Swarm Robotics
– an overview –

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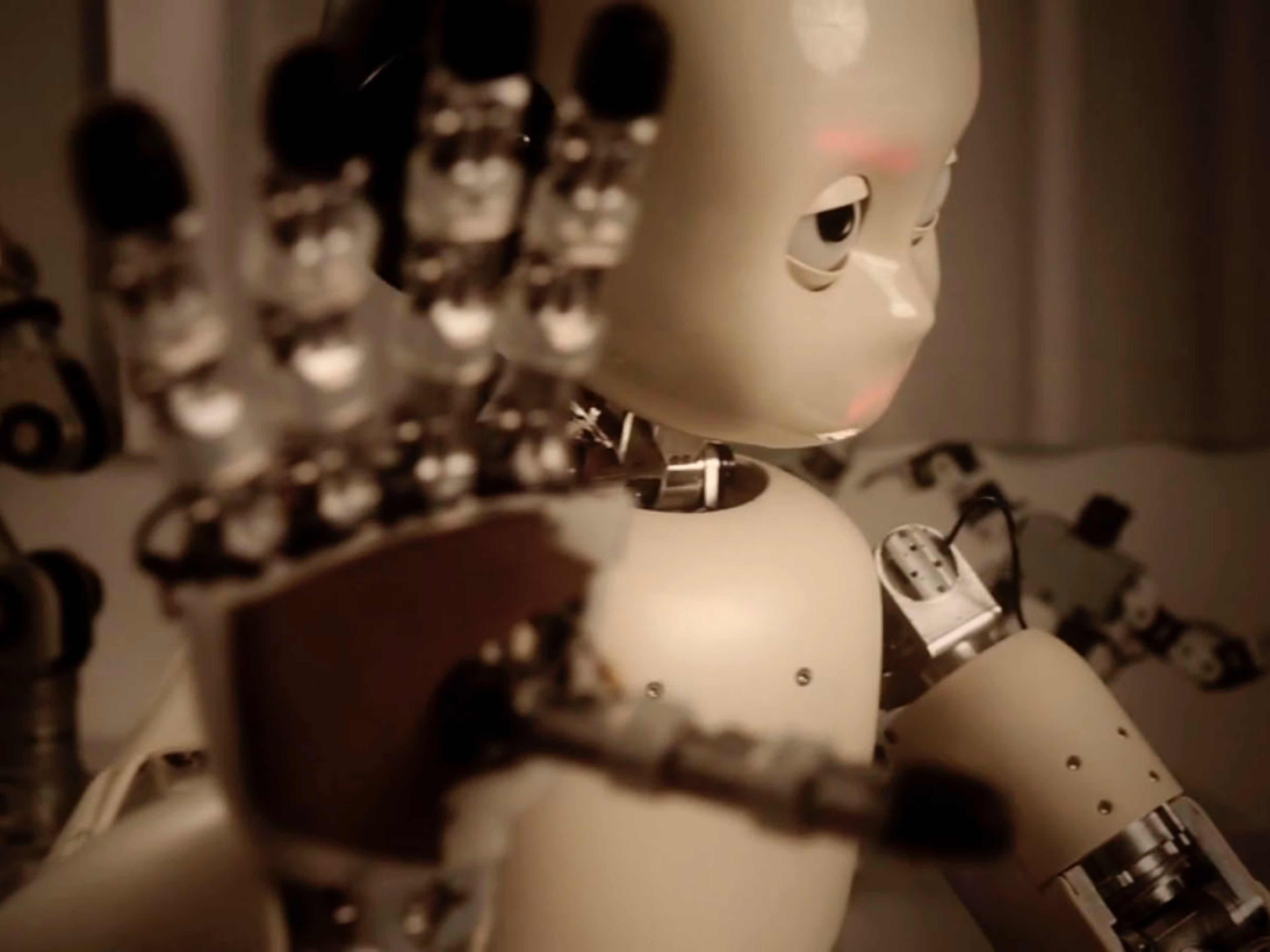


Monolitic Robots

- High complexity
- Planned movements
- High cost
- Low intrinsic robustness

Spirit and Opportunity

BY THE NUMBERS

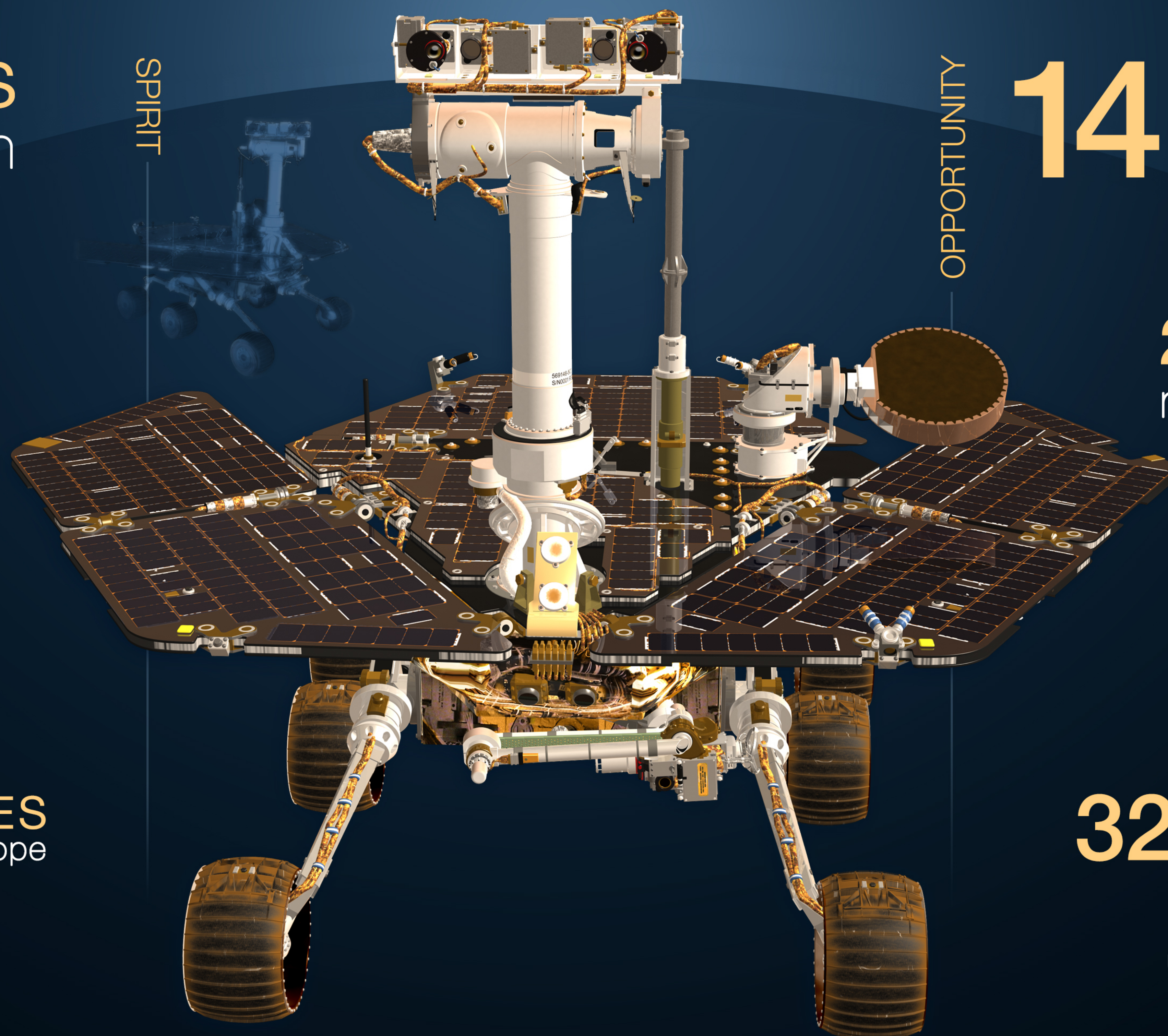
SPIRIT

6 YEARS lifespan

128,000 raw images

4.8 MILES traveled

30 DEGREES steepest slope



OPPORTUNITY

14 YEARS lifespan

225,000 raw images

28 MILES traveled

32 DEGREES steepest slope

Updated February 2018

Opportunity

- Dimensions: 1,5 x 2,3 x 1,6 m
- Weight: 180 Kg
- Max speed: 5 cm/s (1 cm/s in average)
- Covered distance > 45 km
- Time elapsed > 14 years
  (ceased communications on June 2018)
- The twin Spirit got stuck after 6 years

