Collective Intelligence

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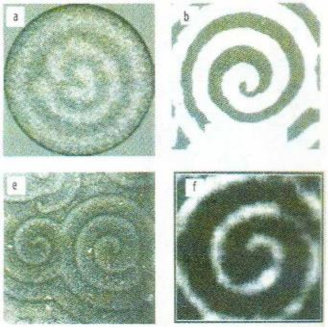
Learning Outcomes

- What is self-organising behaviour?
- What is stigmergy?
- What are the adaptive properties of intelligent collective decision making systems?
- What are the details of specific case-studies that show how individual local rules lead to collective intelligence?
- Why are self-organising principles desirable for engineers?
- How are these implemented in swarm robotics?

Self-organisation



Scott Camazine:

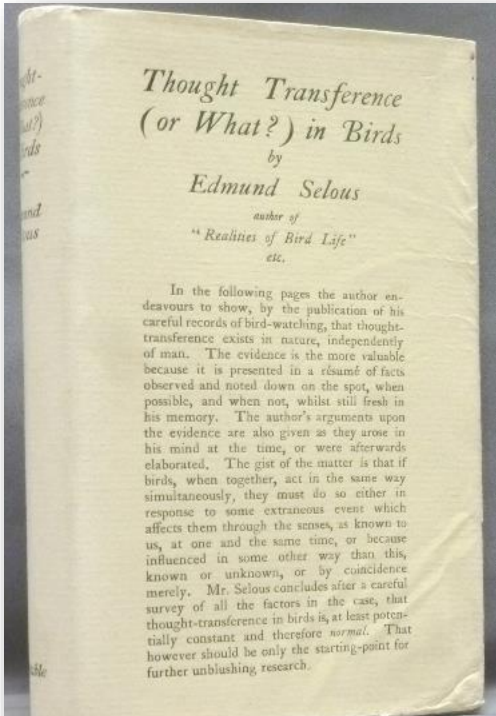
"… … self-organization is a process in which pattern at the global level of a system emerges solely from numerous interactions among the lower-level components of the system… …

… …moreover, the rules specifying interactions among the system's components are executed using only local information, without reference to the global pattern."

Camazine et al (2001) Self-Organization in Biological Systems

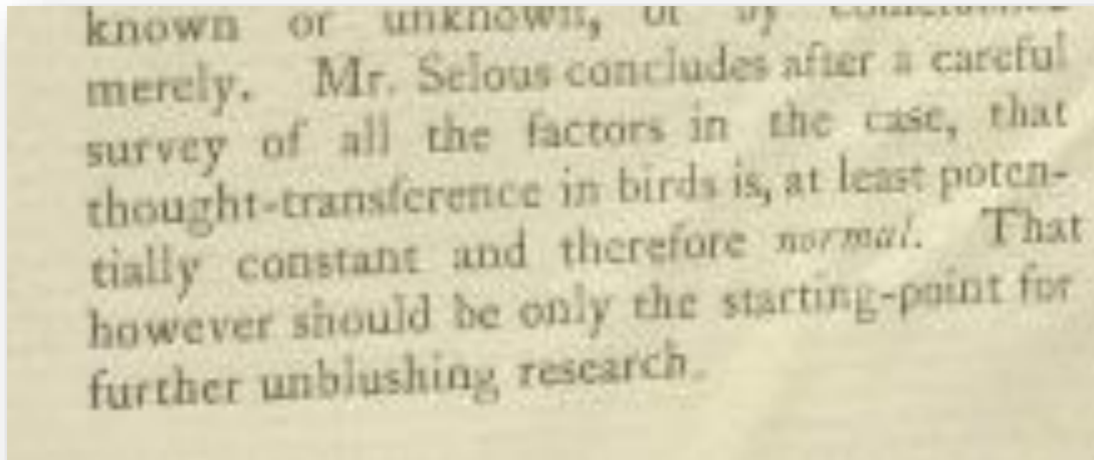
Collective Behaviour

Alternatives to self-organisation?


Thought Transference (or What?) in Birds
by
Edmund Selous
author of
"Realities of Bird Life"
etc.

In the following pages the author endeavours to show, by the publication of his careful records of bird-watching, that thought-transference exists in nature, independently of man. The evidence is the more valuable because it is presented in a résumé of facts observed and noted down on the spot, when possible, and when not, whilst still fresh in his memory. The author's arguments upon the evidence are also given as they arose in his mind at the time, or were afterwards elaborated. The gist of the matter is that if birds, when together, act in the same way simultaneously, they must do so either in response to some extraneous event which affects them through the senses, as known to us, at one and the same time, or because influenced in some other way than this, known or unknown, or by coincidence merely. Mr. Selous concludes after a careful survey of all the factors in the case, that thought-transference in birds is, at least potentially constant and therefore *normal*. That however should be only the starting-point for further unblushing research.

Thought transference (or What?) In Birds. Selous 1931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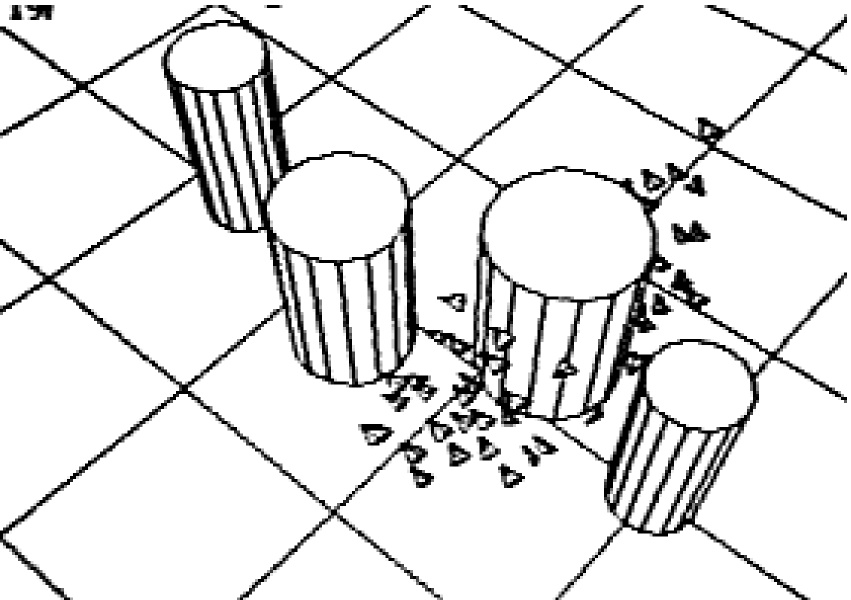
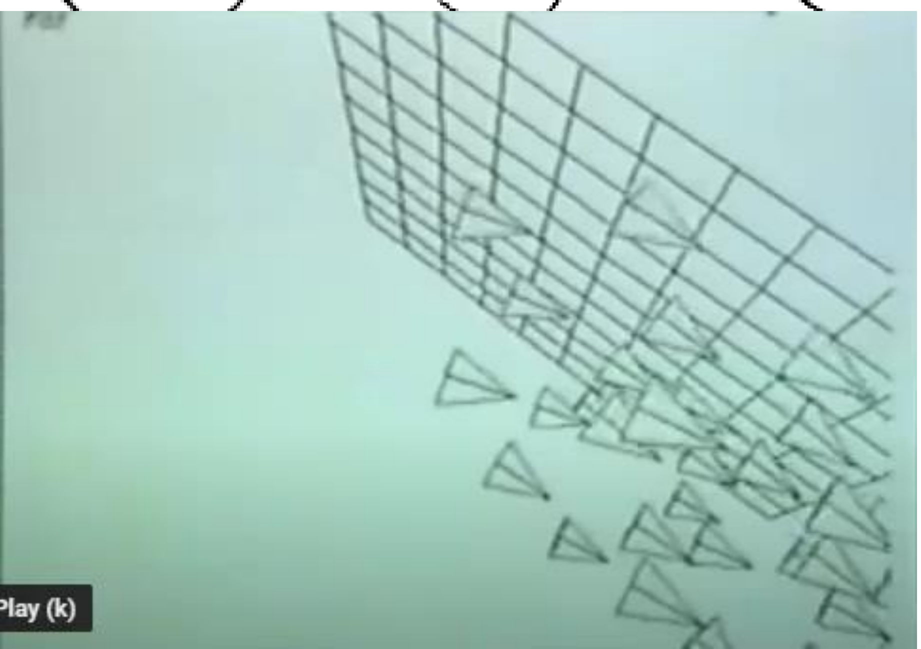
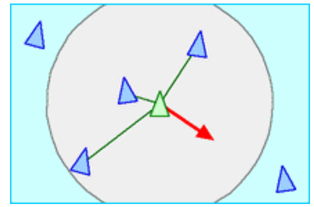
"concludes after a careful survey of all the factors in the case, that thought-transference in birds is, at least potentially constant and therefore normal."

