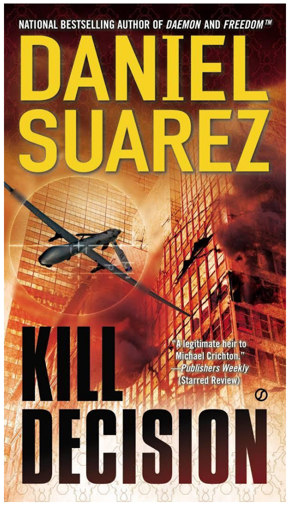
Robot Swarms are “popular” They are mind boggling...

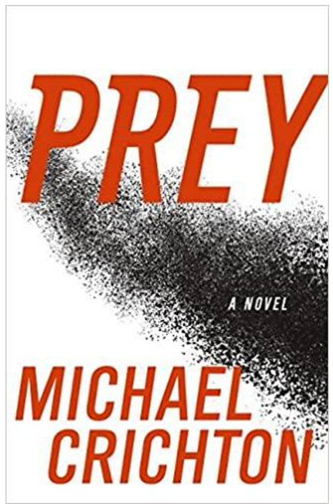
... although quite scary, too

(From Hated in the Nation, 2016.)

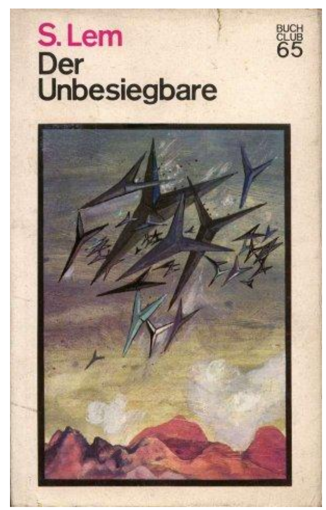
Despite they aren’t “that new”…



In fact, the colony is the real organism, not the individual.
—Daniel Suarez, Kill Decision (2012)



But it was one thing to release a population of virtual agents inside a computer’s memory to solve a problem.
It was another thing to set real agents free in the real world.
—Michael Crichton, Prey (2002)



The flying swarm is immediately sent into the ‘cloud-brain’ formation and its collective memory reawakens.
—Stanisław Lem, The Invincible (1964)

… they don't exist yet (fortunately)

Theory barrier: A useful complex and powerful behavior of a large number of robots is wanted to emerge* from the local and little informed behaviors of the simple and expendable individuals.

* in a robust, flexible, adaptable, scalable, provable way

Practice barrier: Very many simple, and small, robots are required, but they need to be versatile and autonomous.

In others' words:

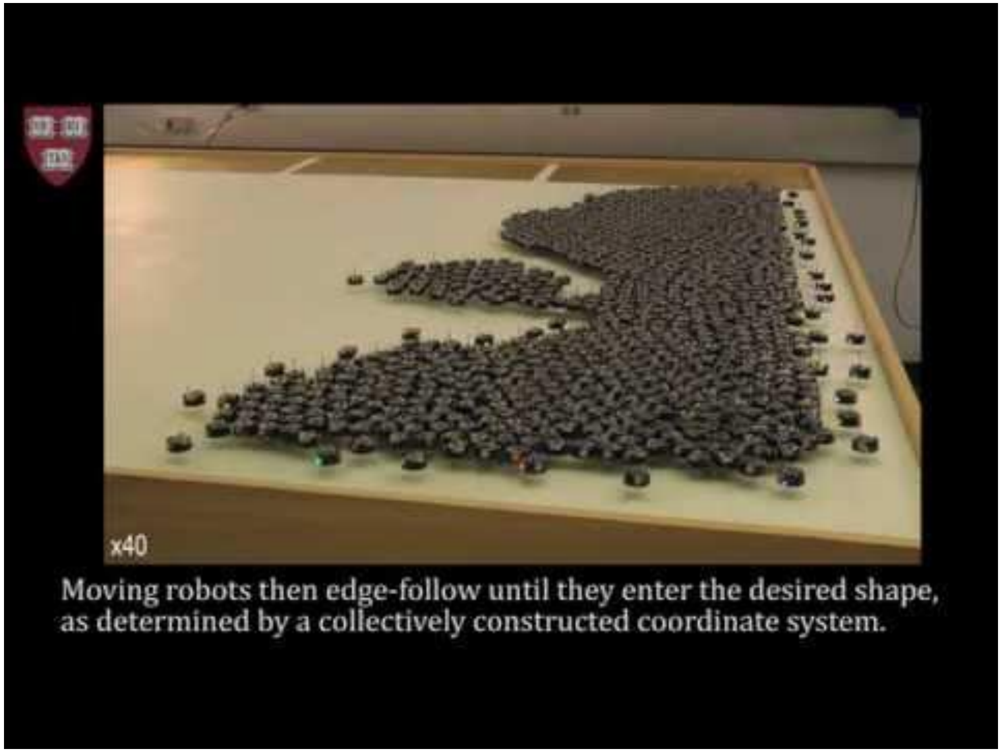
*"Swarm robotics has **several possible applications**, including: exploration, surveillance, search and rescue, humanitarian demining, intrusion tracking, cleaning, inspection and transportation of large objects.*

