CROWDS IN MOTION: HERDING, FLOCKING, SWARMING

THIRTEEN WAYS OF LOOKING AT A BOID

OR: A WALK FOR A WALK'S SAKE

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video: Robert E Fuller https://www.youtube.com/watch?v=98ZzHACTy1Q

“The blackbird whirled in the autumn winds.
It was a small part of the pantomime.”

— Wallace Stevens, *Thirteen Ways of Looking at a Blackbird* (1917)

“The boid is on the wing,
But that’s absoid—
From what I hoid,
The wing is on the boid!”

— Anonymous, *Spring Has Sprung*

photo: Søren Solkær

At six o'clock the following morning I started out for a swim, when at the foot of the laboratory steps I saw a swiftly-moving, broad line of army ants on safari, passing through the compound to the beach … Later I followed along the column down to the river sand, through a dense mass of underbrush, through a hollow log, up the bank, back through light jungle—to the outhouse again, and on a large fallen log, a few feet beyond the spot where their nest had been, the ends of the circle *actually came together*! It was the most astonishing thing, and I had to verify it again and again before I could believe the evidence of my eyes. It was a strong column, six lines wide in many places, and the ants fully believed that they were on their way to a new home, for most were carrying eggs or larvæ, although many had food, including the larvæ of the Painted Nest Wasplets … Careful measurement of the great circle showed a circumference of twelve hundred feet … All the afternoon the insane circle revolved; at midnight the hosts were still moving, the second morning many had weakened and dropped their burdens, and the general pace had very appreciably slackened. But still the blind grip of instinct held them. On, on, on they must go!

—William Beebe, *Edge of the Jungle* (1921) *image*: TC Schneirla (1944), American Museum Novitates, 1253, 1-26.

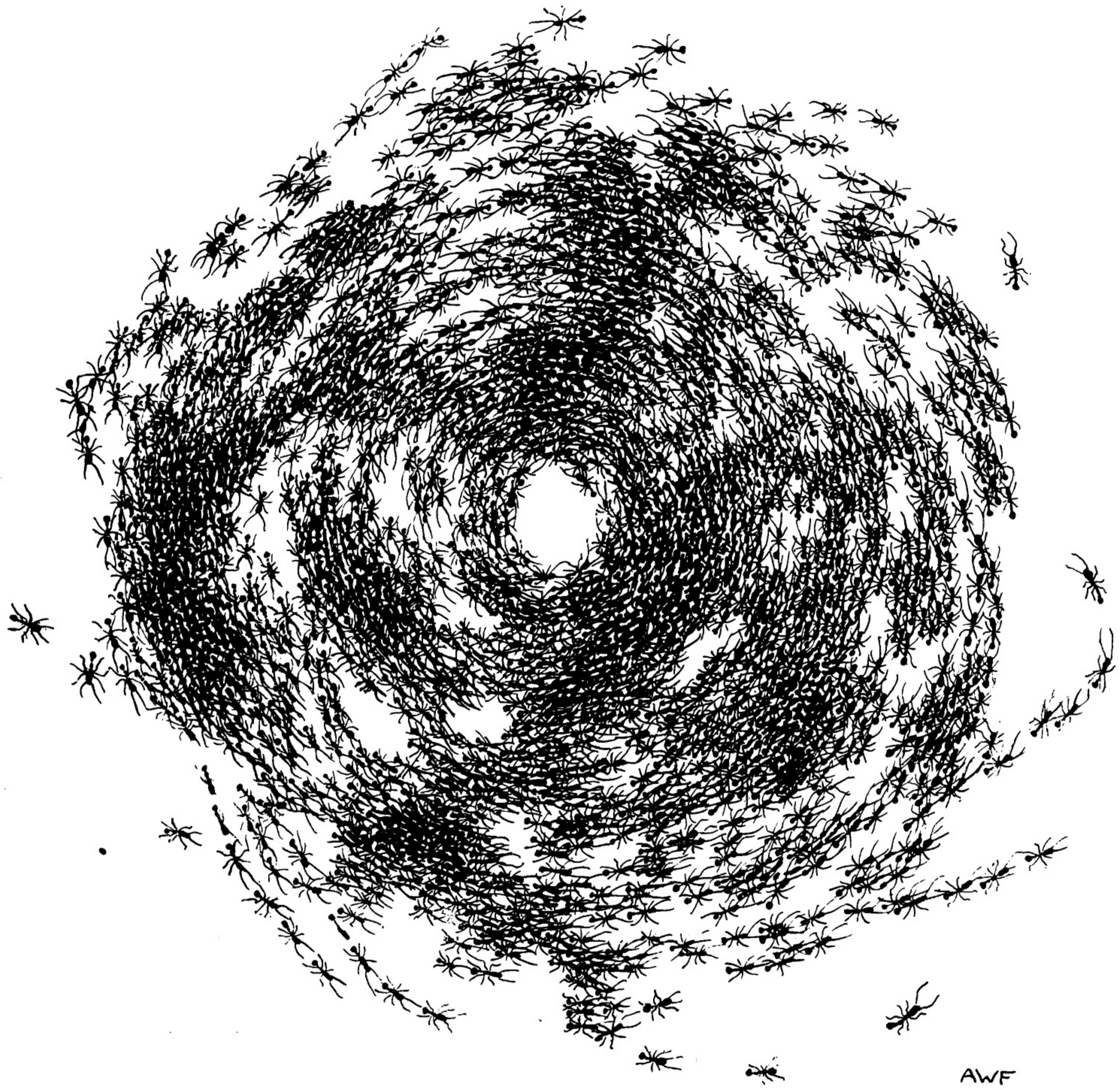


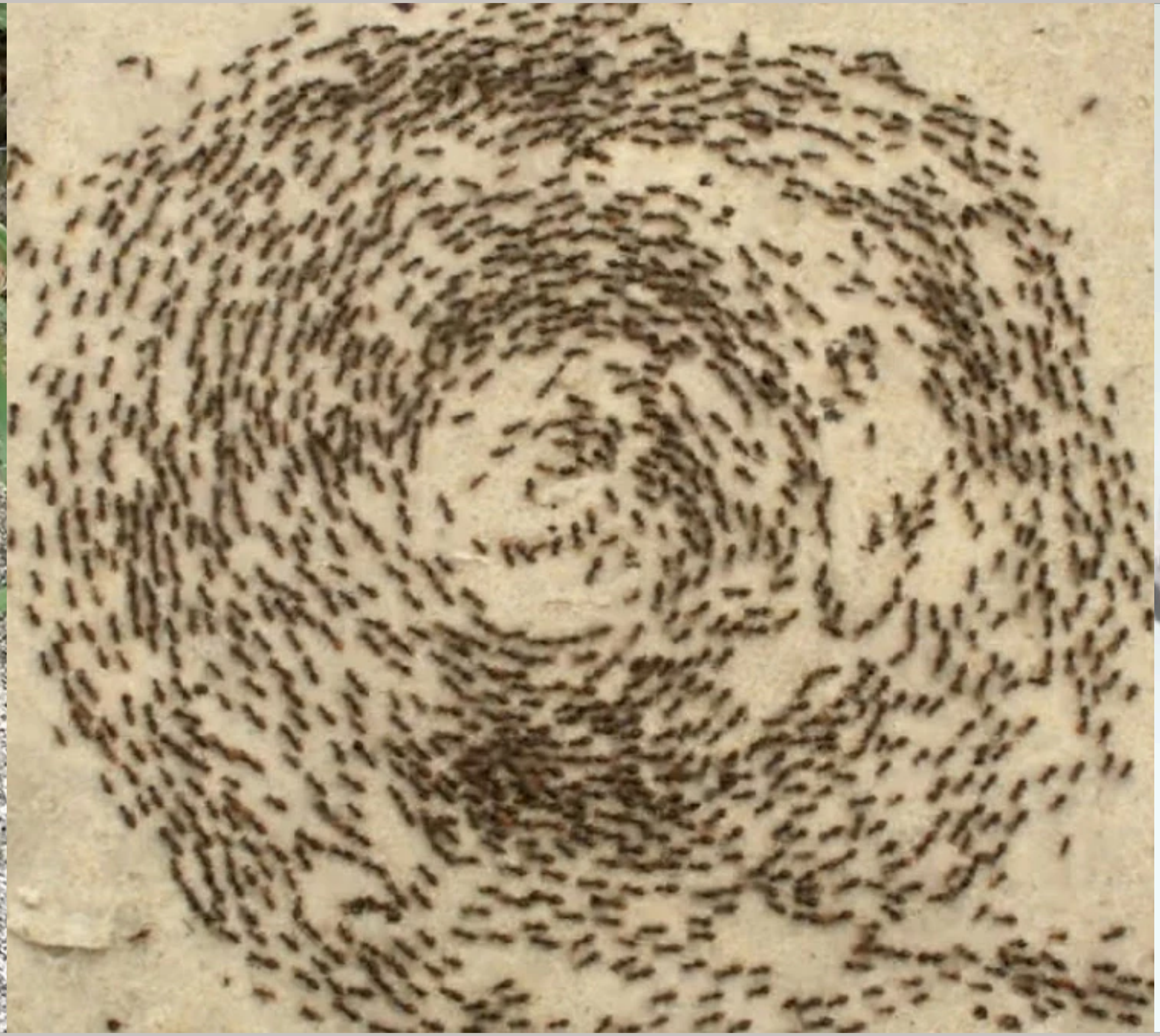
Fig. 1. The circular column of *Eciton praedator*, as drawn from a photograph taken shortly before 12:00 P.M. At that time the ring was approximately 14 cm. in diameter.

ANT MILLS

- These are large vortex formations observed primarily in army ants, such as *Eciton burchellii*.
- These ants are usually blind and forage with the help of pheromones.
- If some ants deviate from the trail and accidentally rejoin it at a earlier position, this can lead to a closed loop.
- Ants in the mill persist until they (usually) die of exhaustion.
- It has been argued (Brady, 2003) that the reason for this is that, unlike almost all other ant species, army ants exhibit obligate collective foraging, and have done so for over 100 million years.