Modelling to understand self-organising behaviour

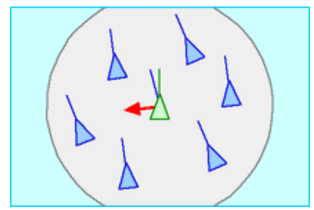




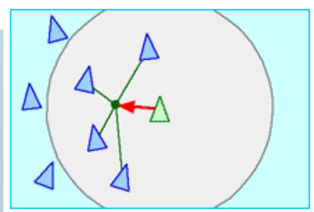
Local Rules



Separation



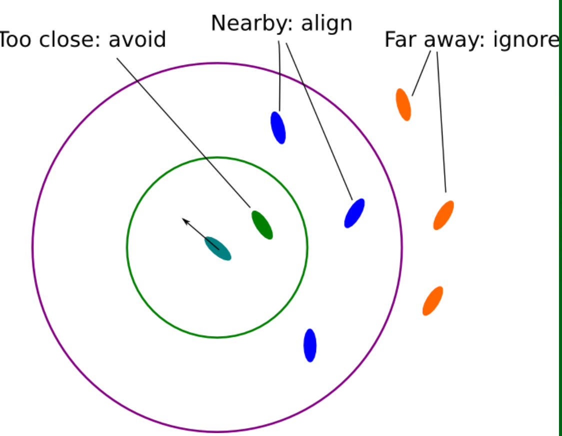
Alignment

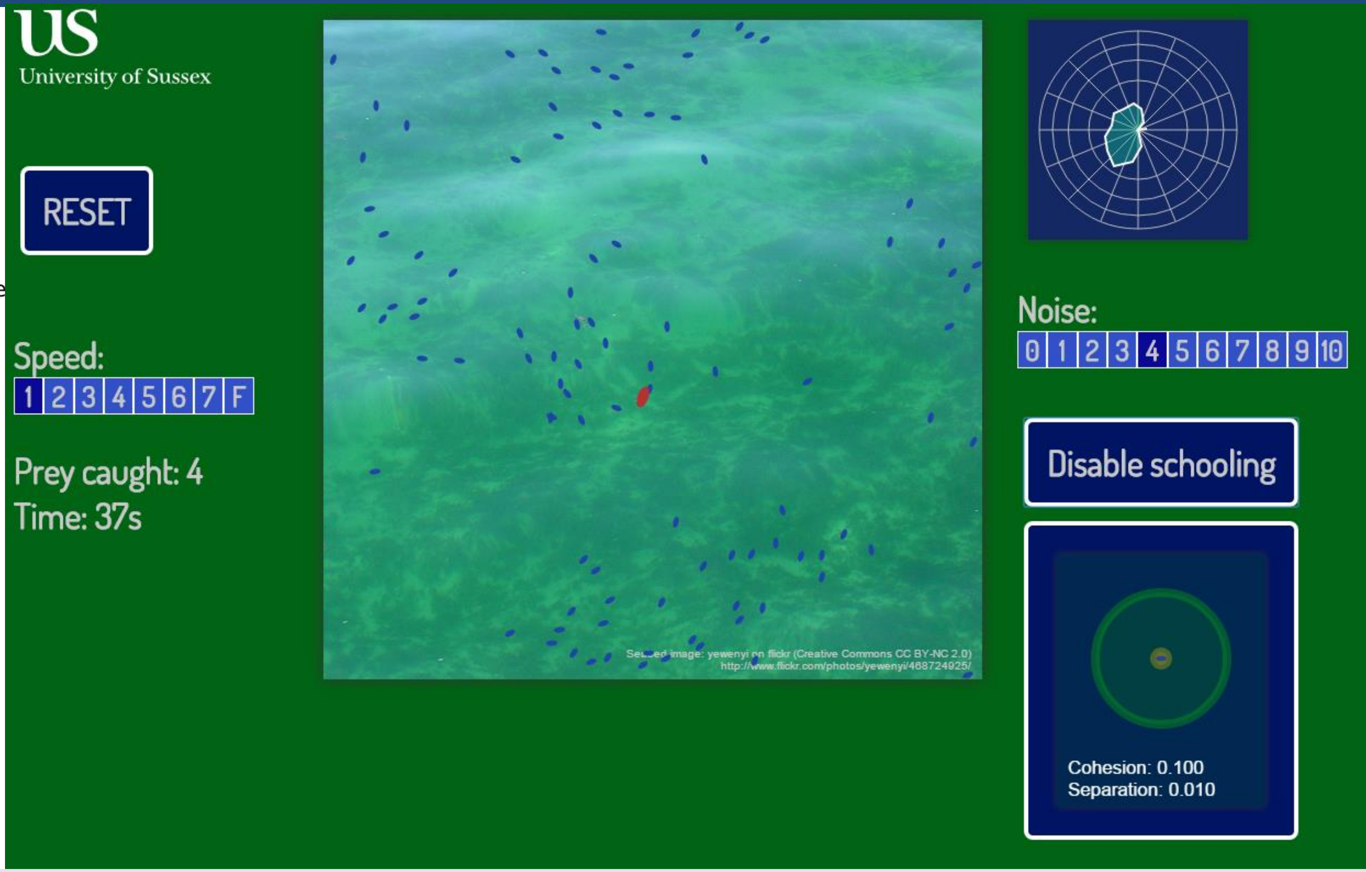


Cohesion

Craig Reynolds BOIDS (1986)
www.red3d.com/cwr/boids/

Boids-like swarming model

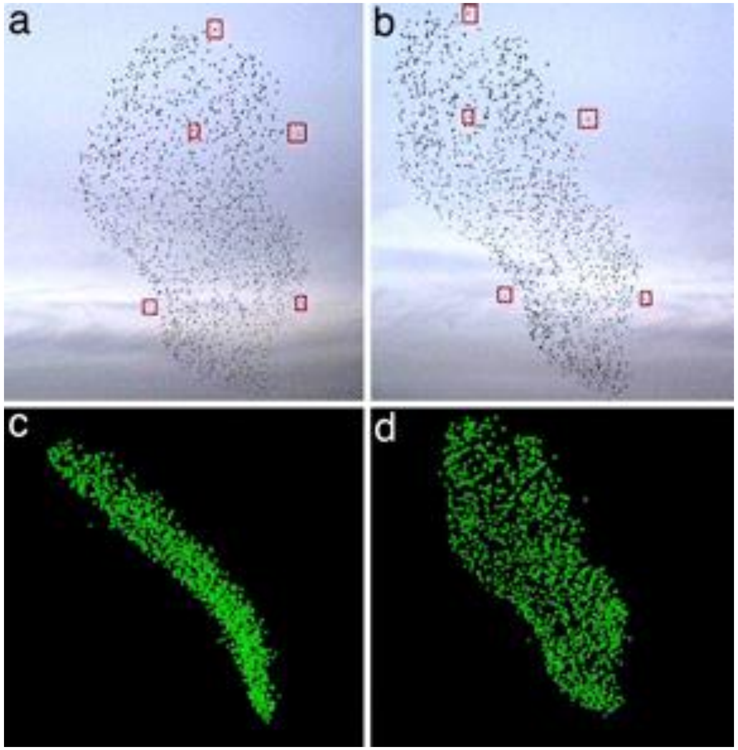


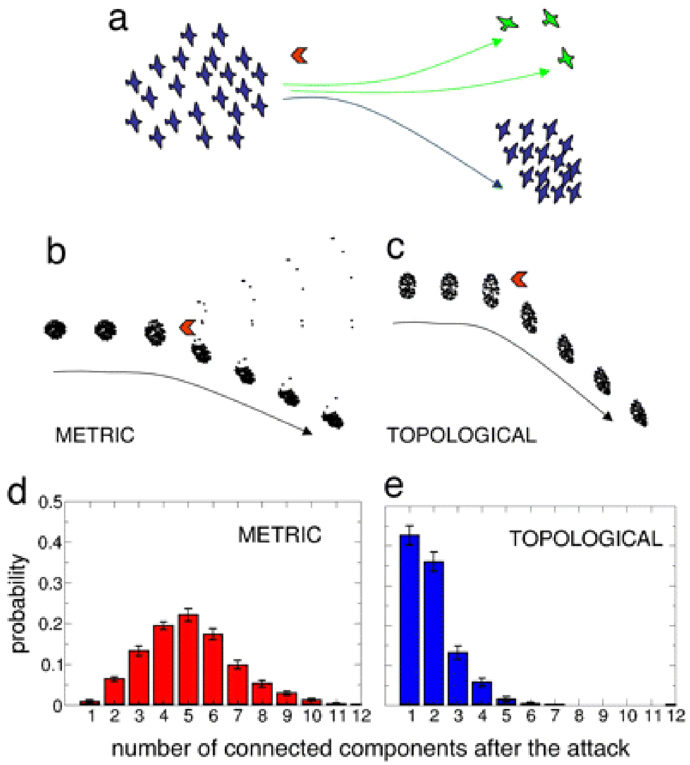


http://sussexsim.appspot.com/?predator

So what are the local rules?

Ballerini et al. (2008) *Interaction ruling animal collective behavior depends on topological rather than metric distance: Evidence from a field study.* PNAS





Starlings seem to be paying attention to nearest 6 birds

Topological is more robust to different densities

Stigmergy

… coordination between agents or actions, through a trace left in the environment.

- Coined by Pierre-Paul Grassé after studying termites.
- We do this all the time, e.g. writing notes to offload memory

Grasse PP (1959) Insectes Sociaux

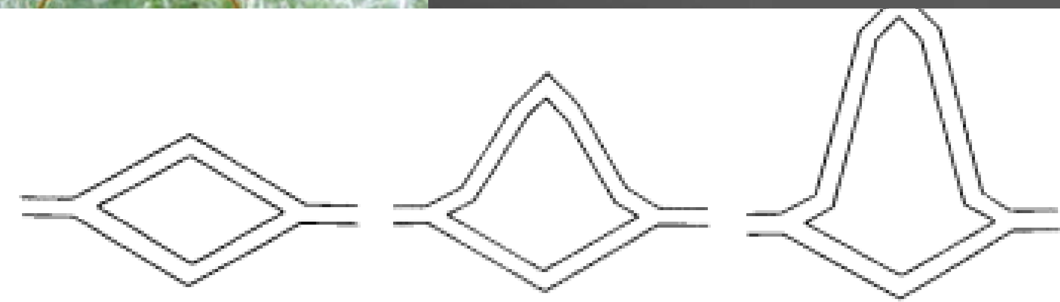