swarm robotics

- *swarm robotics* studies robotic systems composed of a multitude of interacting units
  - homogeneous systems or few heterogeneous groups
  - each unit is relatively simple and inexpensive
- individual limitations, absence of global information
  - limitations can be physical or functional
  - access to local and incomplete information only
- decentralised control
  - no *single point of failure*
  - *redundancy* is built-in in the system
- expected properties:
  - parallelism
  - robustness
  - scalability
  - adaptivity

swarm robotics

- simple individuals and simple behaviours
- complexity results from cooperation
- research mainly focuses on:
    - development of specific hardware to support communication and physical interactions
    - development and test of swarm control systems
- *problem:* how to define individual rules?
- *solution:* inspiration from super-organisms observed in Nature

perspectives

- swarm robotics still confined into the lab
    - self-organisation in natural and artificial systems
- cognition in decentralised systems
    - collective decision-making
    - categorisation
    - learning
- potential application domains
    - Precision agriculture, environmental monitoring
    - Security, search&rescue
    - Logistics
    - Space exploration

a catalogue of collective behaviours

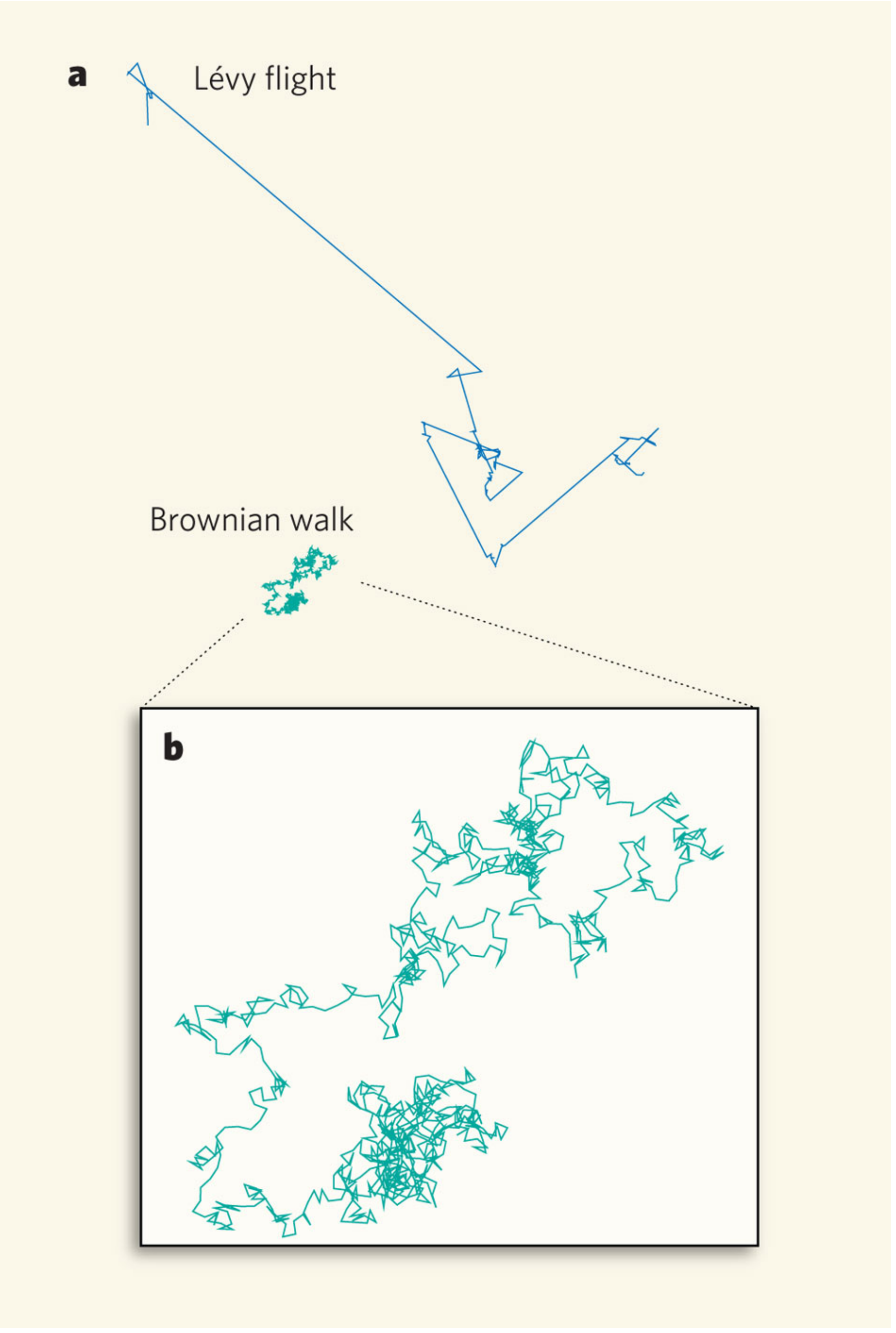
- <u>aggregation</u>
- <u>coordinated movement</u>
- <u>collective exploration and area coverage</u>
- <u>task allocation</u>
- <u>collective decision-making</u>

how do swarm robots move around?

Trianni, V., & Campo, A. (2015). Fundamental Collective Behaviors in Swarm Robotics. In J. Kacprzyk & W. Pedrycz (Eds.), Springer Handbook of Computational Intelligence (pp. 1377–1394). Berlin, Heidelberg: Springer Berlin Heidelberg.

random walks

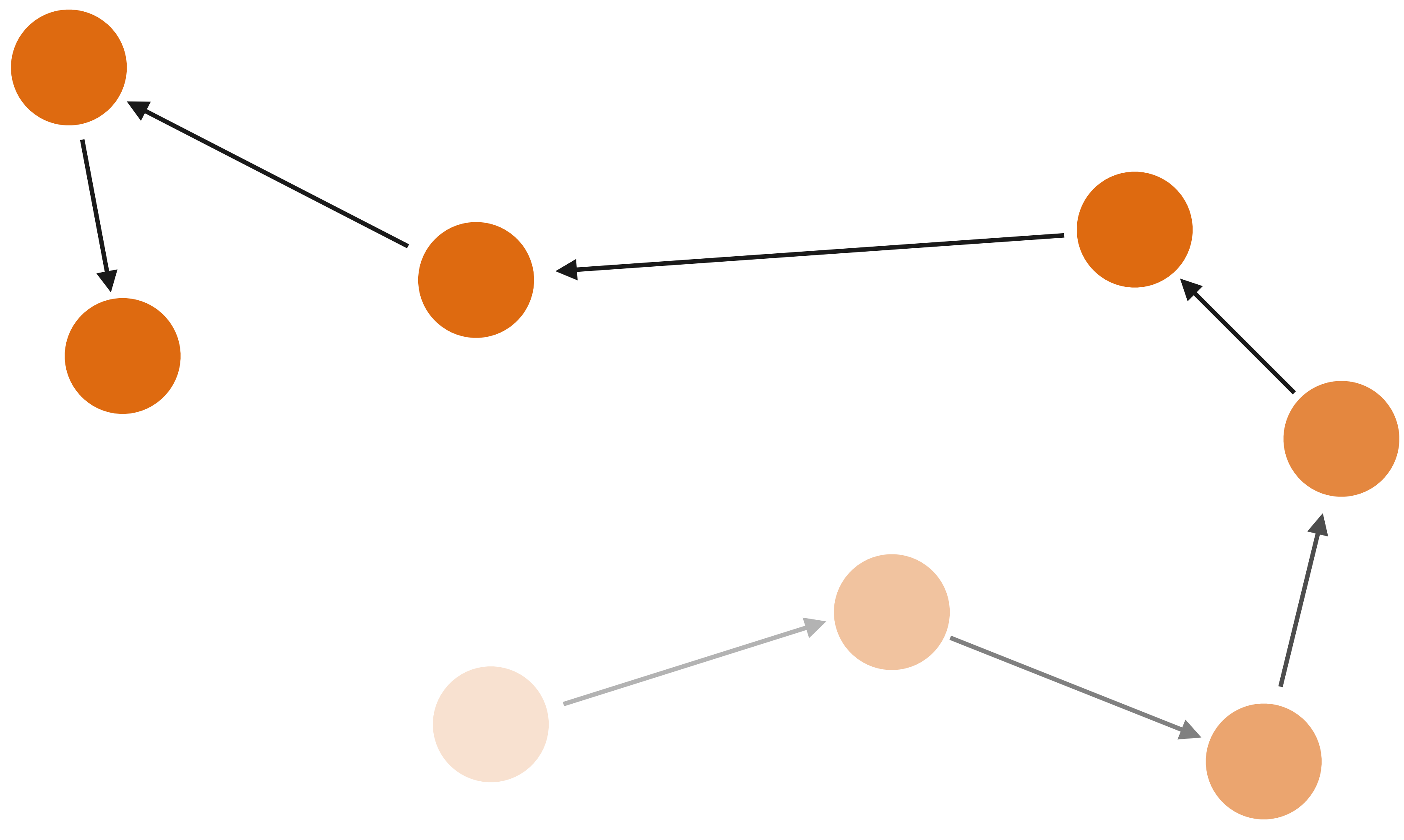
- basic search strategies for animals and robots
- used to search food or to meet others
- no assumption on
  - individual knowledge
  - memory
  - learning abilities