Multiple species display similar sorts of collective motion

Processionary caterpillar circle



Ant mill

Reindeer cyclone

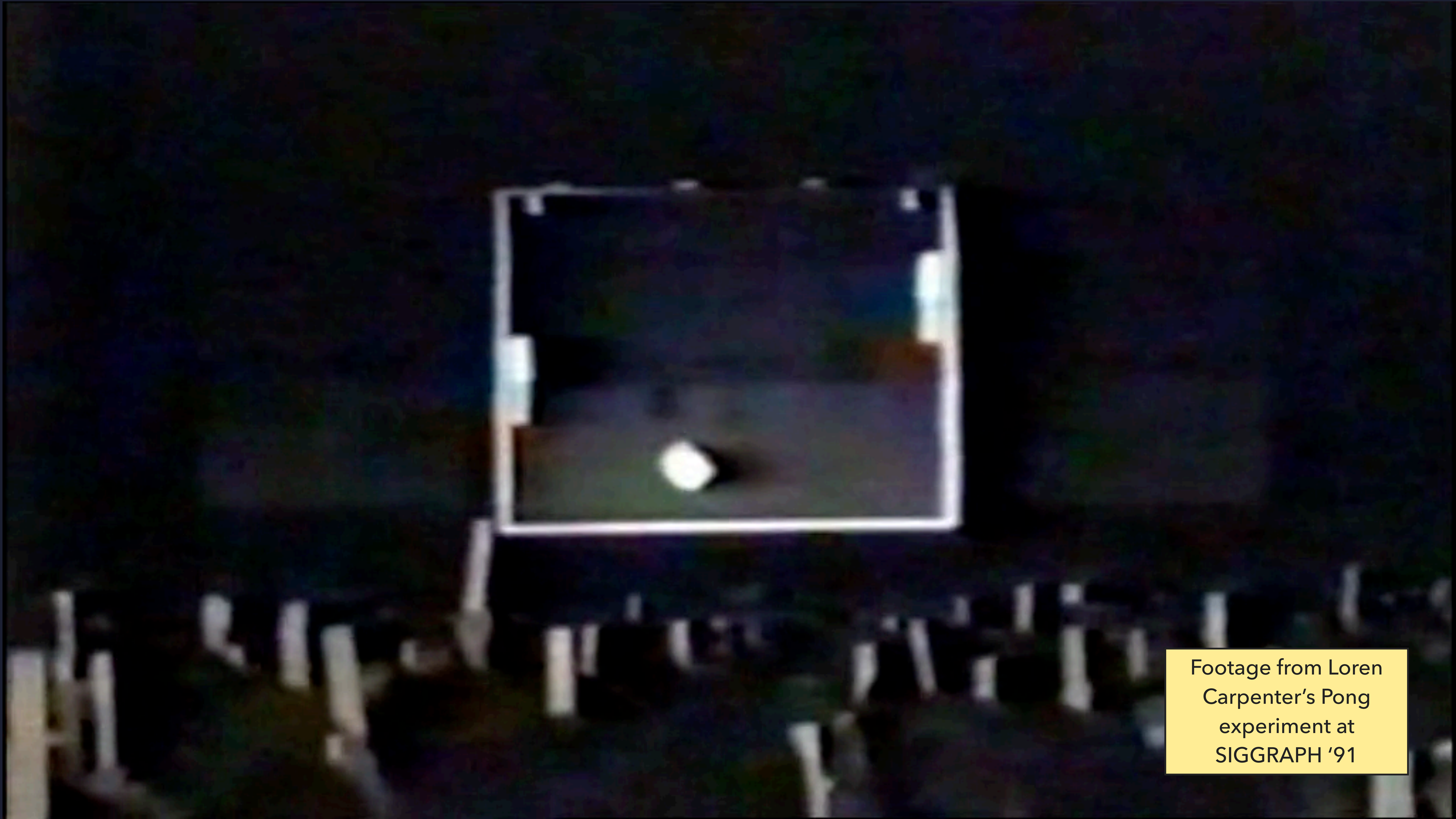
images: [L] Yahoo News, [M] India Today, [R] https://www.youtube.com/watch?v=HOr8I0rh0hE

- Collective motion: motile properties of individuals (directional bias, speed, etc) show some degree of correlation as a result of interactions.
- It is an emergent phenomenon seen over a vast range of length scales across the living world.
- These phenomena lie at the cross section of complexity science, behaviour, ecology, condensed matter physics, computer science, social science, and more!

video: STV News https://www.youtube.com/watch?v=yCI_3Y0Nv78

BUT FIRST… A SHOW OF HANDS?

...OR PERHAPS A GAME OF PONG?



Footage from Loren Carpenter's Pong experiment at SIGGRAPH '91

image: https://ronmitchelladventure.com

...AND ALSO INFORMATION FROM THEIR NEIGHBOURS!

MEMBERS OF FLOCKS MAKE DECISIONS USING INFORMATION FROM THEIR ENVIRONMENT...

GIF from "The Jungle Book" (1967)

REASONS TO FLOCK: PREDATION AVOIDANCE

- Individuals minimise their "zone of danger" by attempting to move to gaps within neighbouring groups (Hamilton, 1971).
- Due to a "dilution effect" the likelihood of being a victim in an attack is reduced (Foster & Treherne, 1981).
- Herding can induce a "confusion effect" in predators (Landeau & Terborgh, 1986).

video: BBC Earth https://www.youtube.com/watch?v=okacULqnDDQ

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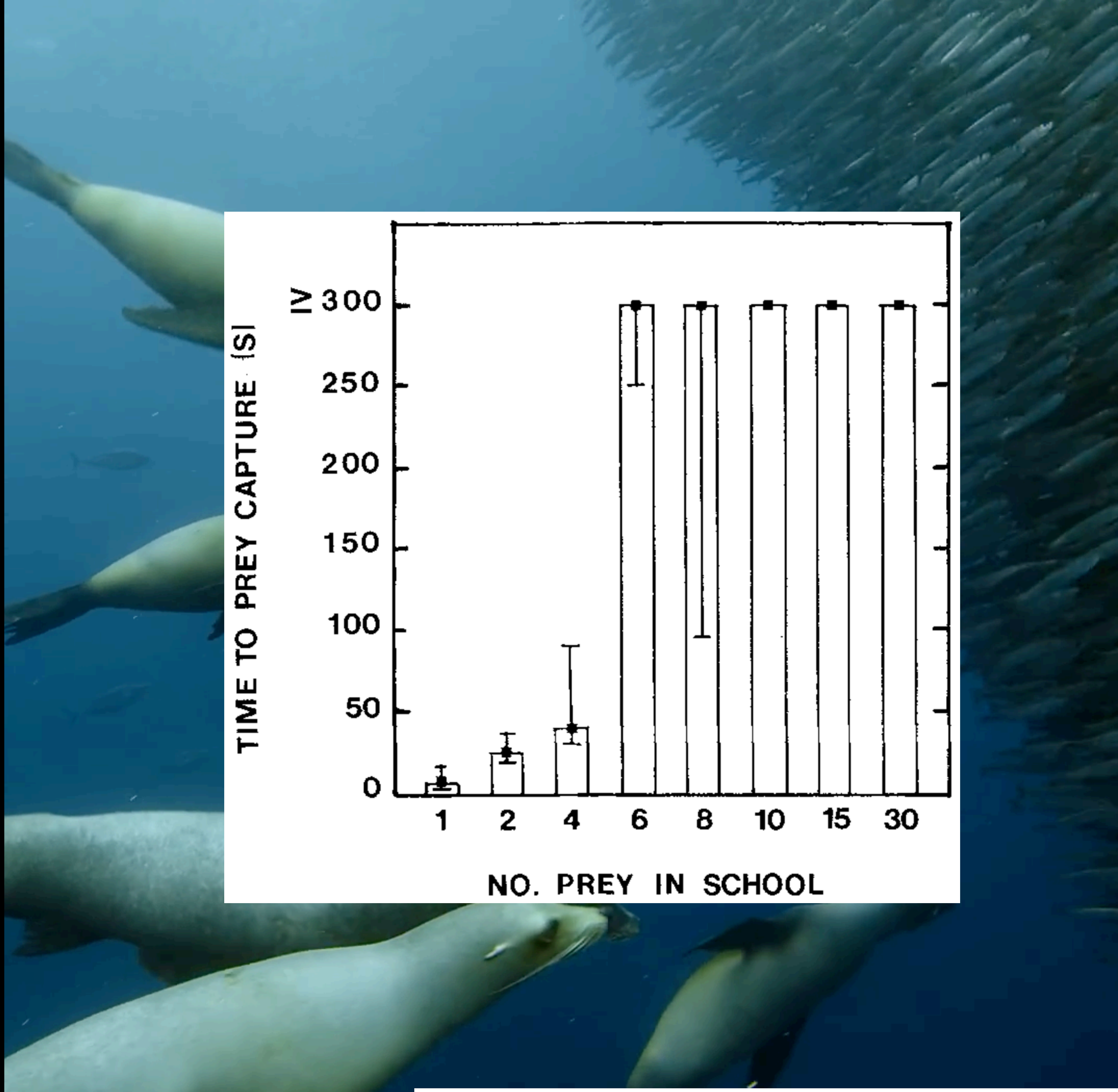

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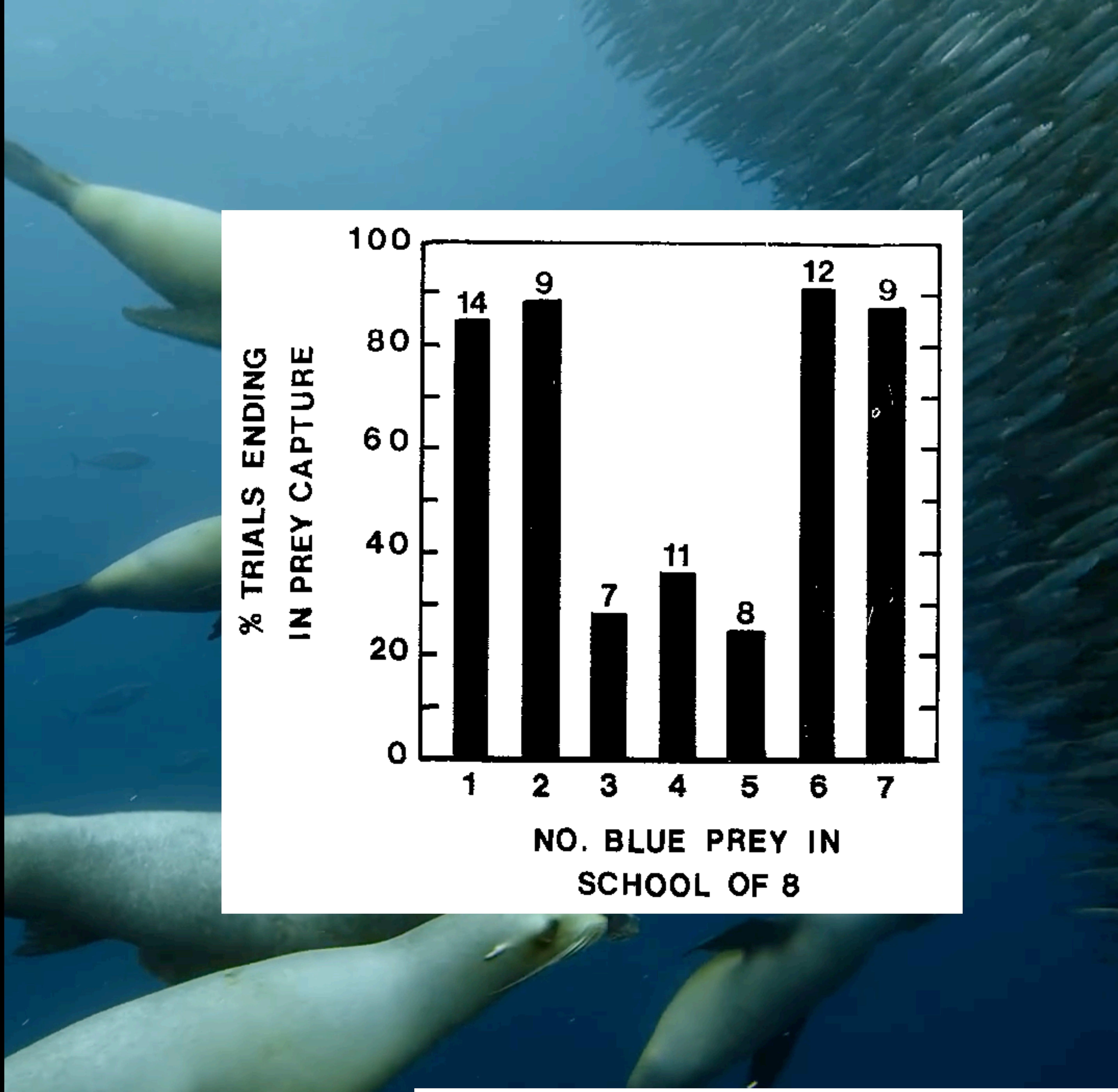