Stigmergy in termite building

Termite mound building:

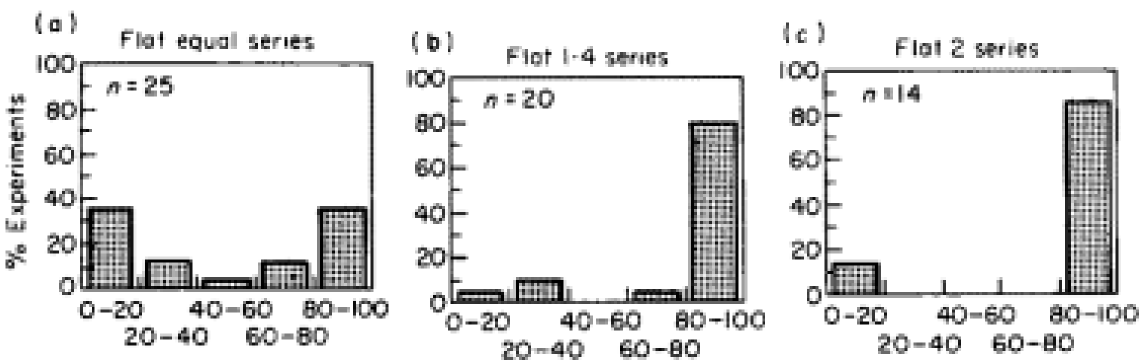
- First, they simply move around at random, dropping pellets of chewed earth and saliva on elevated patches of ground. Soon small heaps of moist earth form.
- The heaps encourage the termites to concentrate their pellet-dropping activity and soon the biggest heaps develop into columns.
- Finally, if a column has been built close enough to other columns, one other behaviour kicks in: the termites will start building diagonally towards neighbouring columns.

Grasse PP (1959) Insectes Sociaux

Classic stigmergic behaviour – pheromone trails



Collective Behaviour
is sometimes
Collective Intelligence

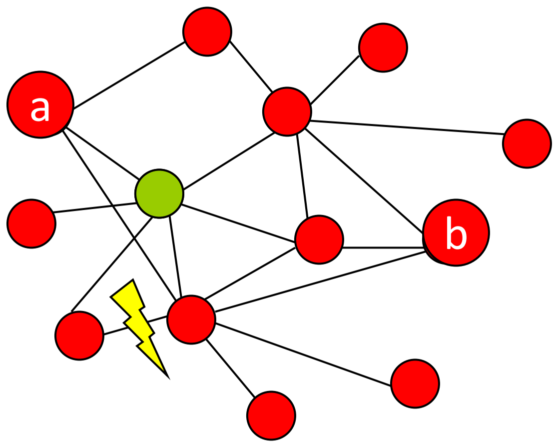


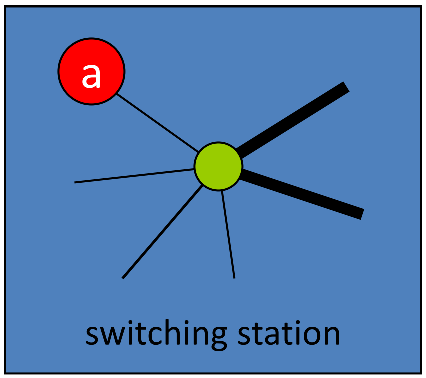
% Traffic on short branch

Beckers et al. (1992) Insectes Sociaux

Ant Colony Optimisation (ACO) algorithms

- Pheromone trails are decentralised control systems.
- They have inspired algorithms for optimisation and routing
- I.e. Local rules rather than top down control

