained in a democracy.
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