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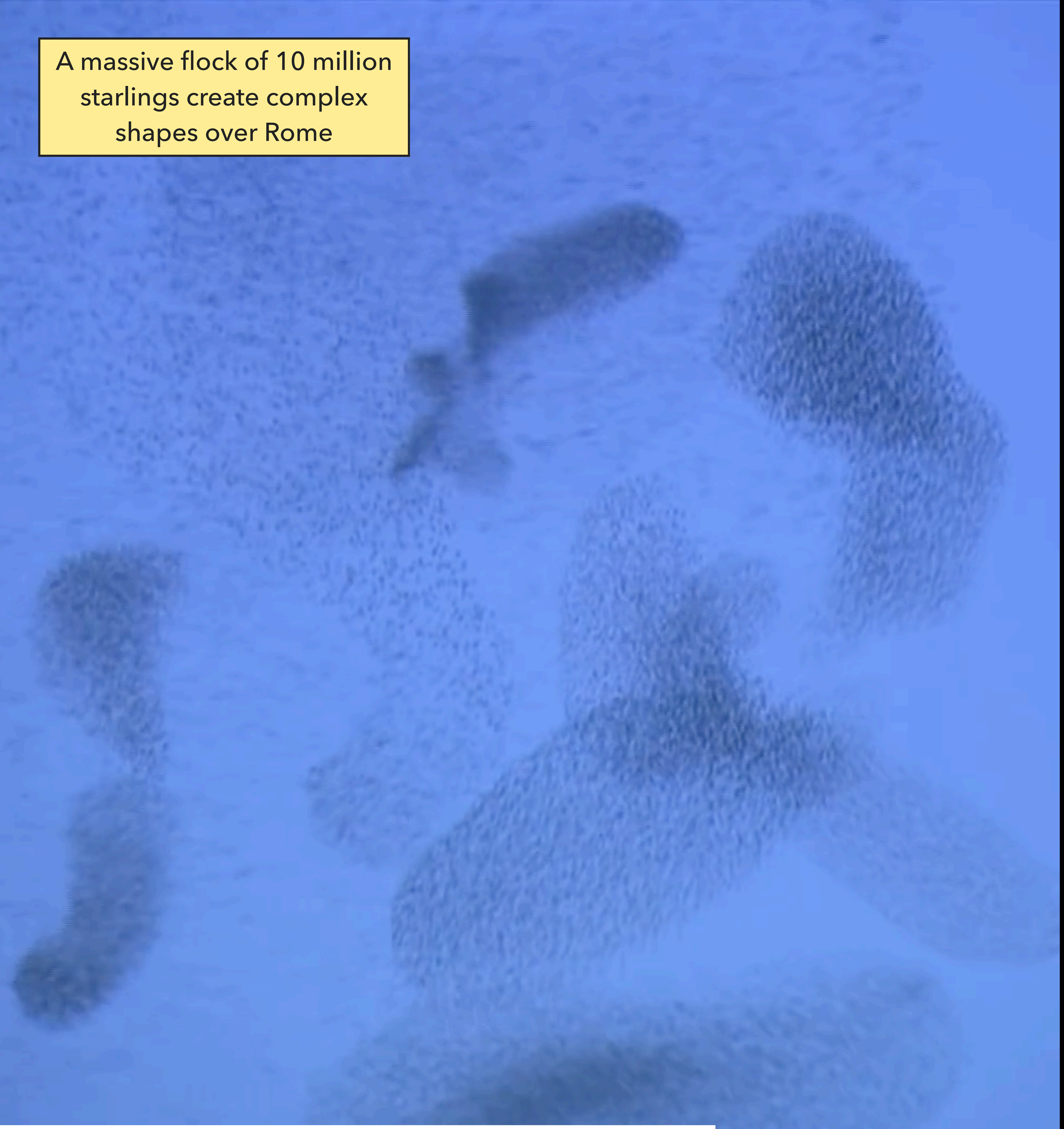


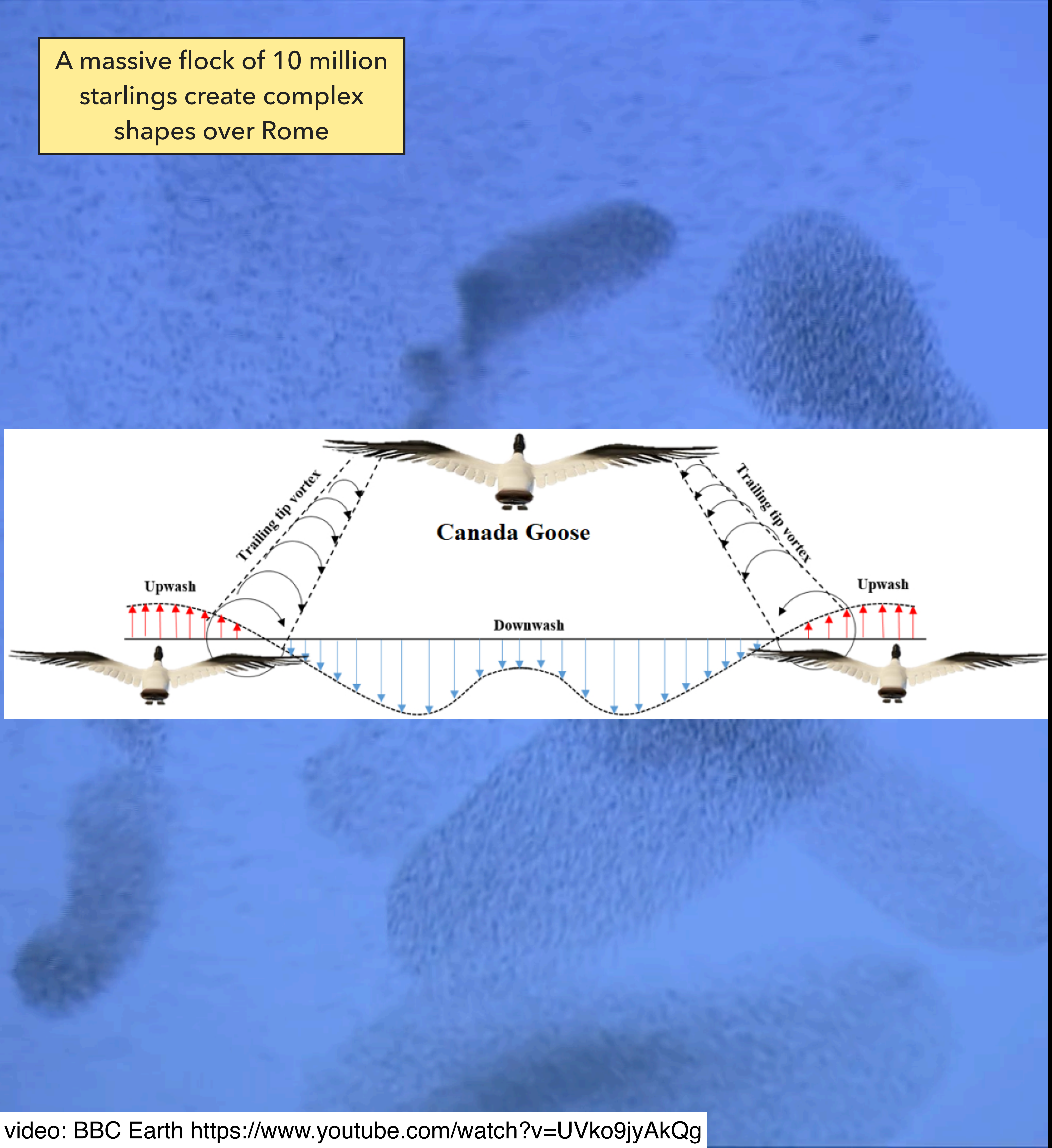
video: BBC Earth https://www.youtube.com/watch?v=UVko9jyAkQg

REASONS TO FLOCK: AERODYNAMIC BENEFITS

- Flying in the upwash of the wingtip vortex of the bird in front can massively reduce the effect of drag and increase efficiency (Lissaman & Shollenberger, 1970).
- This was conclusively demonstrated in 2014 by Portugal et al., who showed that birds actively flap in phase or in anti-phase, depending on their location, to save energy.

image 1: A Mirzaeinia et al. *Swarm. Intell.* **14**, 117–141 (2020).

image 2: Portugal et al. *Nature* **505**, 399–402 (2014)