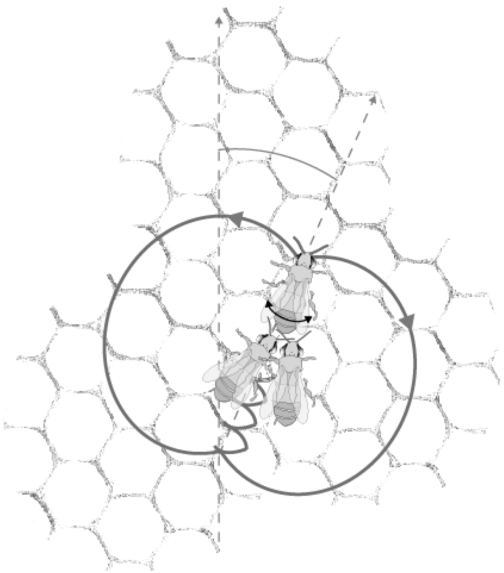




Bonabeau, Dorigo & Theraulaz (2000) Inspiration for optimization from social insect behaviour
Nature **406**, 39-42

Case study. Decision making in honey bee swarms

- A swarm is a temporary home
- Scouts fly out looking for new sites
- Decision needs to be:
  - Fast
  - Accurate
  - Unified



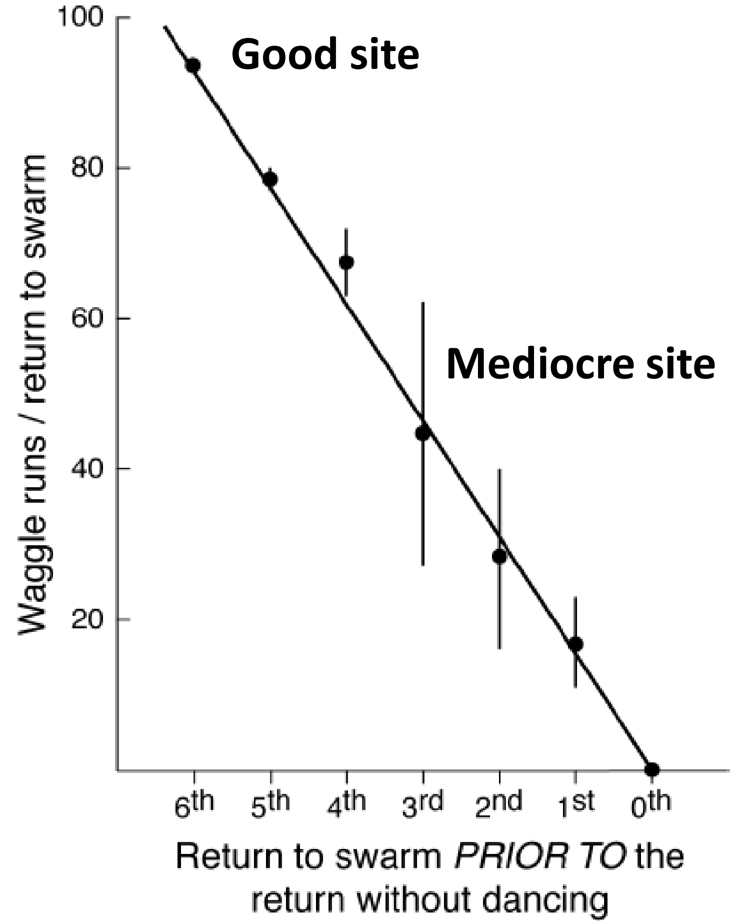
- Returning scouts dances to indicate location.
- Number of dance circuits is related to the quality of the site.

A quick aside on the honeybee waggle dance

- **Angle of waggle phase indicates direction to the food**
- **Duration of waggle proportional to the distance**

Dance rate

- After each visit a bee reduces number of waggle runs
- Good sites are initially advertised with more runs
- Scouts from good sites will recruit more new scouts
- Recruits make their own assessment
- No comparison of dances or sites by individuals

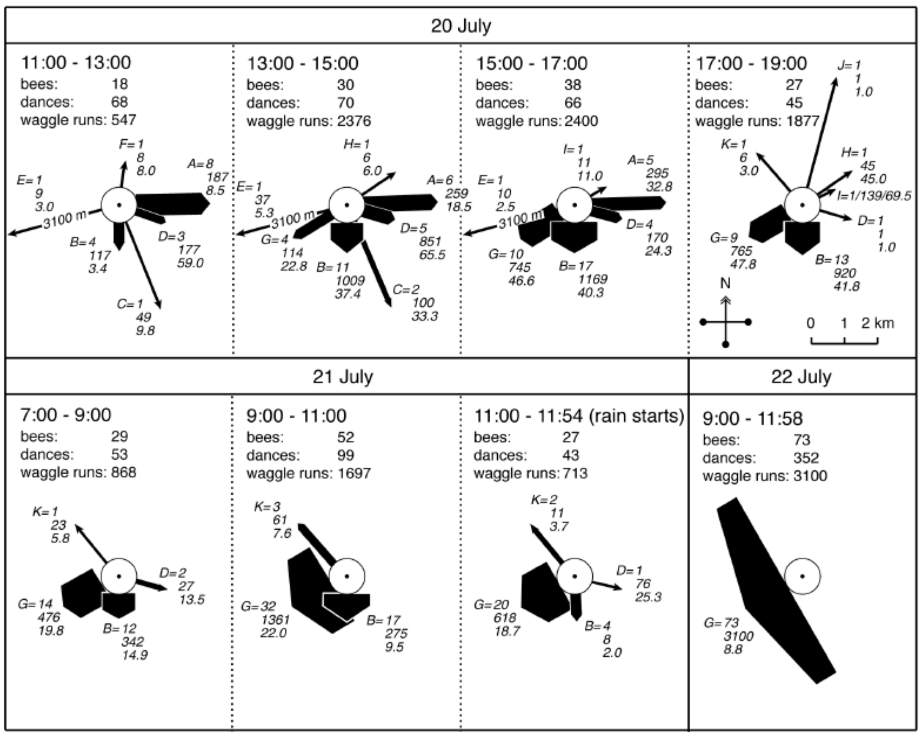


Tom Seeley et al (2006) *American Scientist*

Multiple options are assessed in parallel

Multiple parallel options explored

Good sites overtake mediocre sites



Tom Seeley et al (2006) *American Scientist*

When is the decision process halted?

Decision depends on the number of other scouts visiting a site

A scout can then be sure that there are independent votes for that site

The size of an acceptable quorum indicates the balance between speed and accuracy

Benefits of collective behaviour

- **Self-organising.** No need for a leader or organiser.
- **Scalable.** Variable numbers of individuals.
- **Flexible.** The collective takes into account the environment and social context via the local rules.
- **Fault tolerance.** No single point of failure.

For Decision making

- Explore many options, collect evidence about each, report evidence freely, and vote **independently.**
- Give up on options supported by weak evidence. **Decay.**
- A quorum ensures that several individuals approve and prevents error-prone individuals from leading the swarm astray. **Robust to individual opinion.**

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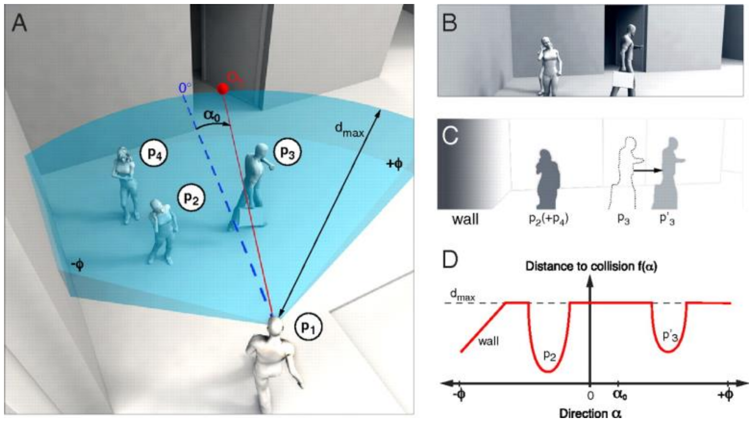
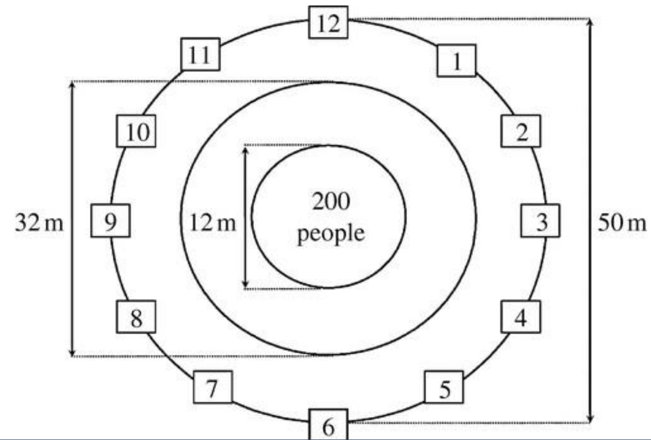
More than the sum of its parts?