random walks

random walks

alternate straight motion and random turns



need to choose step length and turning angle

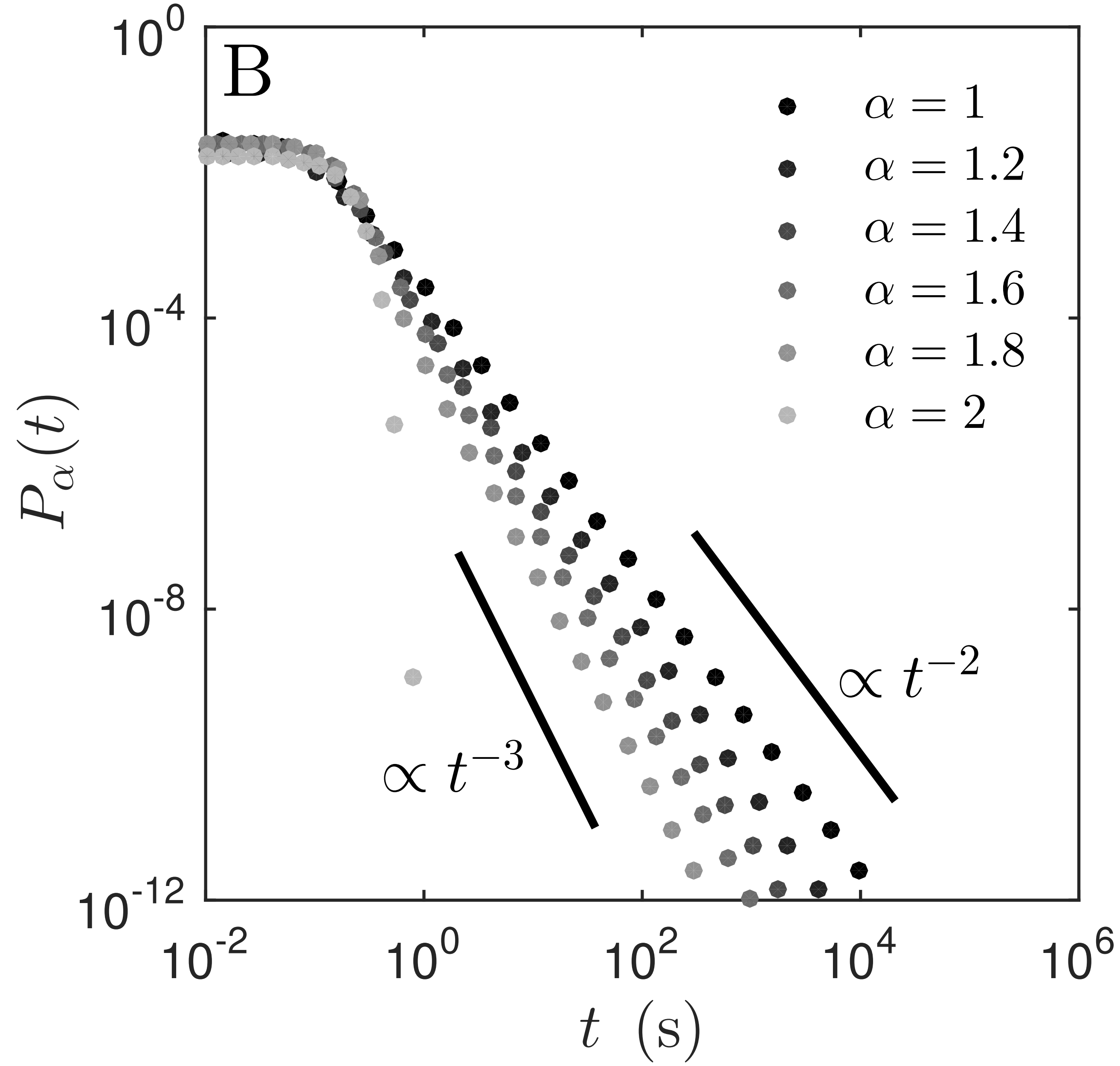
random walks

straight walks drawn from a Lévy distribution

$$P_\alpha(t) \sim t^{-(\alpha+1)}$$

$\alpha = 2 \rightarrow$ Brownian Walk

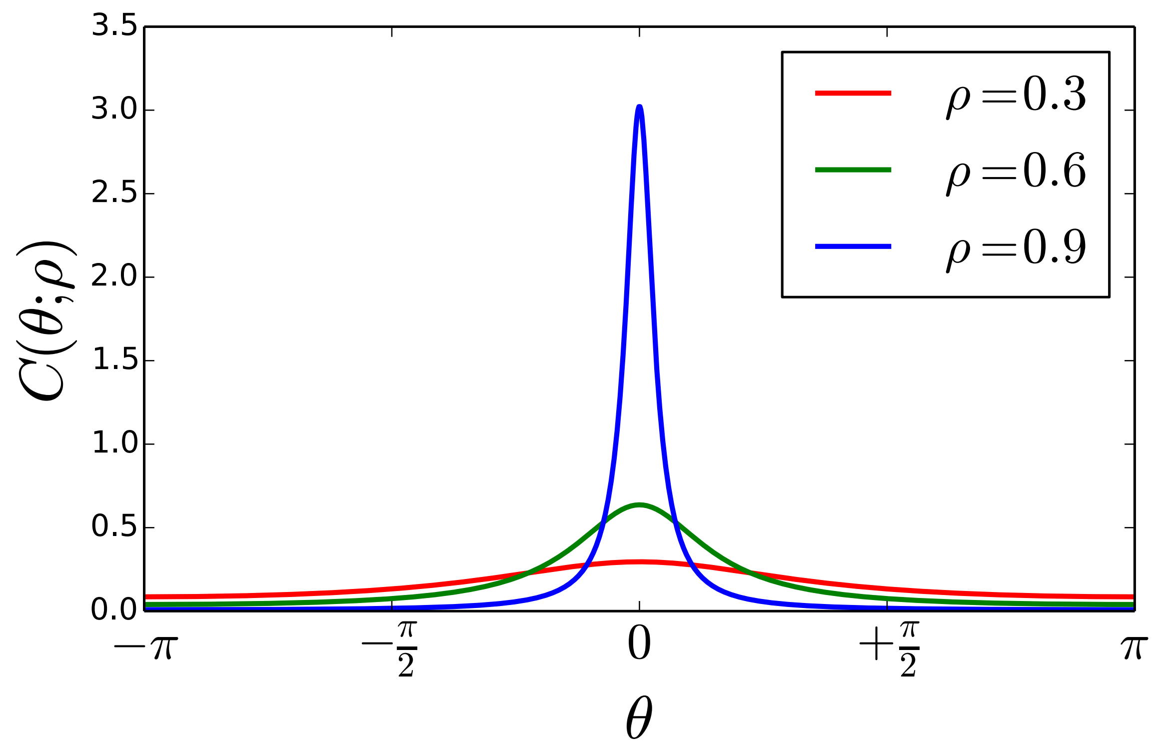
$\alpha < 2 \rightarrow$ Lévy Walk



random walks

random turns drawn from a wrapped Cauchy distribution

$$f_w(\theta;\rho) = \frac{1}{2\pi}\frac{1-\rho^2}{1+\rho^2-2\rho\cos(\theta)}$$



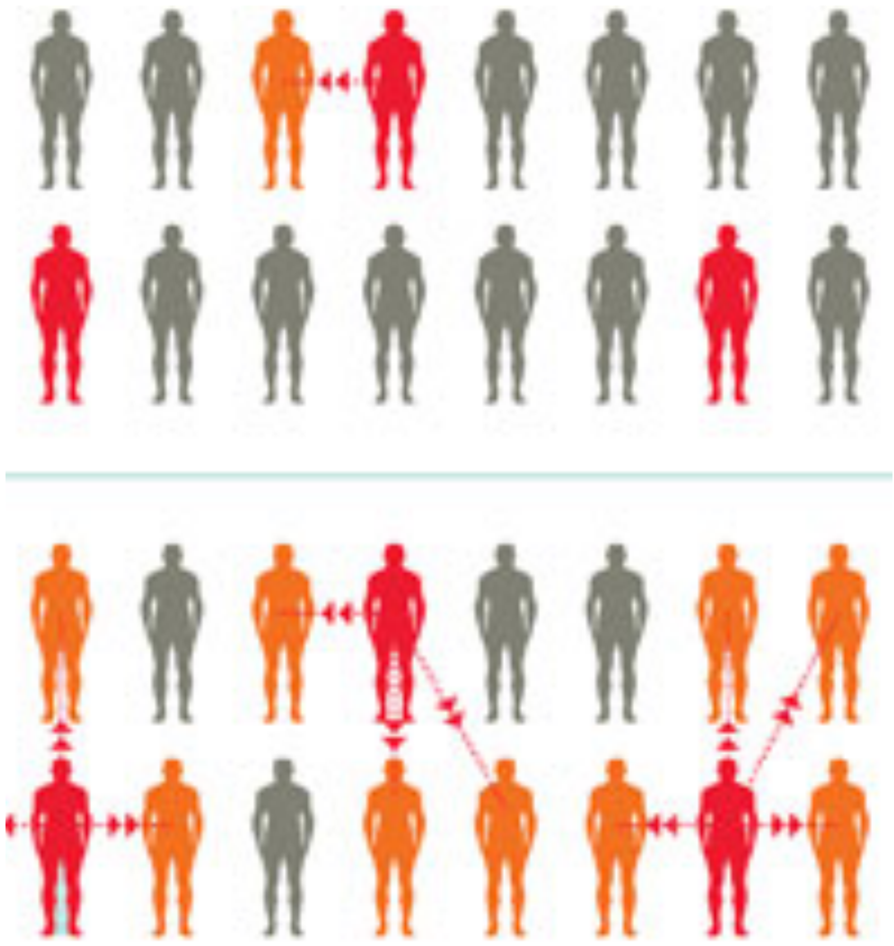
$\rho = 0 \rightarrow$ Isotropic Walk

$\rho > 0 \rightarrow$ Correlated Random Walk

bias toward home with fixed probability
to deal with an open space

random walks

- diffusion of agents in space
- peer to peer contacts within a population
- epidemic spreading of information



aggregation

- *definition*:
  the process that leads a group of agents (robots) to cluster in a specific location

- *precondition*:
  random (uniform) distribution of agents in space

- *postcondition*:
  formation of one or more clusters

- *constraints*:
  limited knowledge and communication range