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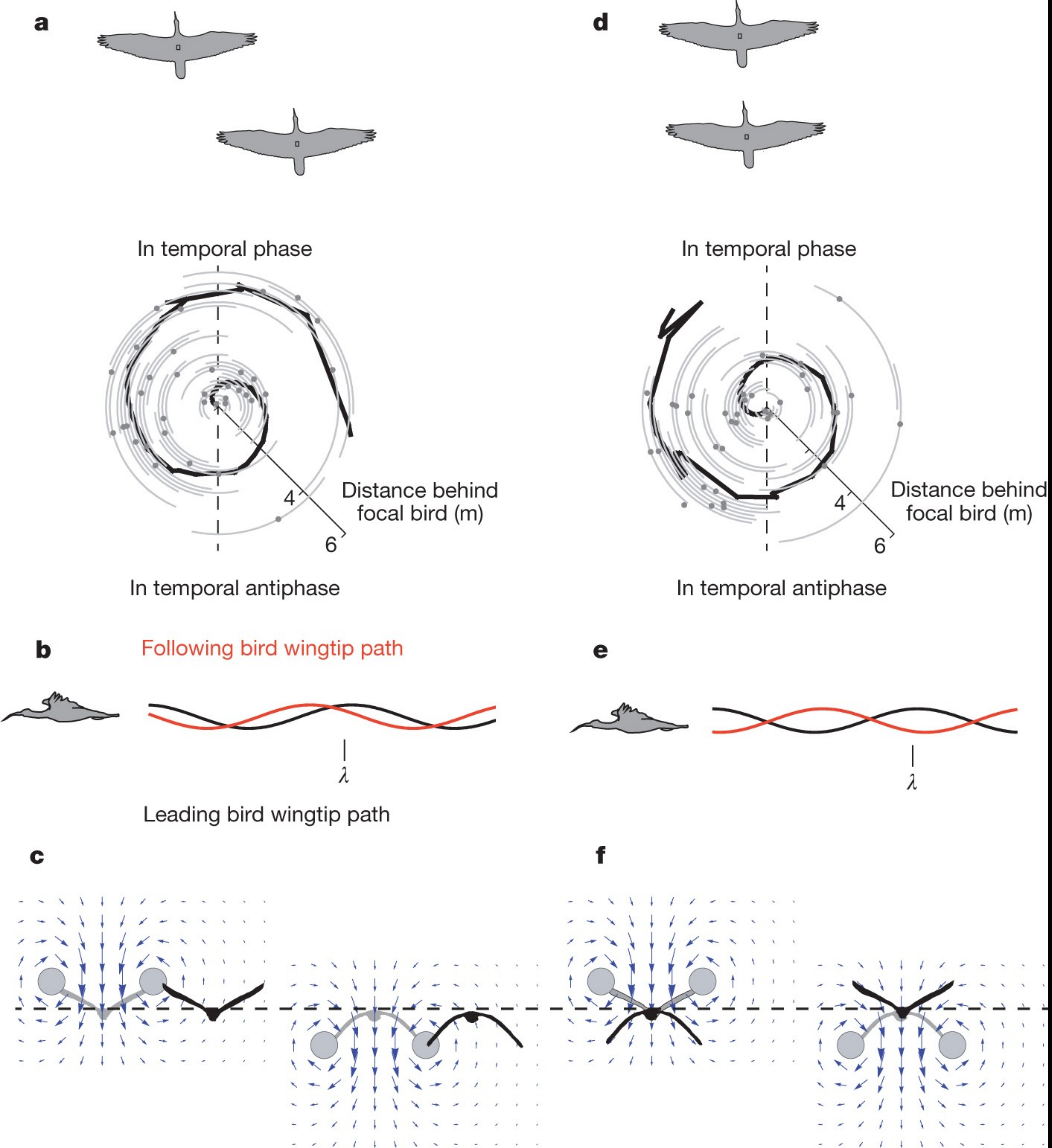

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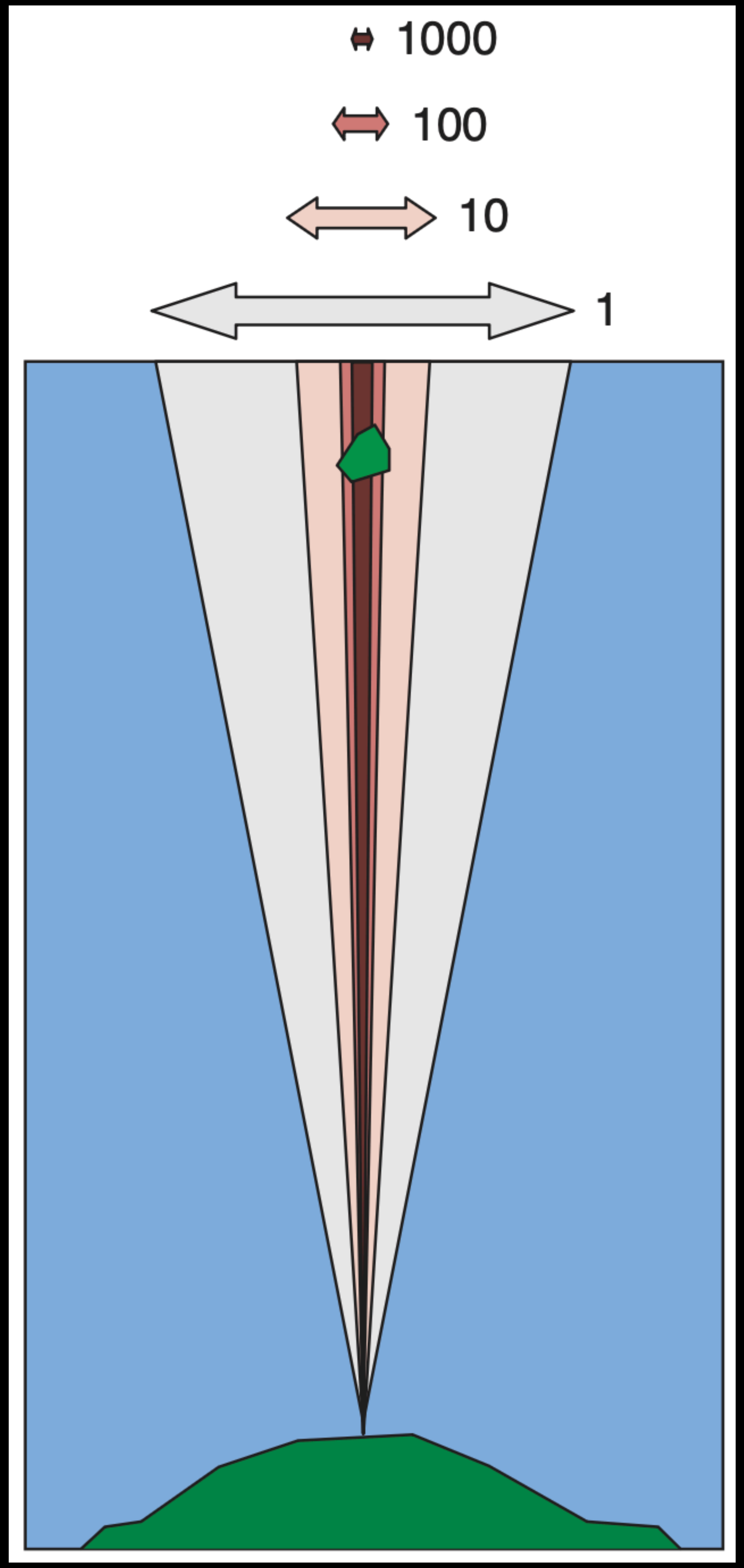
SOME FURTHER REASONS

- Improved navigational accuracy ("many wrongs principle", Bergman & Donner, 1964).
- Some species, such as penguins, move in a coordinated huddle to maintain body temperature (Zitterbart et al., 2011).

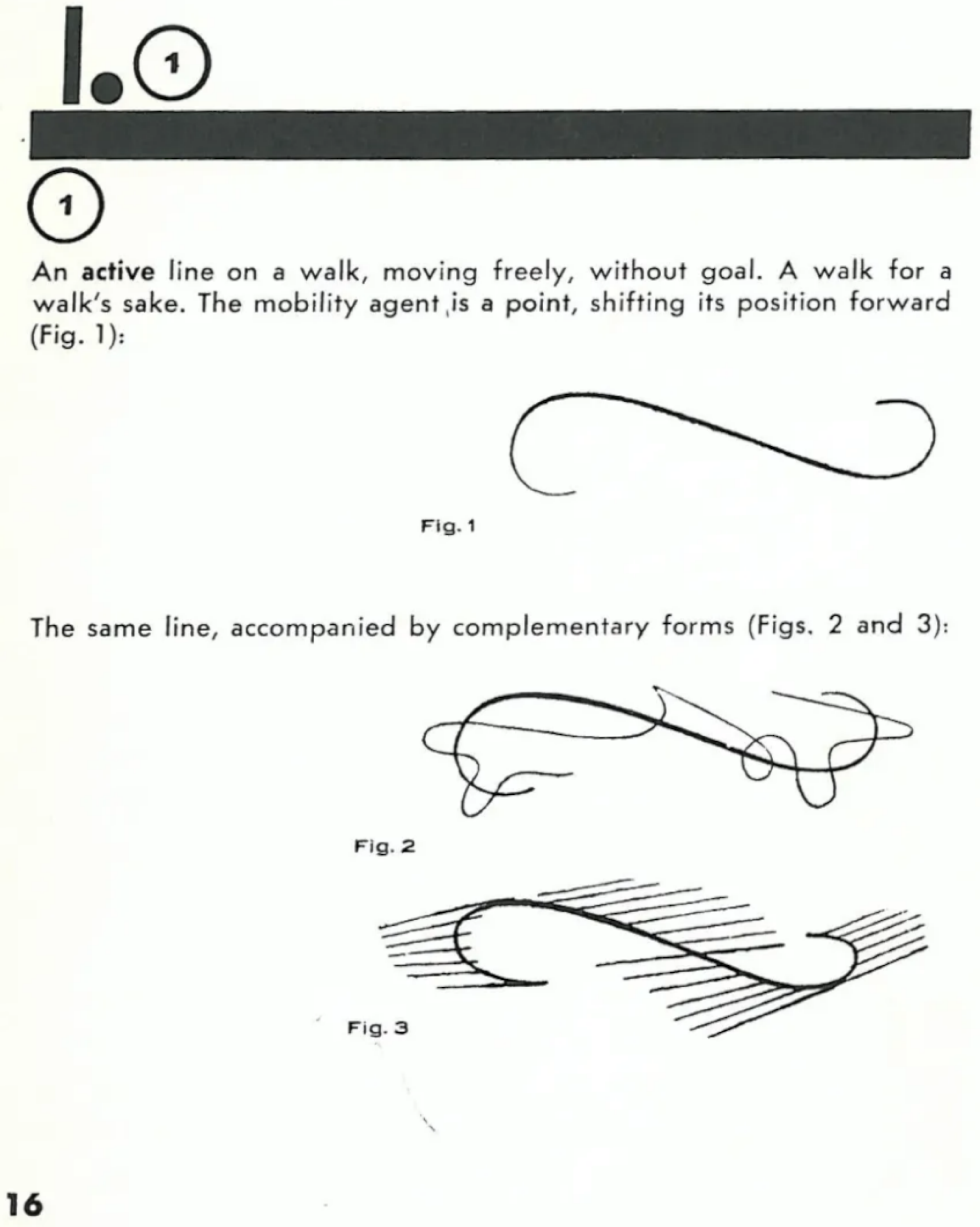


video: Zitterbart et al. (2011)

WHY STUDY FLOCKING?