Mini-break

Collective movement in humans





Individual paths and group behaviour can be replicated with two simple local rules:
"A pedestrian chooses the direction that allows the most direct path"
"A pedestrian maintains a distance from the first obstacle in the chosen walking direction that ensures a minimum time to collision"

Informed individuals can drive behaviour of large groups.

200 subjects told to move whilst staying "within arms reach" of somebody

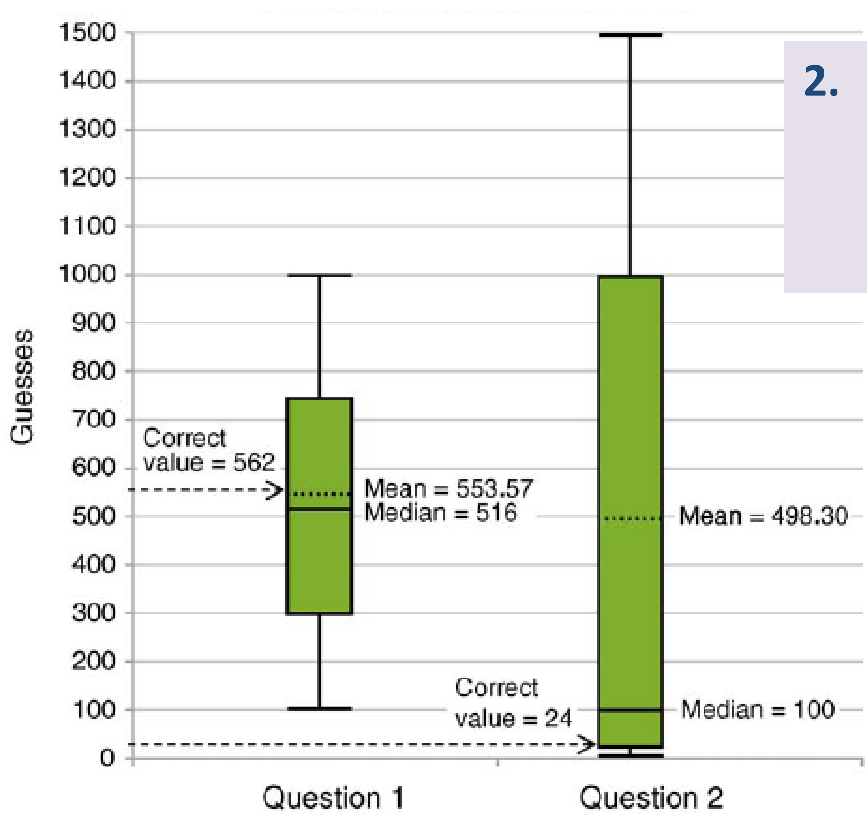
Small minority told to move to a target, but still stay in group

Moussaïd et al (2011) PNAS

Dyer et al (2008) Phil Trans

Collective intelligence in humans

1. How many marbles in the jar?



2. How many coin flips until the odds of getting all heads is the same as winning the lottery?

Krause et al (2010) TREE

Can collective intelligence be useful in humans?

- On an IQ test, crowd IQ plateaus after a group size of 30 is reached. A crowd of 100 individuals has a joint IQ score of merely 120.
- A group of 100 individuals is very likely to contain a few people with near-genius level (>135).
- Sometimes it must be worth the effort to find an actual expert rather than relying on the crowd.

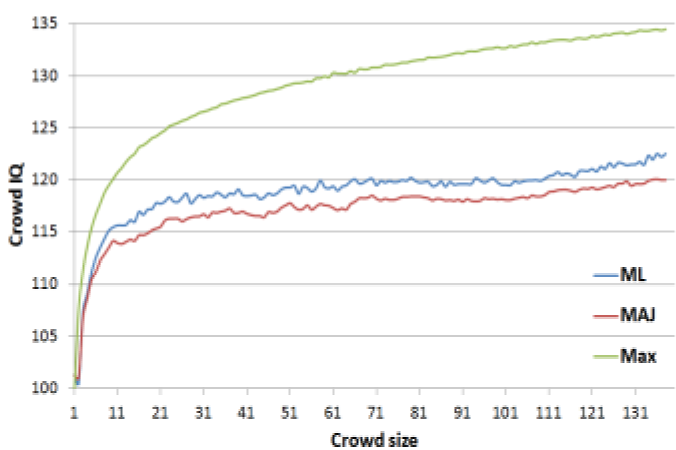


Figure 6: Crowd IQ and maximal IQ (entire dataset)

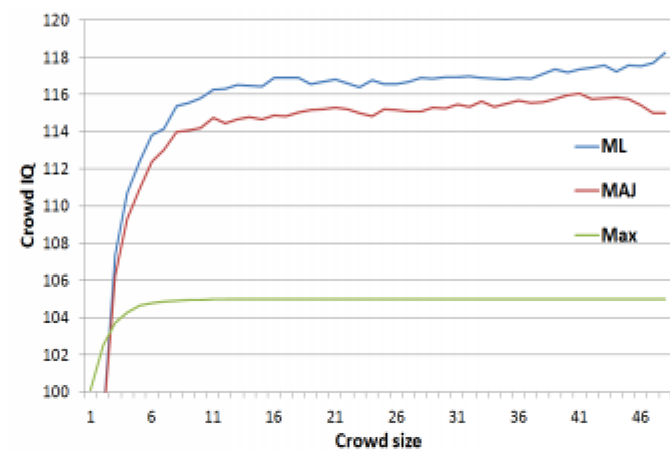
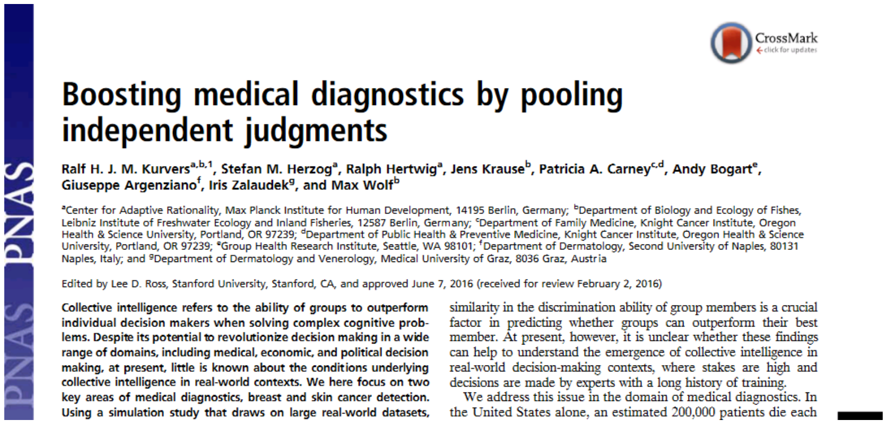


Figure 7: Crowd IQ and maximal IQ for $P_{[95,105]}$

Kosinski et al (2024) arxiv

Can collective intelligence be useful in humans?