  (no maps, no self-localisation)

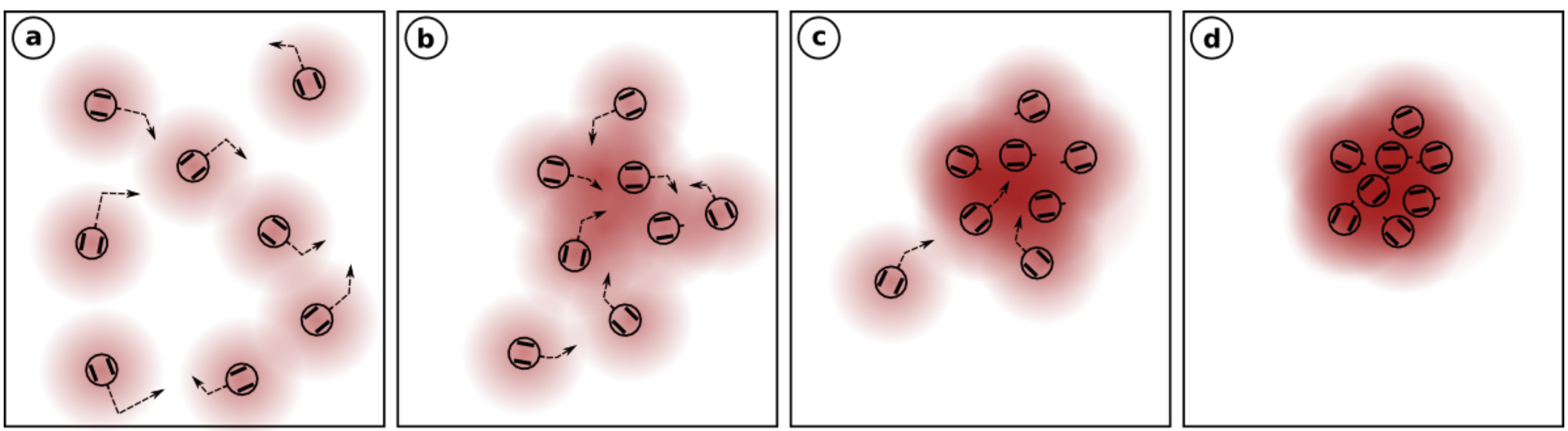
aggregation: variants

- presence or not of environmental heterogeneities (light, humidity, corners)
- homogeneous environment ⇨ agents need to create heterogeneities
  - explicit communication
  - embodiment
- self-organising mechanisms
  - *positive feedback*: amplification of heterogeneities
  - *negative feedback*: physical constraints

aggregation

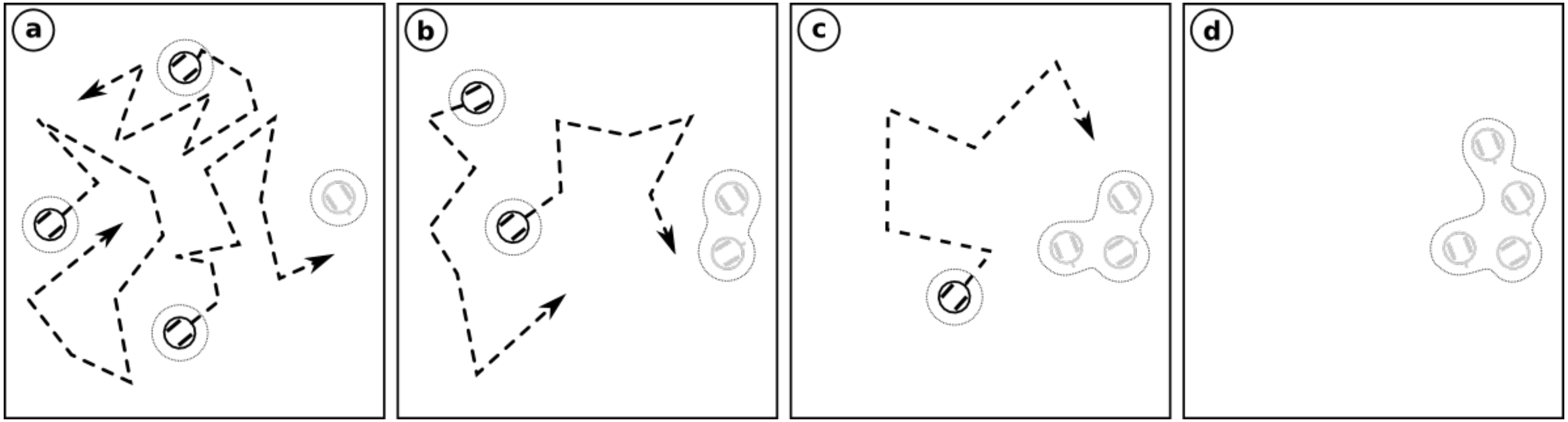
implementation

- every agent emits a signal that diffuses in space
- signals of neighbouring agents sum up
  to become more attractive
- a positive feedback leads to the formation of a single cluster



implementation

- agents move randomly in the environment
- agents stop upon encounters with other agents
- the stopping time depends on the group size



coordinated movement

- *definition*:
  the process that leads a group of agents to move in a coherent and ordered way
- *precondition*:
  every agent moves in a random direction
- *postcondition*:
  agents are polarised, move with the same speed and change direction as a group
- *constraints*:
  lack of a common agreement on the movement direction