- Predicting global displacements of fish schools.
  - How might climate change affect migratory patterns?
- Preserving the biodiversity of migrating birds or mammals.
  - How can we design better conservation corridors?
- Minimizing fatalities during crowd panic.
  - How can we design better stadiums and enclosed public spaces?
- Understanding the role of leadership/heirarchy.
  - Can collective decisions be made in a decentralised manner?
- Uncovering underlying laws that hold across scales.
  - Can the same principles help explain both cell migration and murmuration?

photo: Enric Sala, National Geographic *source*: Paul Klee, *Pädagogisches Skizzenbuch (Pedagogical Sketchbook)* (1924).


I. 1

1

An **active** line on a walk, moving freely, without goal. A walk for a walk's sake. The mobility agent is a point, shifting its position forward (Fig. 1):

Fig. 1

The same line, accompanied by complementary forms (Figs. 2 and 3):

Fig. 2

Fig. 3

16

SIMULATING FLOCKS

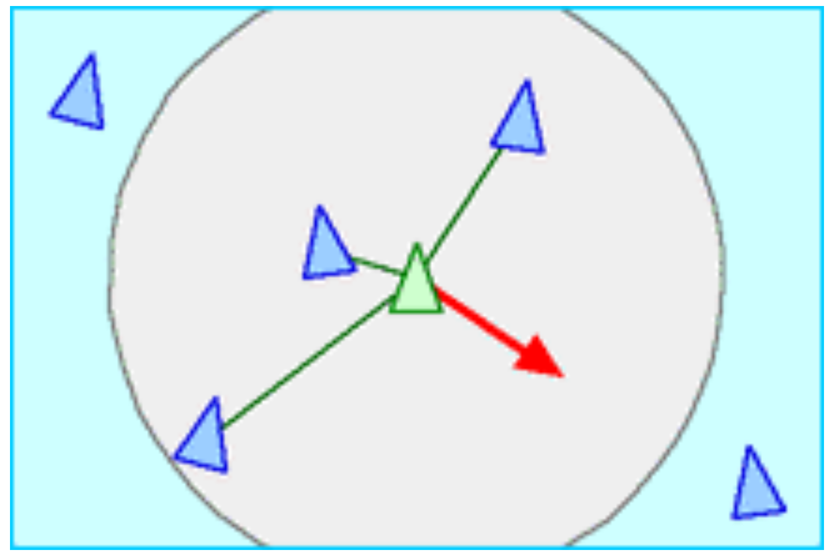
- Flocking/Herding involves a complex interplay between information processing, decision-making and locomotion. How does one even begin to capture it?!
- In the spirit of Newton, we assume a *spatium absolutum* and generate "objects" *ex nihilo*.
- The objects are elementary motile units that, to quote Klee, take "a walk for a walk's sake". Unless specified otherwise they have no goal.
- The interactions between these objects, as well as between objects and the surrounding environment, give rise to collective dynamical behaviours that can qualitatively recapitulate empirical observations.

C. W. Reynolds, *Comput. Graphics* **21**, 25 (1987).

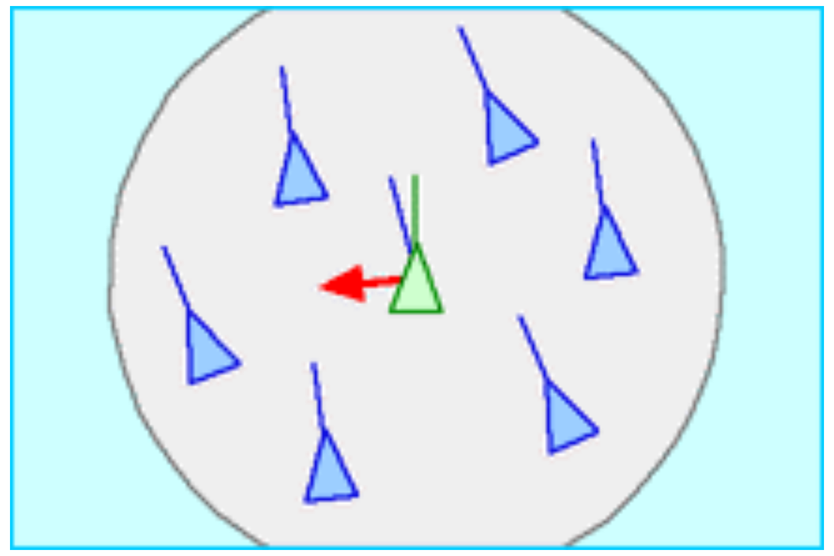
BOIDS

- In 1986, Craig Reynolds developed an algorithm for coordinated animal motion for a system of agents (known as “bird-oids” or “boids”).
- At every point in time, each boid surveys its neighbourhood and notes the **positions** and **directions** of all other boids within it.
- The boid then updates its direction of motion by combining multiple *steering behaviours*: core flocking rules, obstacle avoidance and target seeking.