PNAS PNAS

Boosting medical diagnostics by pooling independent judgments

Ralf H. J. M. Kurvers[a,b,1], Stefan M. Herzog[a], Ralph Hertwig[a], Jens Krause[b], Patricia A. Carney[c,d], Andy Bogart[e], Giuseppe Argenziano[f], Iris Zalaudek[g], and Max Wolf[b]

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Edited by Lee D. Ross, Stanford University, Stanford, CA, and approved June 7, 2016 (received for review February 2, 2016)

Collective intelligence refers to the ability of groups to outperform individual decision makers when solving complex cognitive problems. Despite its potential to revolutionize decision making in a wide range of domains, including medical, economic, and political decision making, at present, little is known about the conditions underlying collective intelligence in real-world contexts. We here focus on two key areas of medical diagnostics, breast and skin cancer detection. Using a simulation study that draws on large real-world datasets,

similarity in the discrimination ability of group members is a crucial factor in predicting whether groups can outperform their best member. At present, however, it is unclear whether these findings can help to understand the emergence of collective intelligence in real-world decision-making contexts, where stakes are high and decisions are made by experts with a long history of training.

We address this issue in the domain of medical diagnostics. In the United States alone, an estimated 200,000 patients die each

Group decision in diagnoses can be more accurate than from the most accurate Doctor in the group.

As long as they don't meet to discuss!

Kurvers et al. (2016) PNAS

Mini-break

Collective Behavior in Machines

Swarm-bots: collective behaviour for tasks that need more than one robot





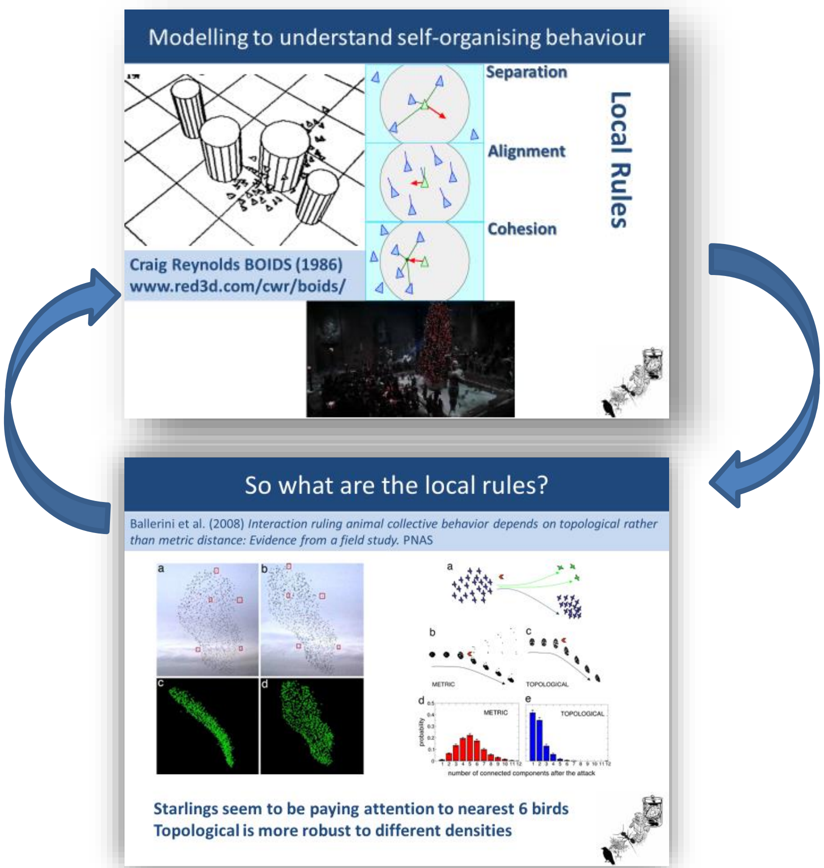


Dorigo et al https://www.youtube.com/watch?v=CJOubyiITsE

Swarm robotics

For Science

Modelling observation loop



For Engineering

Desirable characteristics

- Fault tolerance – If there’s a fault in one robot another can take over. No single point-of-failure
- Scalability - 100 robots doing a task, gets it done (up to!) 100 times faster. Low cost - Simple robots are cheaper to build than complex robots
- Flexibility - Different robots can perform different tasks in parallel
- Collective behaviour: can do things a single robot cannot do

Swarm robotics: past present and future

Swarm Robotics: Past, Present, and Future

By MARCO DORIGO, *Fellow IEEE*
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Centre de Recherches sur la Cognition Animale (CRCA), Centre de Biologie Intégrative (CBI), CNRS, Université de Toulouse-Paul Sabatier, 31062 Toulouse, France
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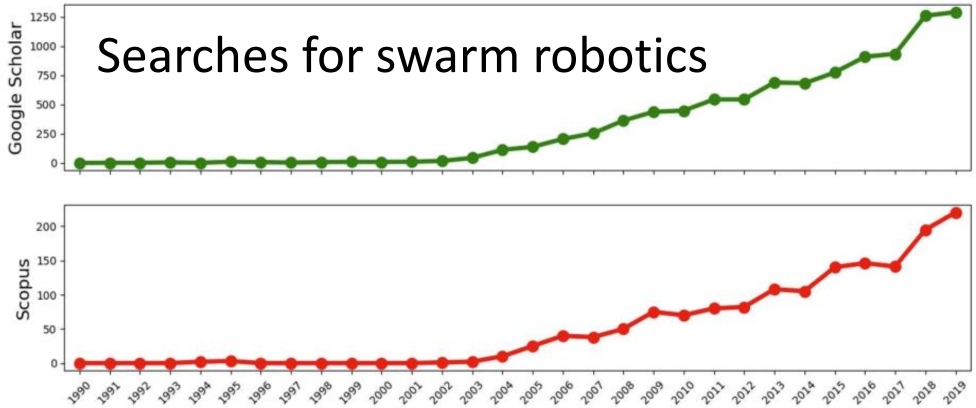
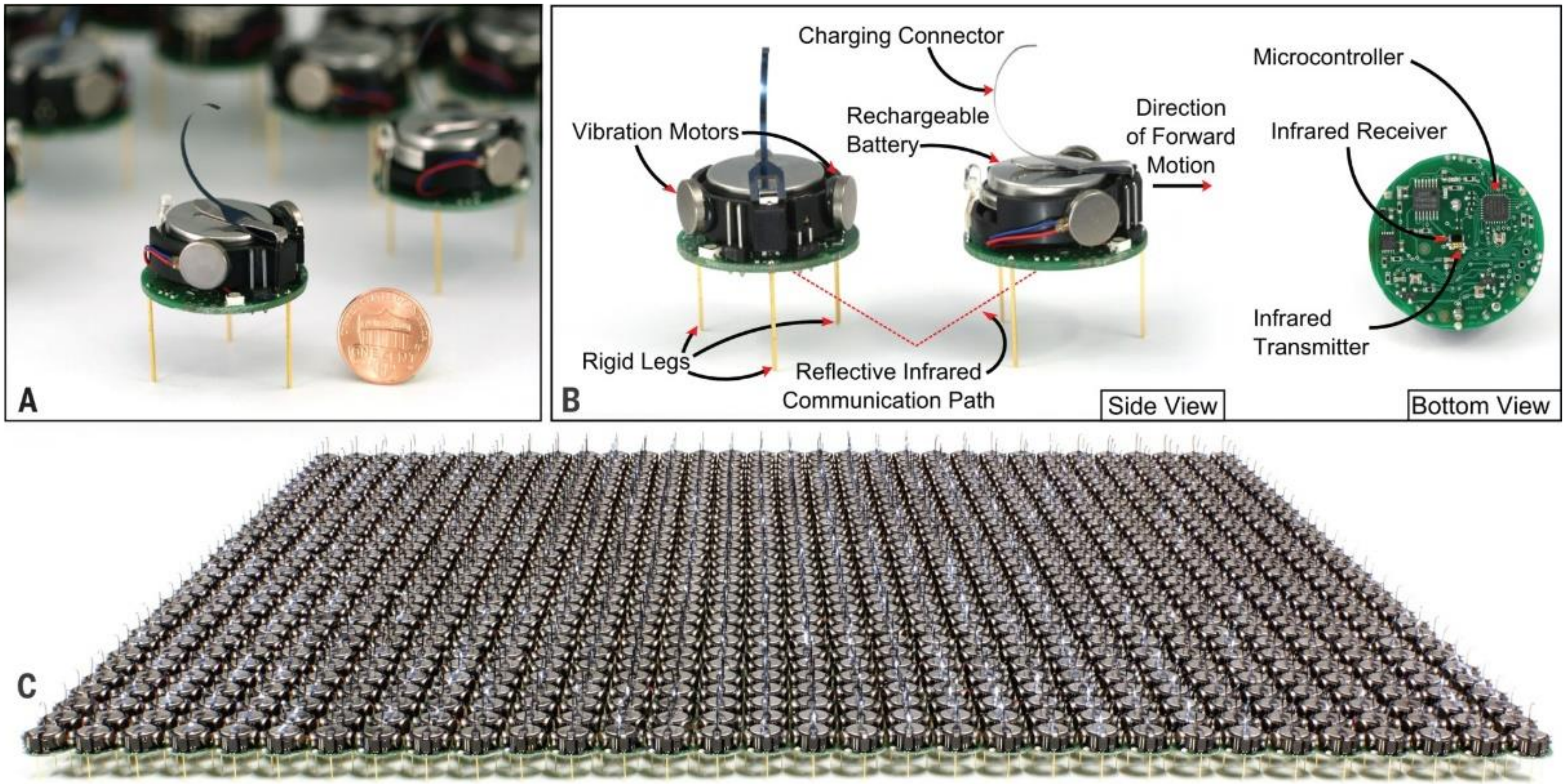