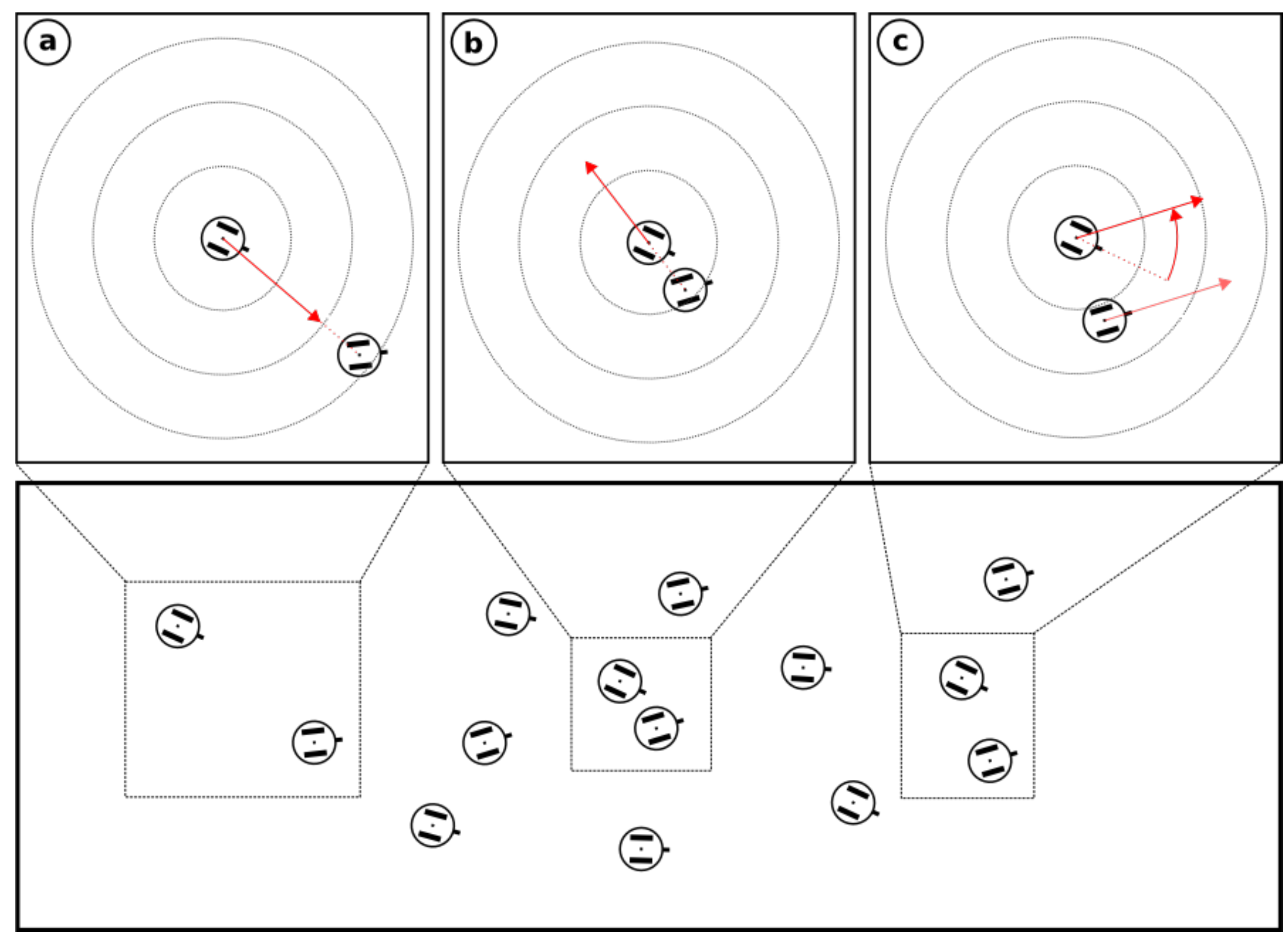
coordinated movement: variants

- a single agent has sufficient information to lead the entire group (centralised approach)
- no agent is more informed than the others (self-organised approach)
- mixed approaches: informed + *naïve* agents

coordinated movement

implementation

- three simple local rules
  - aggregation
  - repulsion
  - alignment
- rules are executed looking at position and orientation of neighbours



collective exploration

- *definition*:
  the process that leads a group of agents to disperse in the environment in search of resources
- *precondition*:
  agents are distributed in the environment
  with some task-dependent rule
  (e.g., start from a home location)
- *postcondition*:
  resources are identified and tracked
- *constraints*:
  limited knowledge and communication range
  avoid to get lost

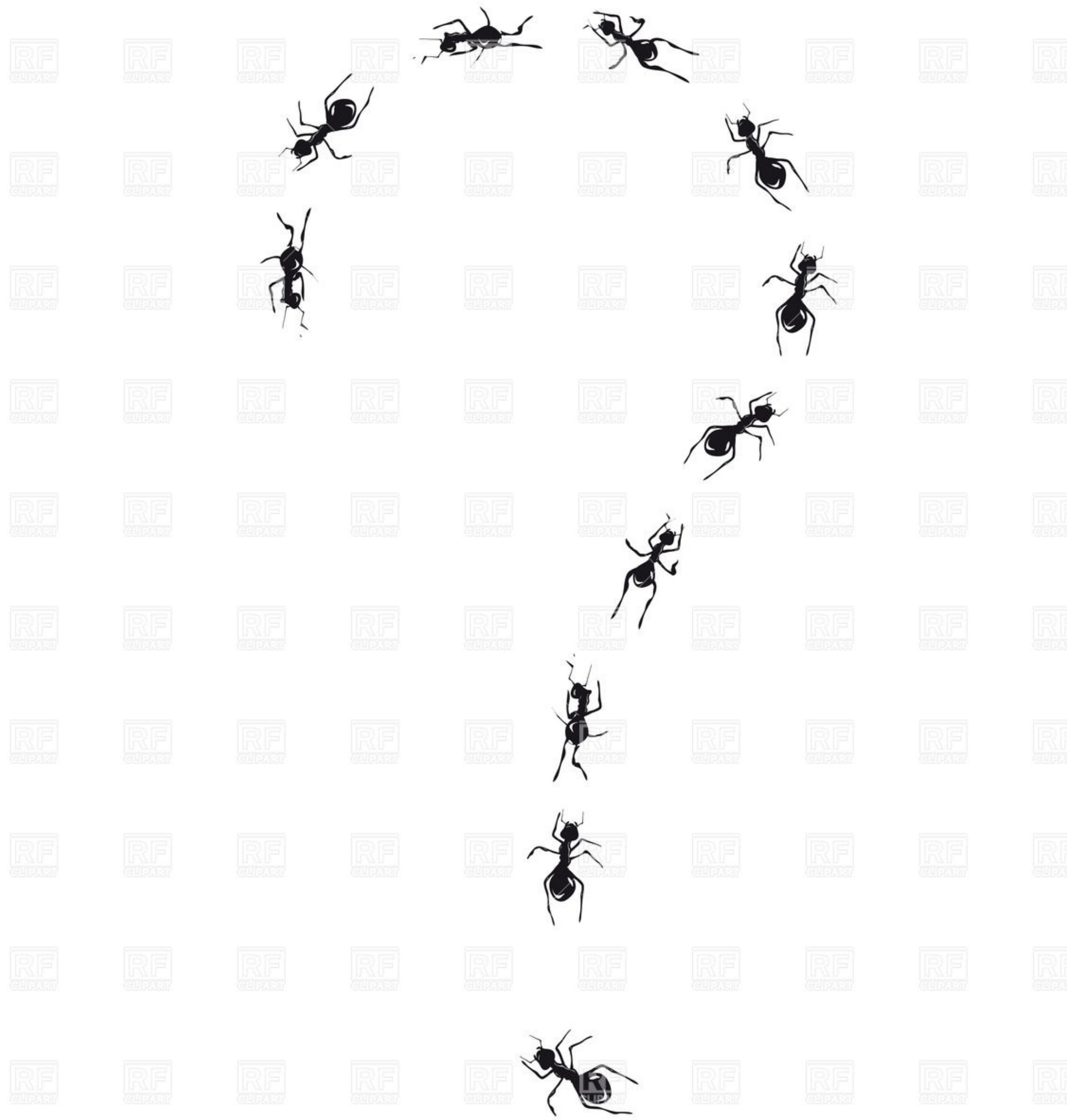
collective exploration: variants

- presence or not of a reference area
  (home location or central place)