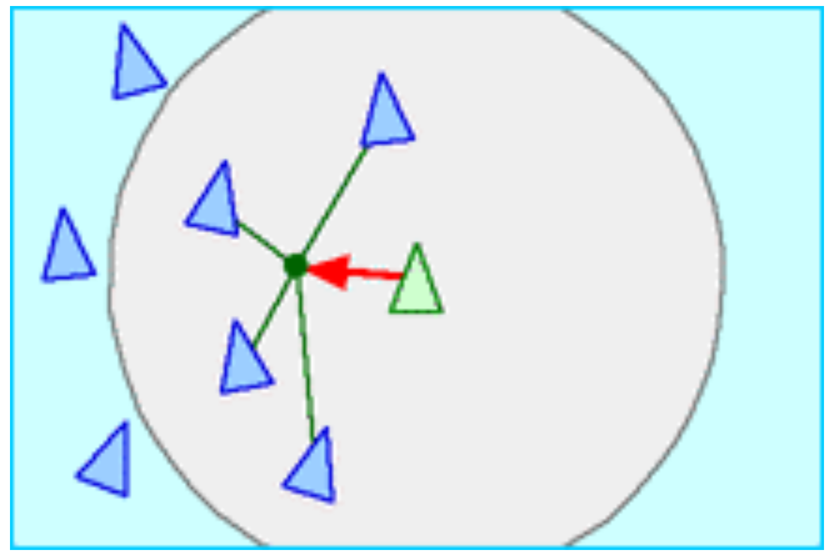
Core flocking rules



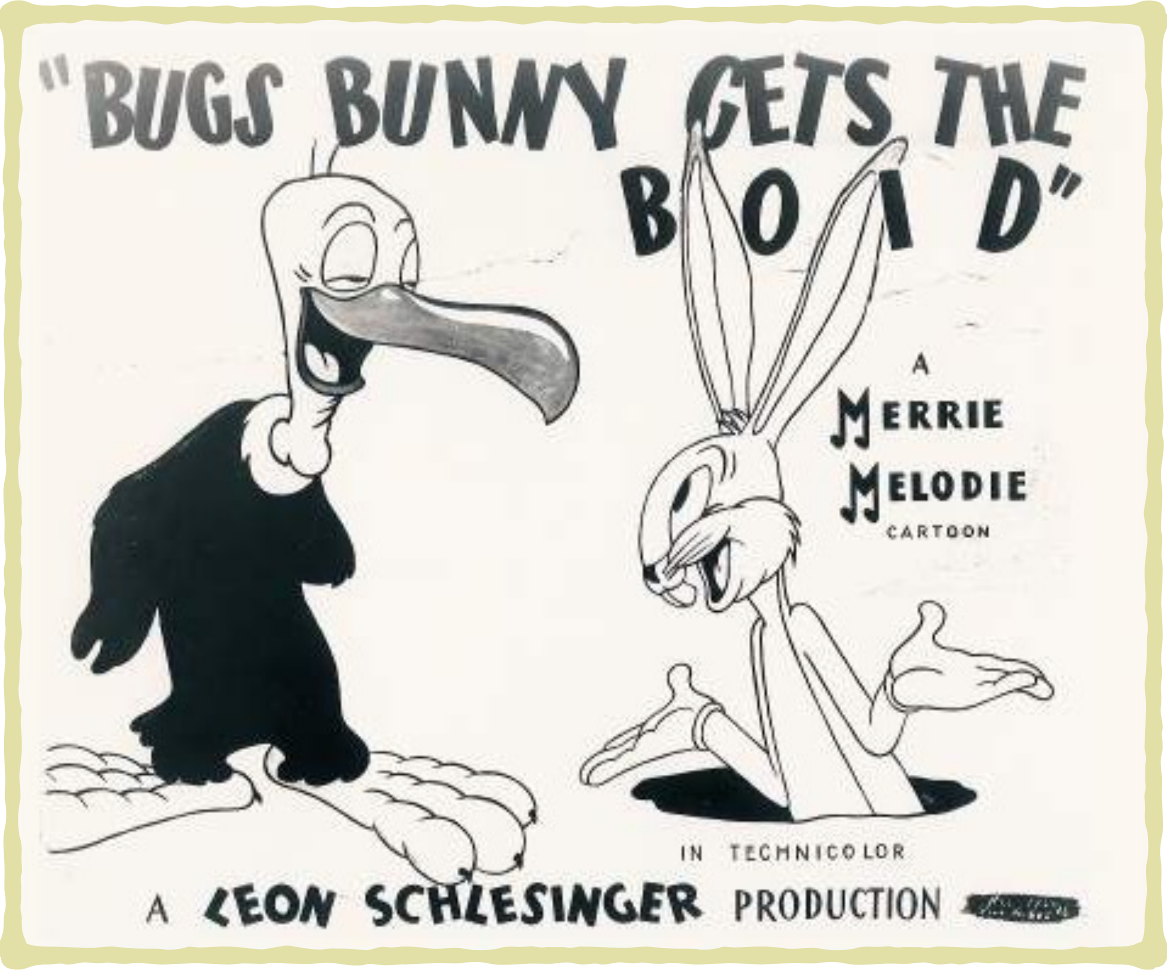
Separation



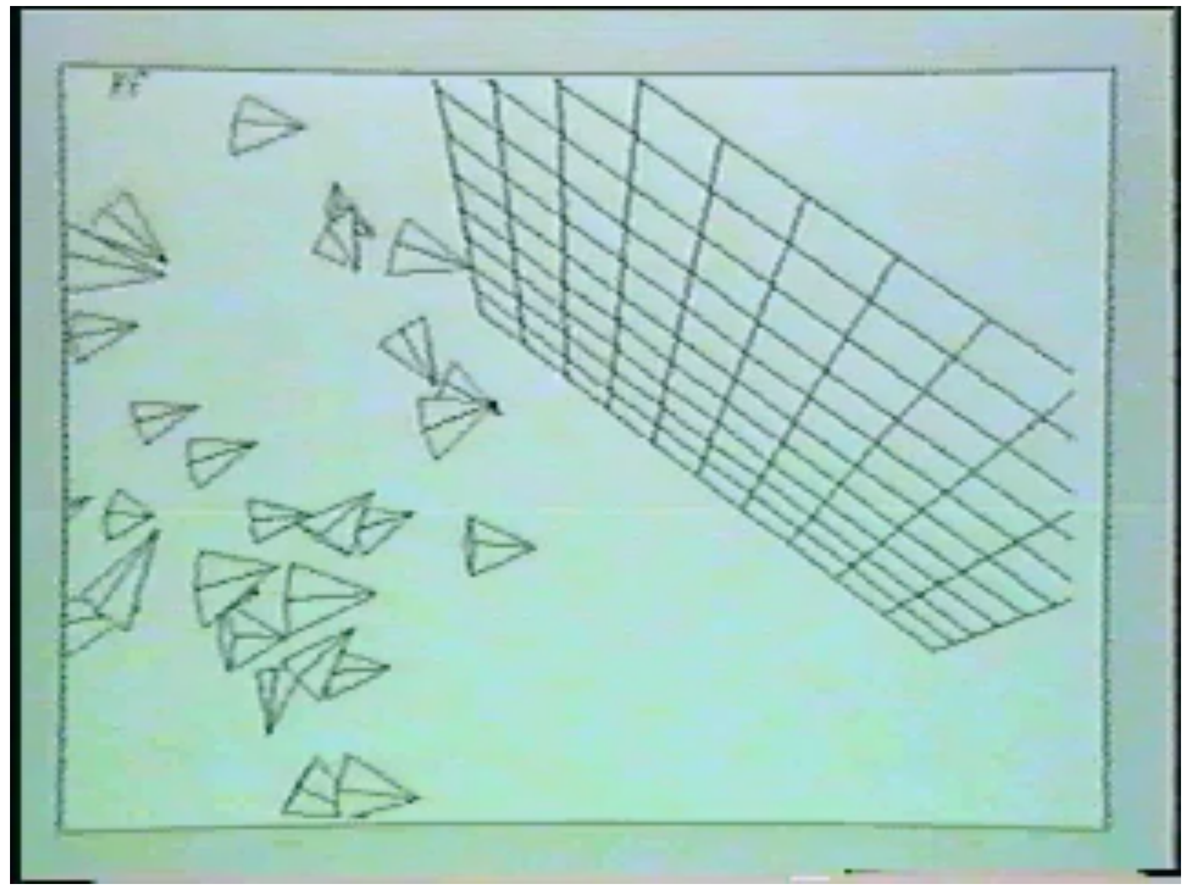
Alignment



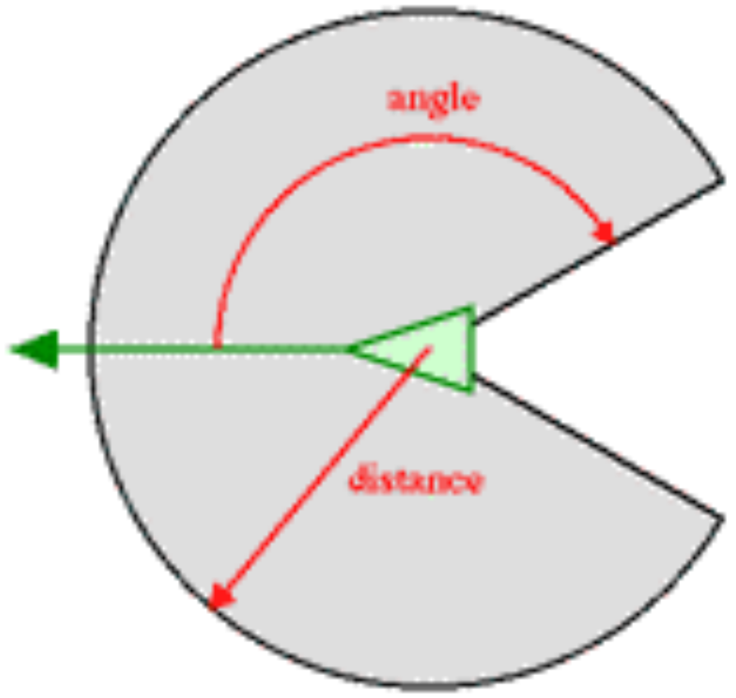
Cohesion



Merrie Melodies lobby card (1942)



Initial simulations



A boid’s neighbourhood

source for all media: http://www.red3d.com/cwr/boids/

I Aoki. *Bull. Jpn. Soc. Sci. Fish* **48**(8): 1081–1088 (1982).

DID BOIDS EVOLVE FROM FISH?

- In 1982 Ichiro Aoki proposed an algorithm for fish schooling.
- His approach predated Reynolds, but used very similar logic, considering 3 core behaviours: approach (cohesion), avoidance (separation) and parallel orientation (alignment).
- Here the speed and direction of individual "fish" are stochastic variables.
- He found that flocking can occur without a leader and with no global knowledge of the school.

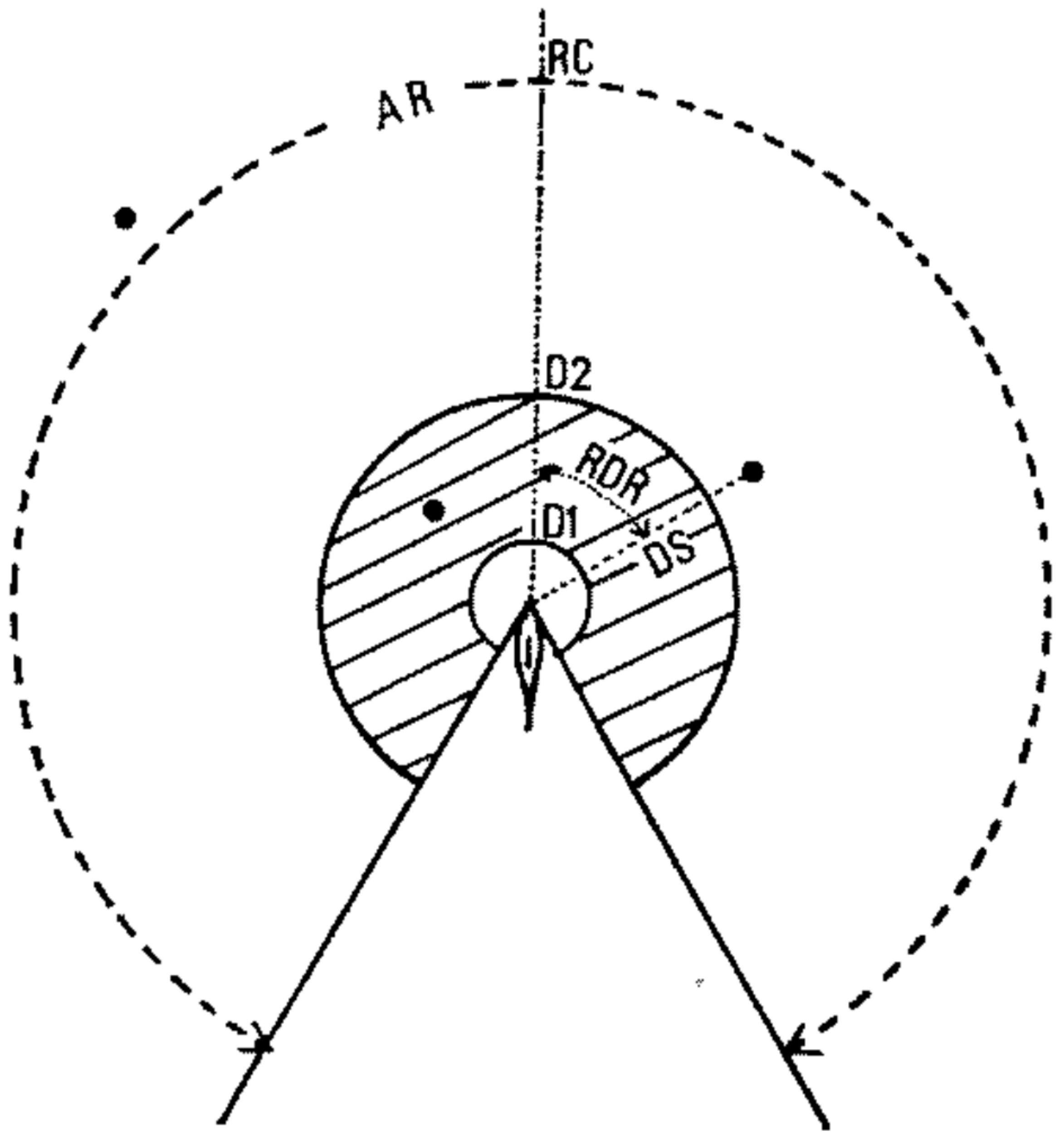


Fig. 1. Geometrical drawing to illustrate parameters specifying interactions.
*D*1, avoidance distance; *D*2, approach distance; *RC*, radius of extent of near-field interactions; *AR*, angular range of interactions; shadowed portion, parallel orientation area; solid circles locations of other individuals (distance denoted by *DS* and relative direction by *RDR*).