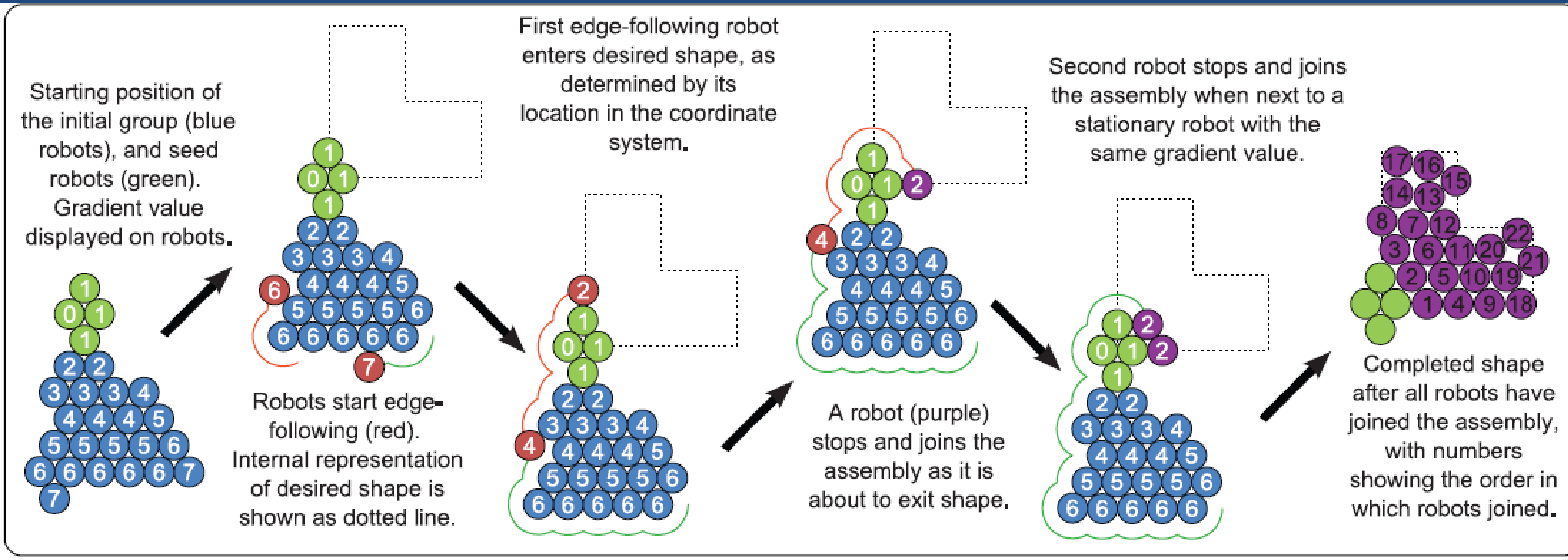
- Swarm robotics has: **"provid[ed] proofs of concept that demonstrated the potential of robot swarms, also contributing to a better understanding of how complex behaviors emerge in nature"** (Dorigo et al, 2021
- However: **"as of, today, only a few experiments have managed to demonstrate a large number of autonomous self-organizing, robots, and no real-world application of swarm robotics exists."**
- Following examples highlight
  - the potential and difficulties of swarm robotics with real robots
  - Self organisation can be harnessed by programming local rules/environment

Programmable Self-organisation. Example 1: Kilobots

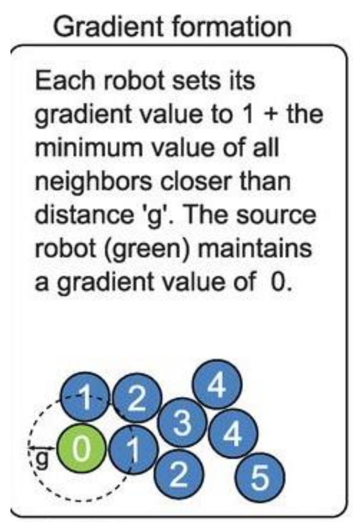


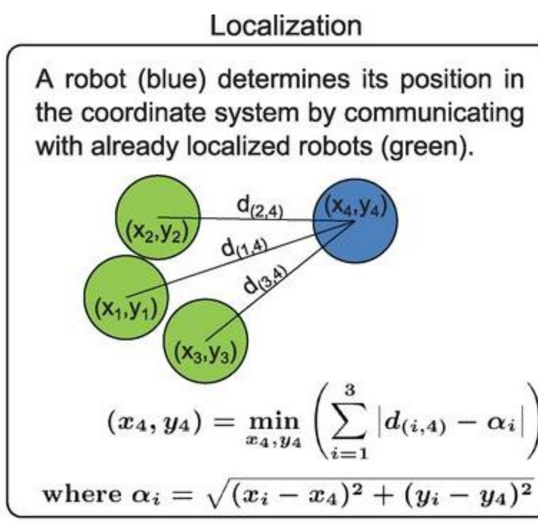
- Much larger numbers of robots more like insect swarms
- Rubenstein, Cornejo, Nagpal (2014) **Programmable self-assembly in a thousand-robot swarm**. Science, 345:795-799

Shape information and local rules



- Following simple rules, robots cover a pre-specified shape (shared with all robots)
- Rules rely on 'gradient' information from local noisy communication filtering out from seed robots (green)
- Seed robots set axes of coordinate system
- Position in shape from locally communicated position info + distances from near robots