- open or closed search area

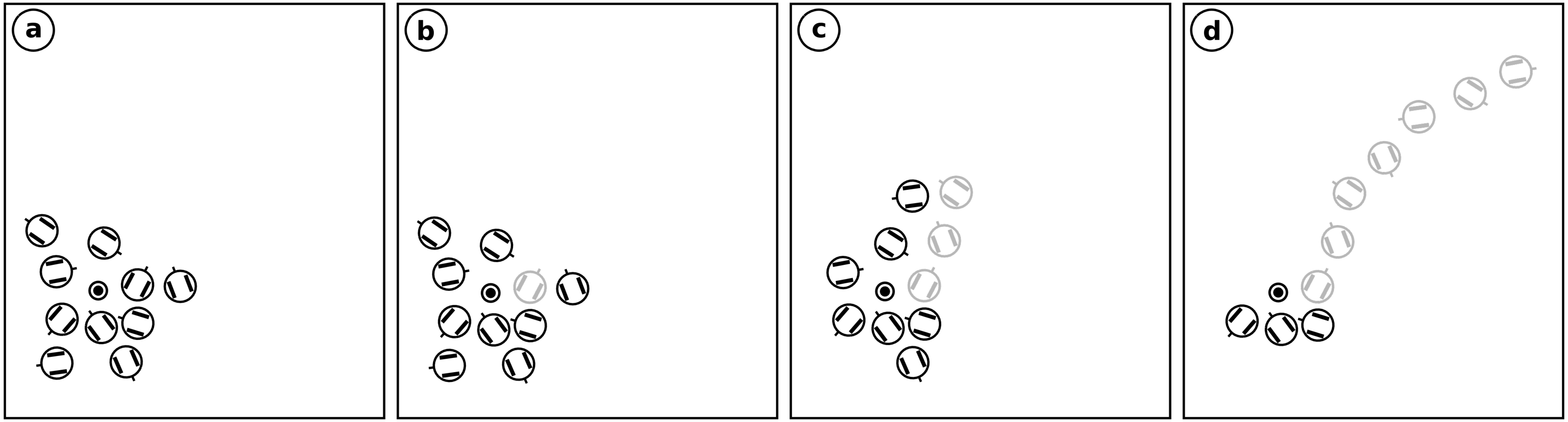
- presence or not of obstacles and varying topology
  (e.g., open space vs. maze)

collective exploration



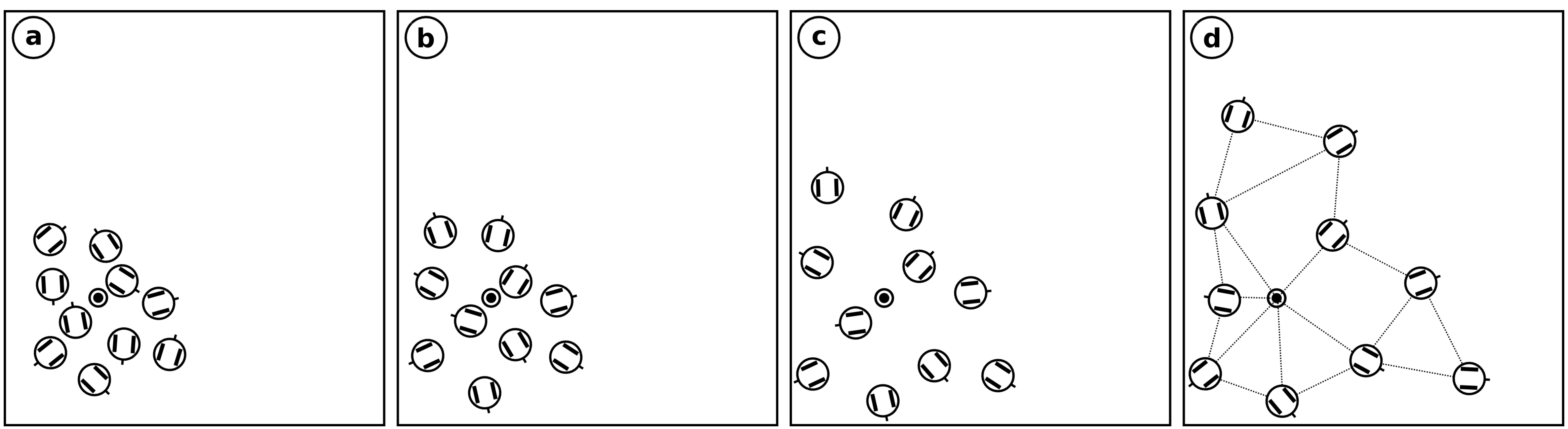
implementation

- creation of chains extending from the central place
- maximisation of search distance
- creation of a navigable structure



implementation

- creation of a connected network of agents that expand starting from the home location
- maximum coverage around the home location
- creation of a navigable structure



task allocation

- *definition*:
  the process that leads a group to (equally) divide labour among the group members

- *precondition*:
  a set of tasks with different labour demands (utility)

- *postcondition*:
  agents are deployed to execute one or more tasks

- *constraints*:
  individuals do not know task requirements
  and other's preferences/choices

task allocation: variants

- single-task (ST) versus multi-task robots (MT)
- single-robot (SR) versus multi-robot tasks (MR)
- instantaneous (IA) versus time-extended assignment (TA)

Gerkey, B. P., & Matarić, M. J. (2004). A Formal Analysis and Taxonomy of Task Allocation in Multi-Robot Systems. The International Journal of Robotics Research, 23(9), 939–954.

TA via response thresholds

Theraulaz, G., Bonabeau, E., & Denuebourg, J. N. (1998). Response threshold reinforcements and division of labour in insect societies. Proceedings of the Royal Society of London. Series B: Biological Sciences, 265(1393), 327–332.

TA via response thresholds

- tasks are associated with a utility (stimulus)

$$S_j, j \in \{1, \ldots, M\}$$

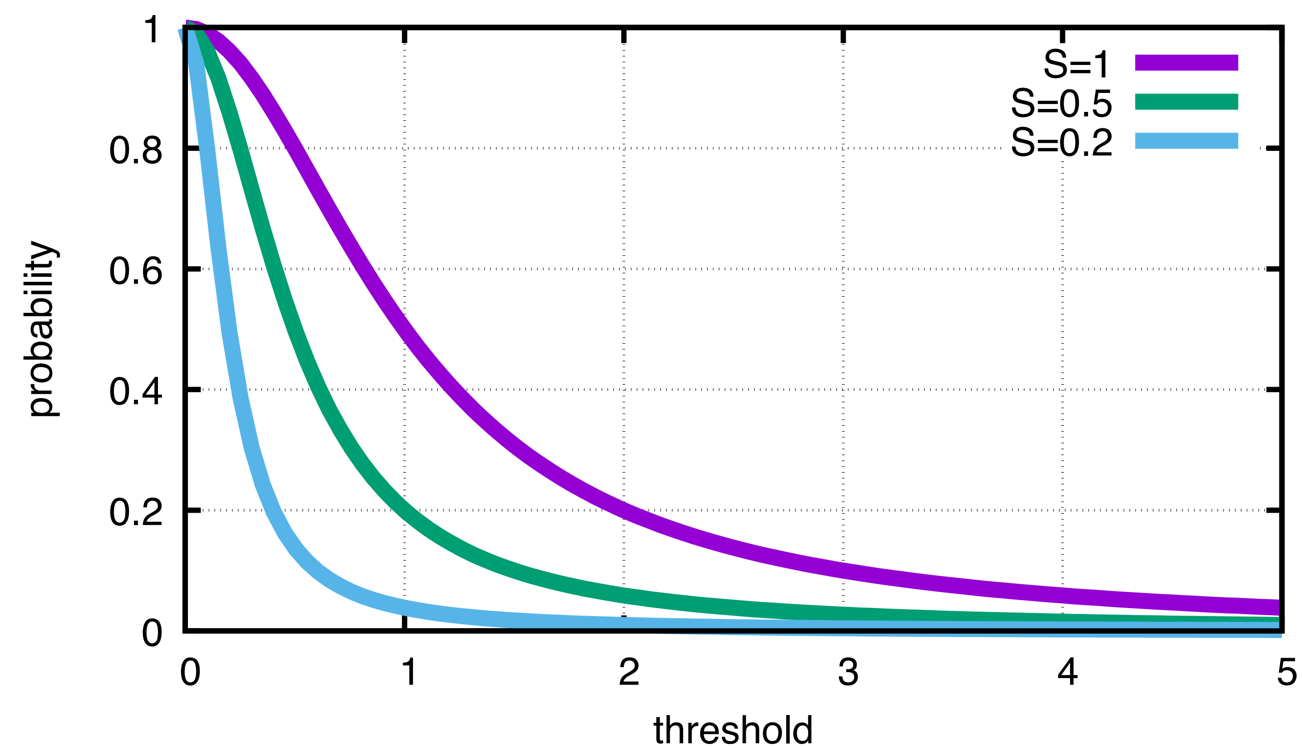
- agents have a response threshold for each task

$$\theta_{ij}, i \in \{1, \ldots, N\}$$

TA via response thresholds

- agents apply a simple decision rule

$$\mathcal{P}_i(S_j) = \frac{S_j^2}{S_j^2 + \theta_{ij}^2}$$



- task utility varies over time

spontaneous growth

enrolled agents

$$\dot{S}_j = \delta - \alpha \frac{n_j}{N}$$

individual execution rate

TA via response thresholds

- How to assign threshold to have specialised agents? What about generalists?
- How would you distribute thresholds if tasks have equal probability?
- What if a task is more frequent?
- Adaptive response threshold model:

$$\theta_{ij} \leftarrow \theta_{ij} - \xi \Delta t \quad \text{if agent } i \text{ performs task } j$$

$$\theta_{ij} \leftarrow \theta_{ij} + \xi \Delta t \quad \text{if agent } i \text{ does not perform task } j$$

collective decisions

- *definition*:
  the process that leads a group to identify
  the best option out of several alternatives
- *precondition*:
  partial/noisy information about the available alternatives
- *postcondition*:
  the group (or a large majority) shares the same choice
- *constraints*:
  individuals cannot know/compare all alternatives

collective decisions: variants

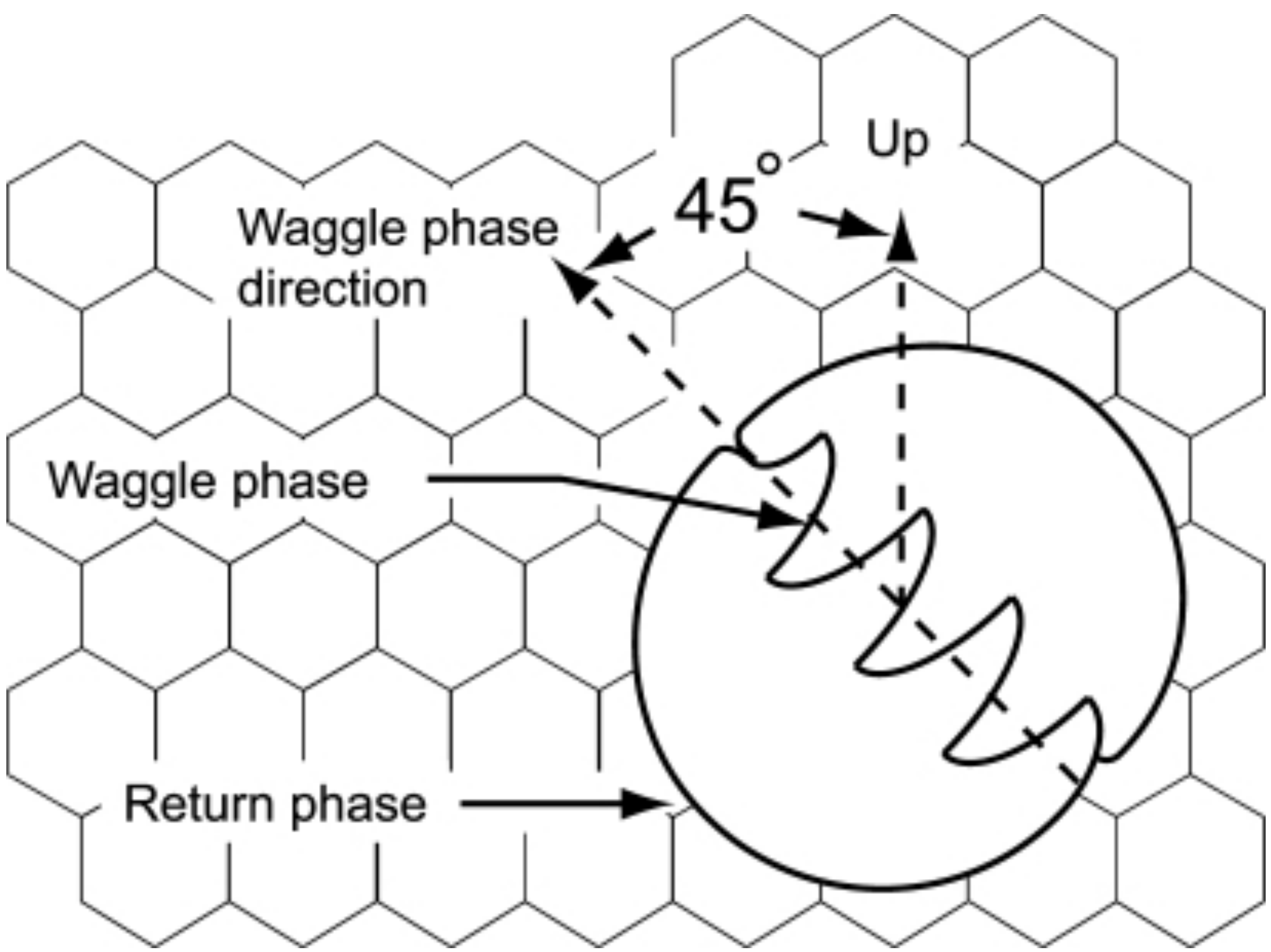
- simple propagation of information
- averaging of opinions (i.e., wisdom of the crowd)
- amplifications of the best choices

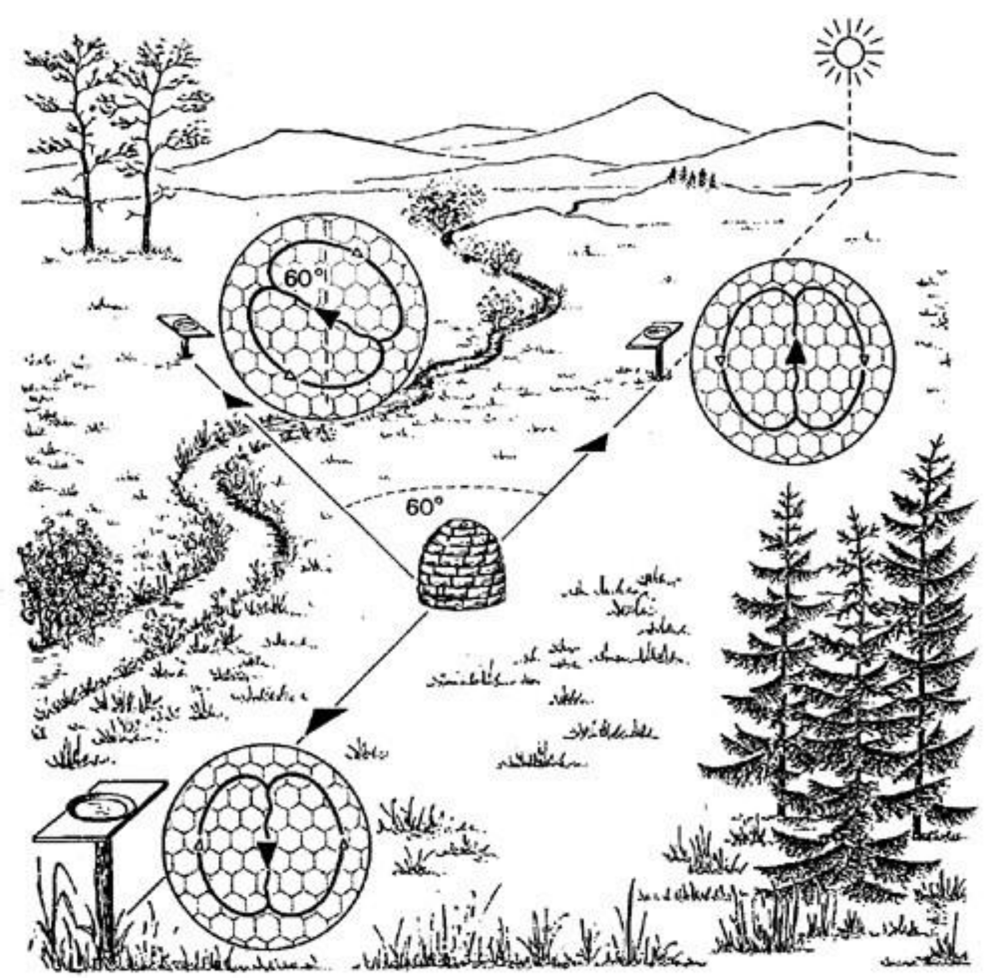
collective decisions in bees

a swarm needs to select the new nesting site

collective decisions

scout bees identify the available alternatives and share information through the 'waggle dance'





nest-site selection model

discovery:

U ⟶ A
U ⟶ B

abandonment:

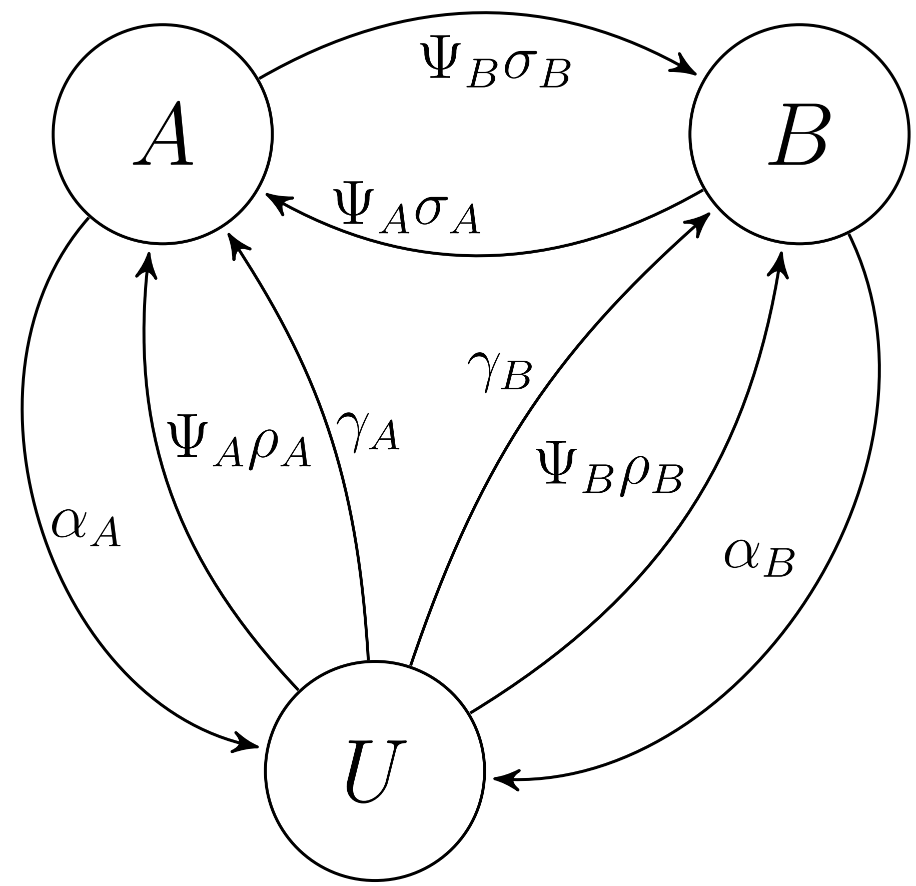
A ⟶ U
B ⟶ U

recruitment:

A+U ⟶ A+A
B+U ⟶ B+B

direct switch:

A+B ⟶ A+A
B+A ⟶ B+B



$$\begin{cases} \dot{\Psi}_A = \gamma_A\Psi_U - \alpha_A\Psi_A + \rho_A\Psi_A\Psi_U - (\sigma_A - \sigma_B)\Psi_A\Psi_B \\ \dot{\Psi}_B = \gamma_B\Psi_U - \alpha_B\Psi_B + \rho_B\Psi_B\Psi_U - (\sigma_B - \sigma_A)\Psi_A\Psi_B \\ \Psi_U = 1 - \Psi_A - \Psi_B \end{cases}$$

nest-site selection model

discovery:

$$U \longrightarrow A$$
$$U \longrightarrow B$$

abandonment:

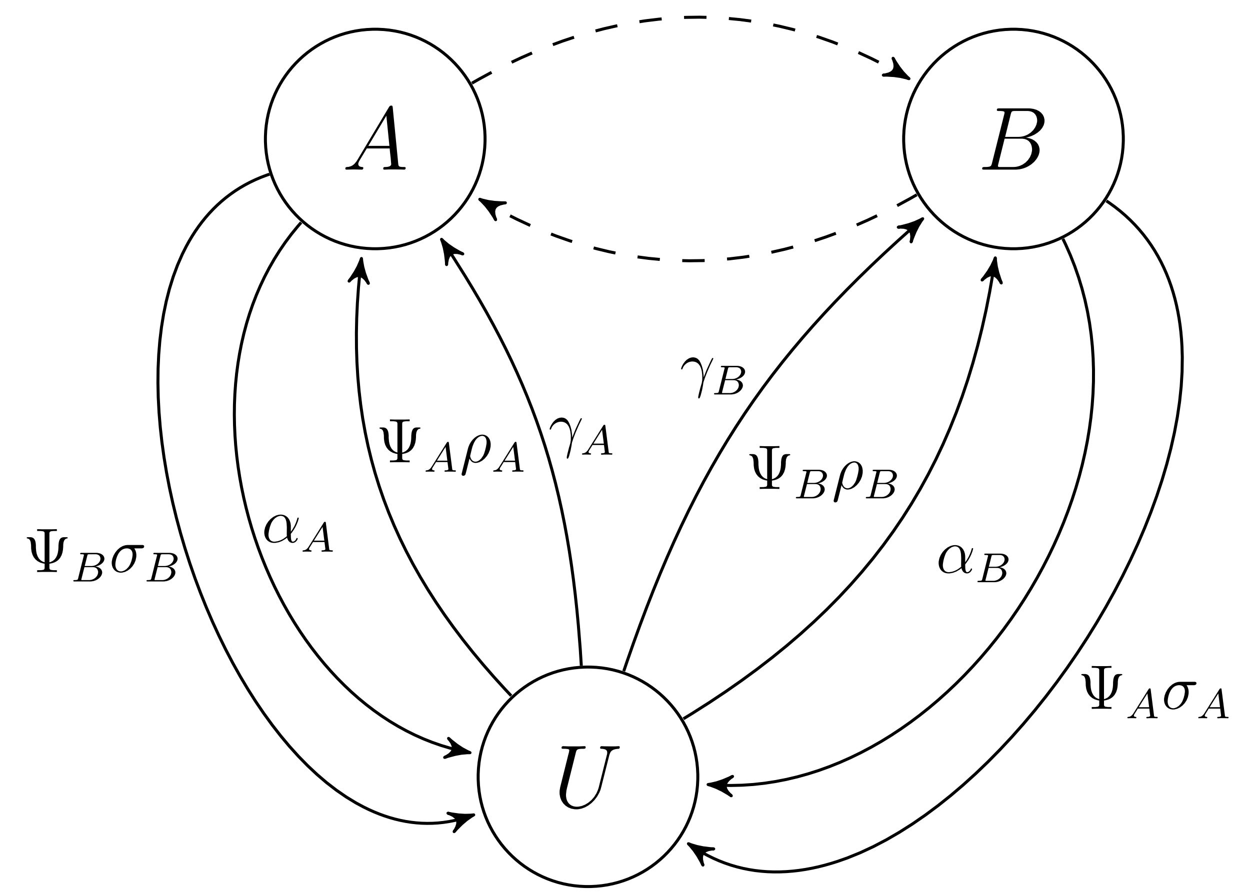
$$A \longrightarrow U$$
$$B \longrightarrow U$$

recruitment:

$$A+U \longrightarrow A+A$$
$$B+U \longrightarrow B+B$$

cross-inhibition

$$A+B \longrightarrow A+U$$
$$B+A \longrightarrow B+U$$



$$\begin{cases} \dot{\Psi}_A = \gamma_A\Psi_U - \alpha_A\Psi_A + \rho_A\Psi_A\Psi_U - \sigma_B\Psi_A\Psi_B \\ \dot{\Psi}_B = \gamma_B\Psi_U - \alpha_B\Psi_B + \rho_B\Psi_B\Psi_U - \sigma_A\Psi_A\Psi_B \\ \Psi_U = 1 - \Psi_A - \Psi_B \end{cases},$$

thanks for your attention

- References:

  - Trianni, V., & Campo, A. (2015). Fundamental Collective Behaviors in Swarm Robotics. Springer Handbook of Computational Intelligence (pp. 1377–1394).
  - Dimidov, C., Oriolo, G., & Trianni, V. (2016). Random Walks in Swarm Robotics: An Experiment with Kilobots. Swarm Intelligence: 10th International Conference, ANTS 2016, Brussels, Belgium, September 7-9, 2016
  - Reina, A., Valentini, G., Fernández-Oto, C., Dorigo, M., & Trianni, V. (2015). A Design Pattern for Decentralised Decision Making. PLoS ONE, 10(10), e0140950–18.
  - Reina, A., Marshall, J. A. R., Trianni, V., & Bose, T. (2017). Model of the best-of-N nest-site selection process in honeybees. Physical Review E, 95(5), 052411–15.

- Resources:
  - DICE — Distributed Cognition Engineering
    http://laral.istc.cnr.it/dice-project/
  - SAGA — Swarm Robotics for Agricultural Applications
    http://laral.istc.cnr.it/saga/
- Master thesis available!

http://laral.istc.cnr.it/trianni/index.php/theses-proposte-tesi/

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