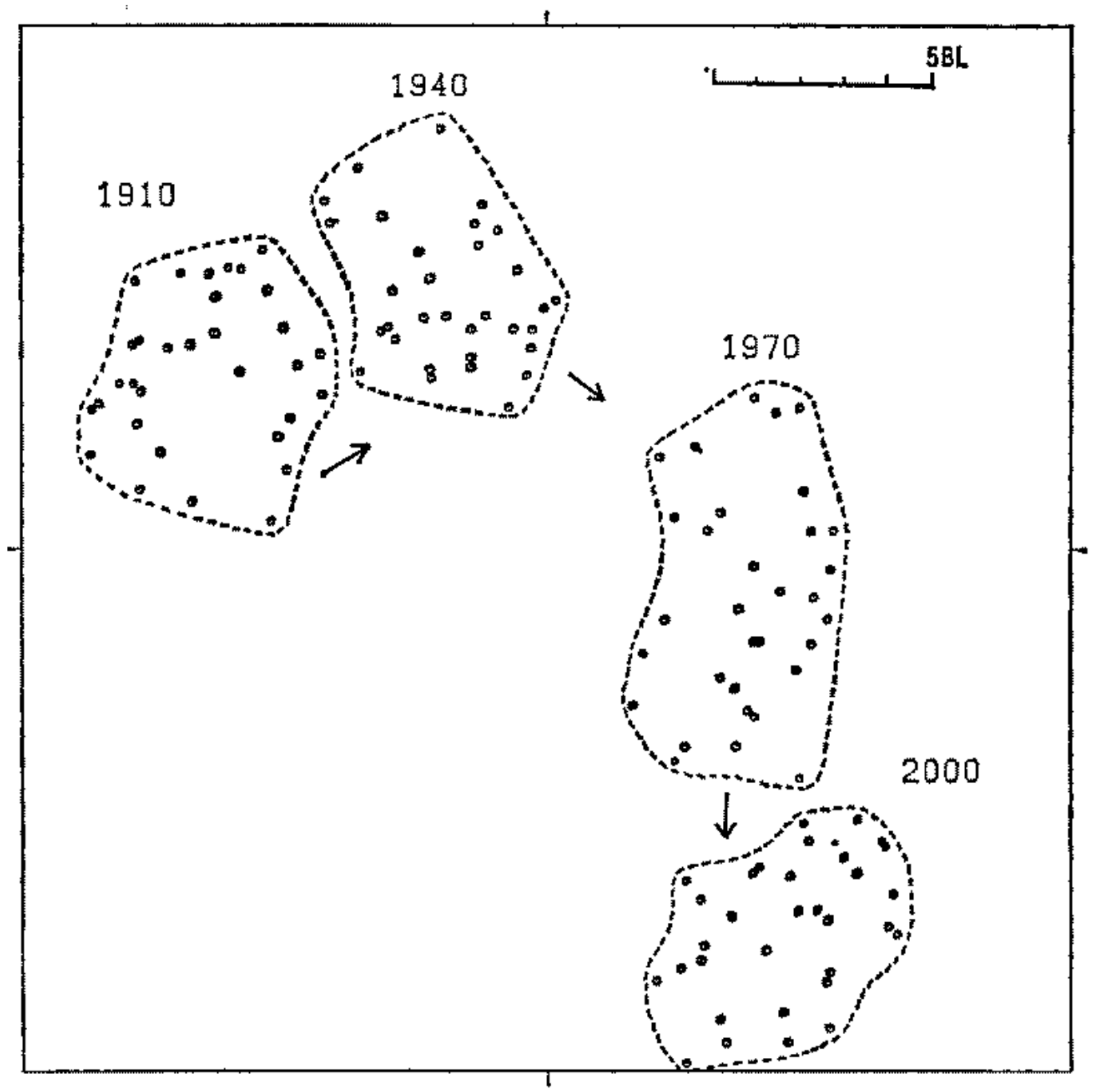
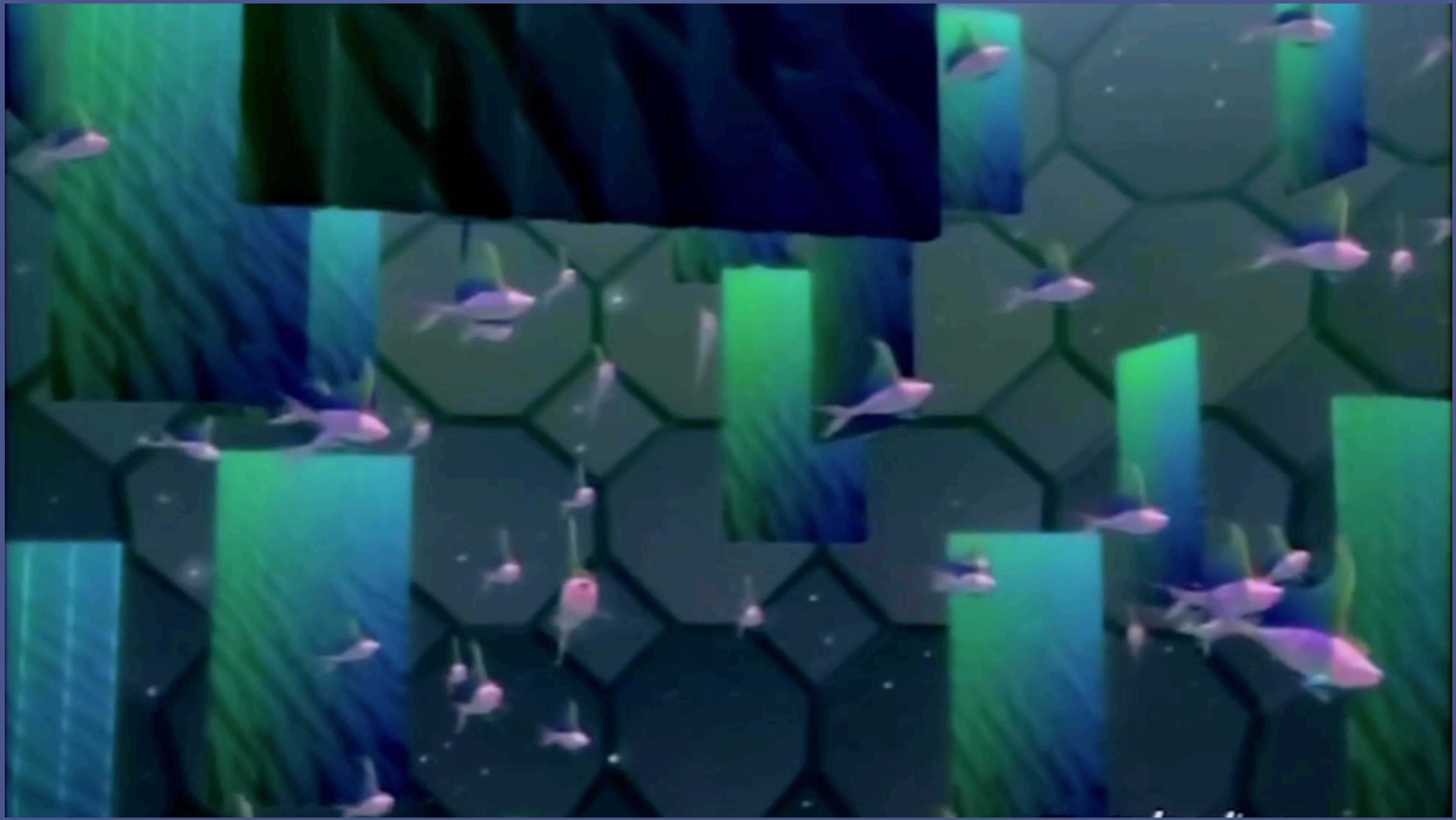


Fig. 5. An example of movement patterns of a simulated school with a larger number of individuals (N=32).

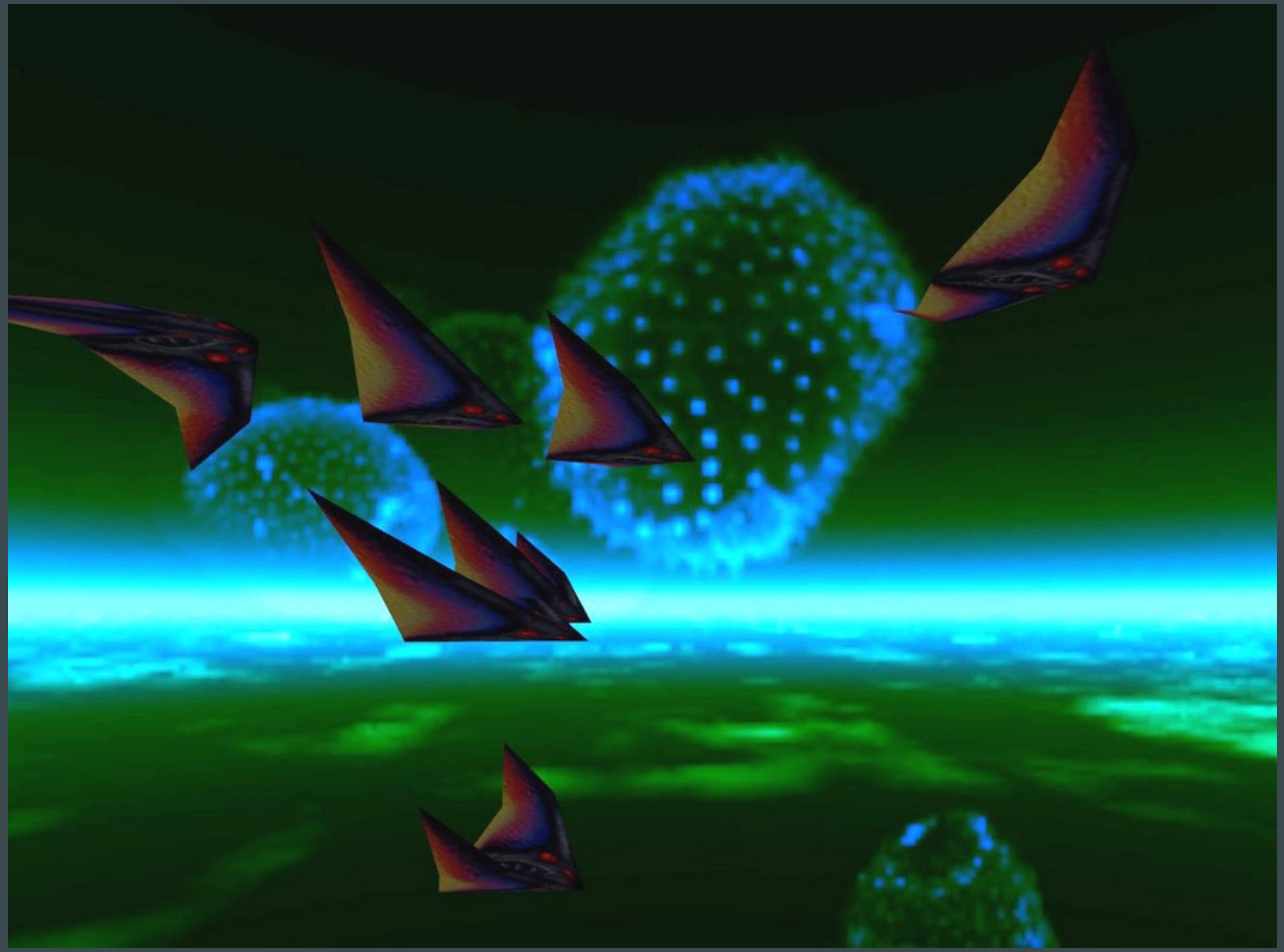
"BOIDS" IN ACTION



A short film developed by Craig Reynolds and others at Symbolics Graphics Division was premiered at SIGGRAPH '87. It showcased the capabilities of the "Boids" algorithm.