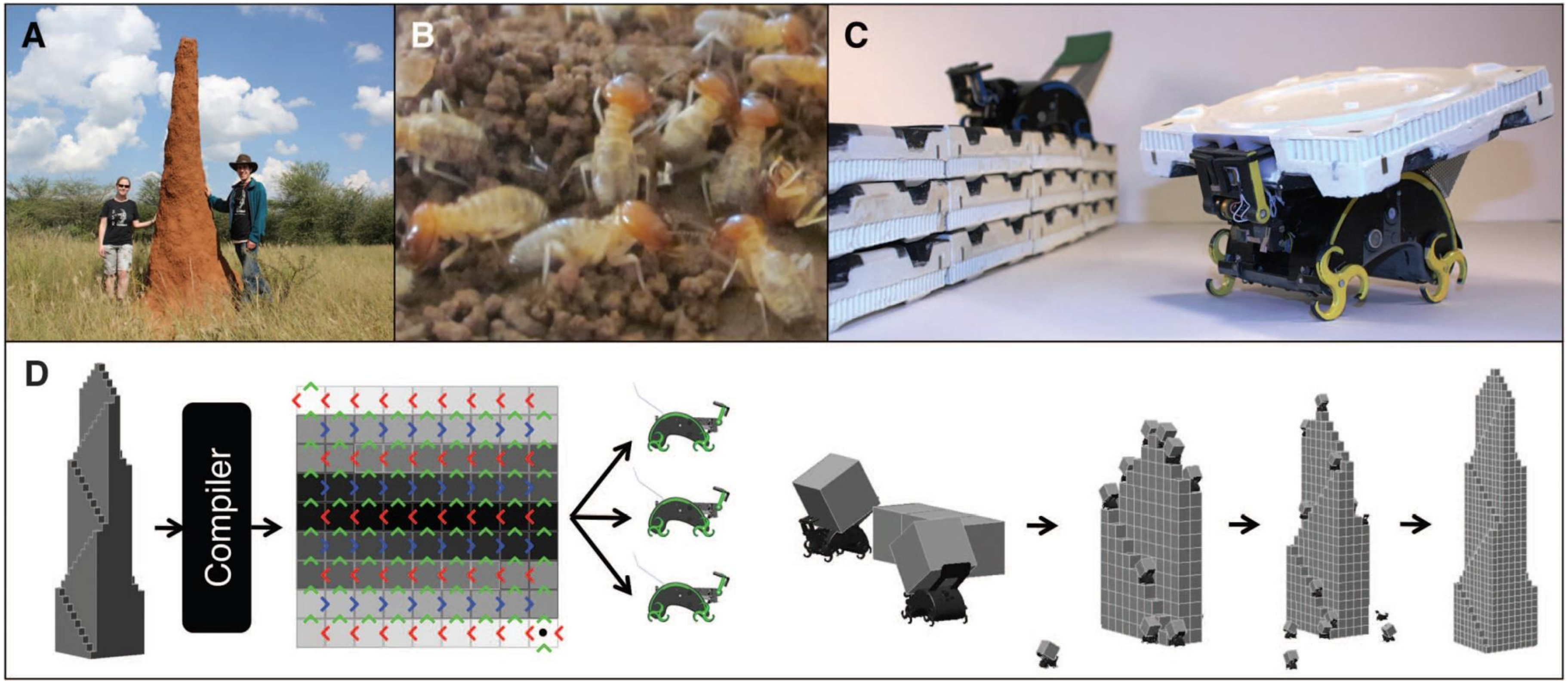


Collective behaviour in Kilobots

Rubenstein et al (2014) "Programmable self assembly" *Science*

https://www.youtube.com/watch?v=JmyTJSYw77g

Programmable Self-organisation.
Example 2: Robot Termites

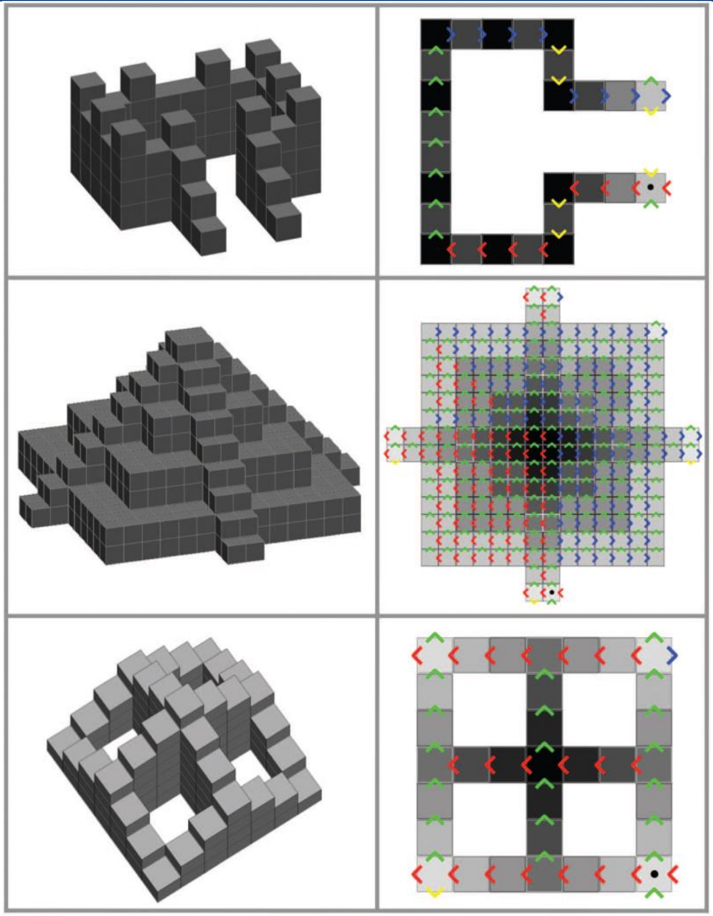


- Werfel, Petersen, Nagpal (2014) **Designing Collective Behavior in a Termite-Inspired Robot Construction Team.** Science 343:754-758
- Robots collectively build a specified shape

Robot Termites

- **Inspired** by termite behaviour
- Each robot has the same ‘traffic’ rules and follows them independently of each other
- Sensing is strictly short range
- Rules given by algorithm fed with desired shape
- Individual robots repeat:

“With a brick, circle the structure perimeter until reaching the seed; climb onto the structure and move along any legal path, keeping track of relative position with respect to the seed; attach the brick at any vacant site whose local neighborhood satisfies a fixed set of geometric requirements”



Robot Termites

Werfel, Petersen, Nagpal (2014) **Designing Collective Behavior in a Termite-Inspired Robot Construction Team.** Science 343:754-758
https://www.youtube.com/watch?v=dd8sIbxN4Zc
https://www.youtube.com/watch?v=LFwk303p0zY

Swarm robotics: outlook

- Fault tolerance – If there's a fault in one robot another can take over. No single point-of-failure:
  - All examples
- Scalability - 100 robots doing a task, gets it done (up to!) 100 times faster eg can search a big area quickly in:
  - Hmmm. Maybe termites but they're not so quick!
- Low cost - Simple robots are cheaper to build than complex robots
  - Not really yet
- Flexibility - Different robots can perform different tasks in parallel:
  - lots of this but not in these egs ("Swarmanoid: a novel concept for the study of heterogeneous robotic swarms." Dorigo et al, 2013) but typically a few robots not a swarm
- Collective behaviour: can do things a single robot cannot do
  - Yes but the things are not really useful

Reading

- **Essential**
  - Krause, J., Ruxton, G. D., & Krause, S. (2010). Swarm intelligence in animals and humans. Trends in ecology & evolution, 25(1), 28-34.
  - Dorigo, M., Theraulaz, G., & Trianni, V. (2021). Swarm Robotics: Past, Present, and Future. Proceedings of the IEEE, 109(7), 1152-1165.
- **Further**
  - Peterson et al (2019) A review of Robot construction. Science Robotics.