"BOIDS" GO MAINSTREAM

Extract from "Batman Returns" (1992), directed by: Tim Burton

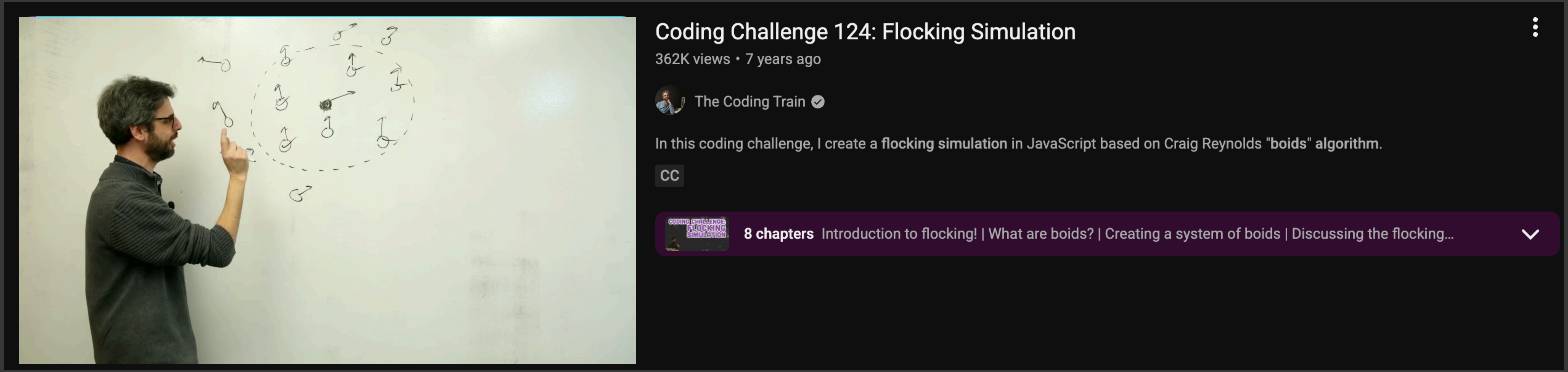


From the game "HλLF-LIFE" (1998), developed by: Valve

- A few years later, this algorithm was implemented in many popular movies and video games to display realistic flocking behaviour.
- Concurrently, this problem attracted the interest of physicists… as we shall see in the next lecture.

CODING EXERCISE!

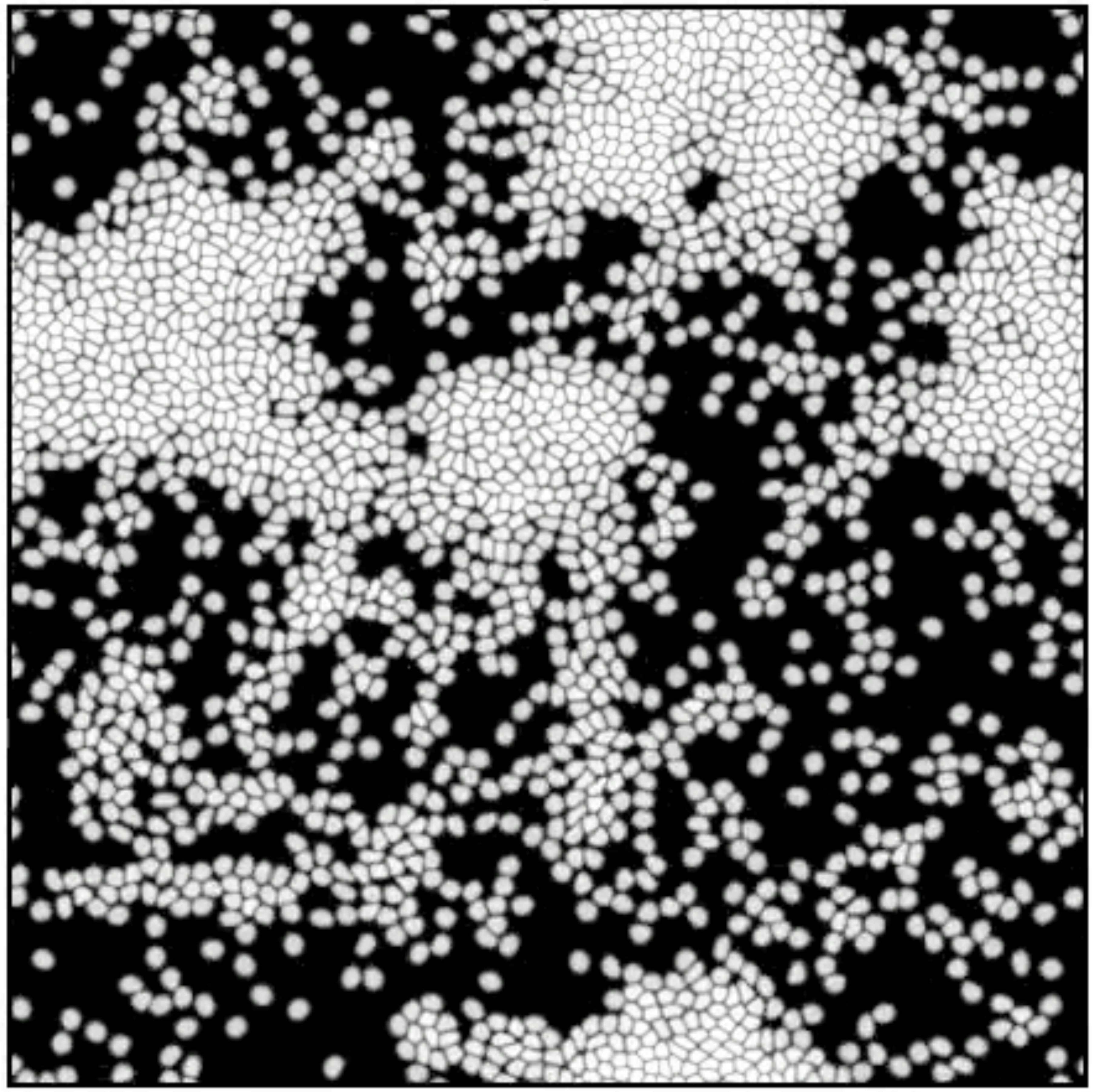
- How does one actually simulate Boids?!
- There is no single way to do it - Boids is an algorithmic framework that encompasses a set of behavioural heuristics.
- Try and simulate Boids yourself! The following step-by-step guide will help you generate them from scratch:



video: A Hopkins, Soft Matter, **19**(42), 8172-8178 (2023).

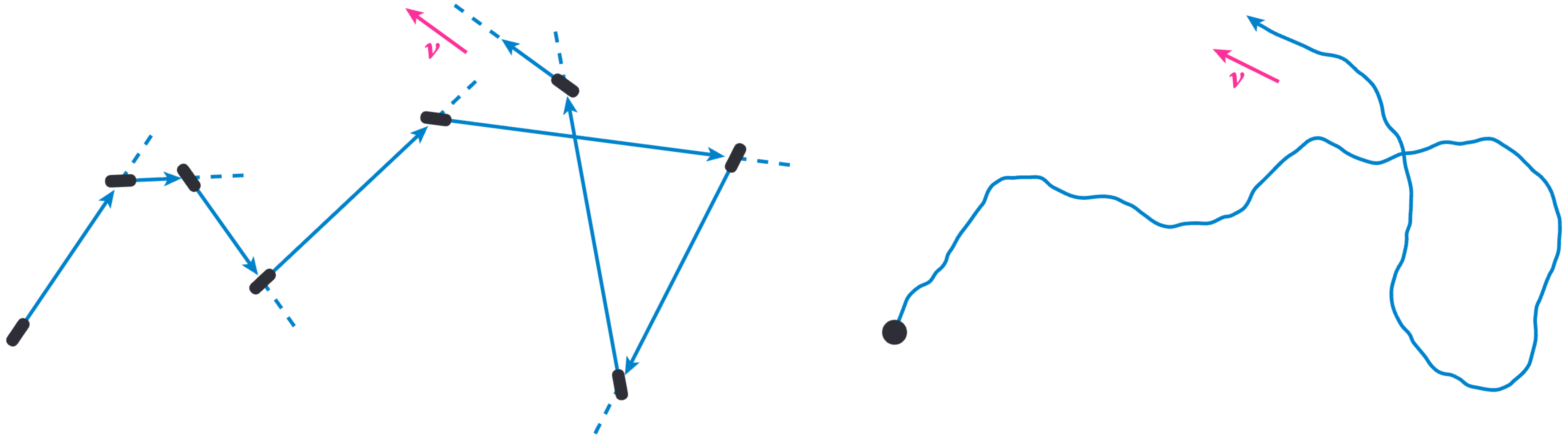
CAN WE INFER THE RULES FROM THE DYNAMICS?

Q: What sort of rules might these boids follow?



A: These aren't boids! 😁

- There exist phenomena such as **motility-induced phase separation** (MIPS) which also yields dense clusters. MIPS arises in a system of purely repulsive "active" particles with isotropic interactions that exhibit persistent motile behaviour and slow down due to high local density. This is basically a "traffic jam" of particles that have no preferred target location.



run-and-tumble particles

active Brownian particles

ME Cates & J Tailleur, Annu. Rev. Condens. Matter Phys., 6(1), 219-244 (2015)

IMPLICATIONS

- Similar spatiotemporal patterns can be obtained with completely different rules. To map observed macroscopic phases to the underlying microscopic rules we need a systematic *statistical physics framework*.

- While the Boids algorithm can simulate aspects of flocking behaviour, it is not a **model** per se. To gain deeper insights we need a strict mathematical framework, as we shall see in the next lecture…

video: https://www.youtube.com/watch?v=IcFW2abCl4

Swarm of locusts invading an area

photo: Owen Humphreys

FURTHER READING

Articles/Reviews

- T. Vicsek & A. Zafeiris, *Collective Motion*, Phys. Rep. 517: 71-140 (2012).
- I. Aoki, *A simulation study on the schooling mechanism in fish*, Bull. Jpn. Soc. Sci. Fish. **48**:1081-1088 (1982).
- C. W. Reynolds, *Flocks, Herds and Schools: A Distributed Behavioral Model*, ACM SIGGRAPH Comput. Graph., **21**(4): 25-34 (1987).

Book

- D. J. T. Sumpter, *Collective Animal Behavior*, Princeton University Press (2010).

THANK

YOU!

video: https://vimeo.com/31158841