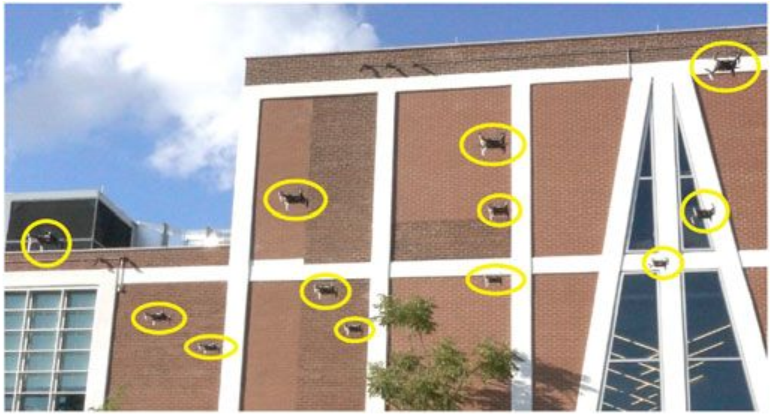
*Despite their **potential to be robust, scalable and flexible**, up to now, swarm robotics systems **have never been used to tackle a real-world application** and are still confined to the world of academic research.*

*At the current state of development of the swarm robotics field, the focus is mostly on **obtaining desired collective behaviors and understanding their properties**. In order to avoid the problems that arise in real-world applications, researchers usually tackle a simplified testbed application."*

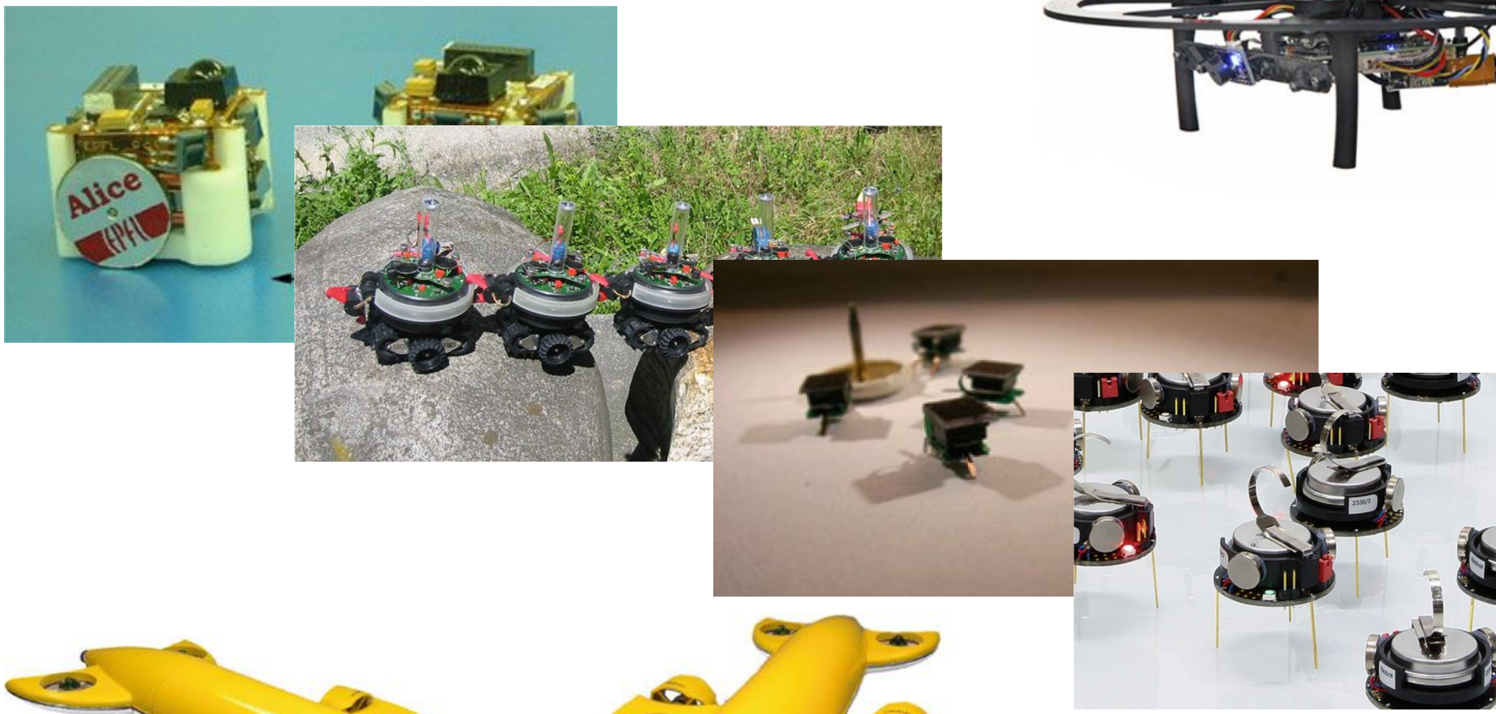
M. Brambilla *et al.* Swarm robotics: a review from the swarm engineering perspective.

Well, in fact they do exist, but...

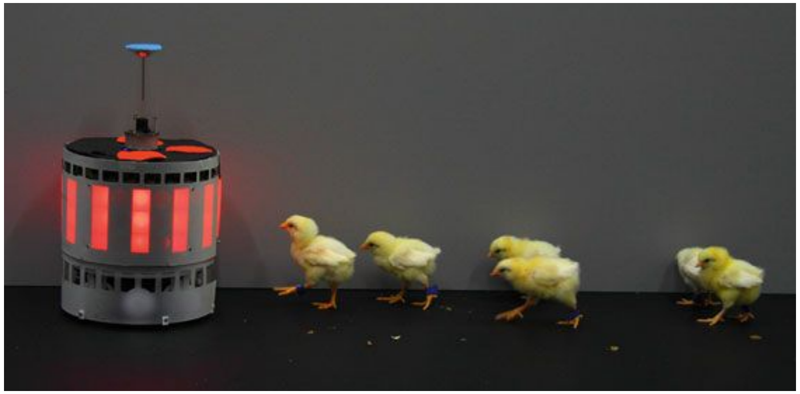


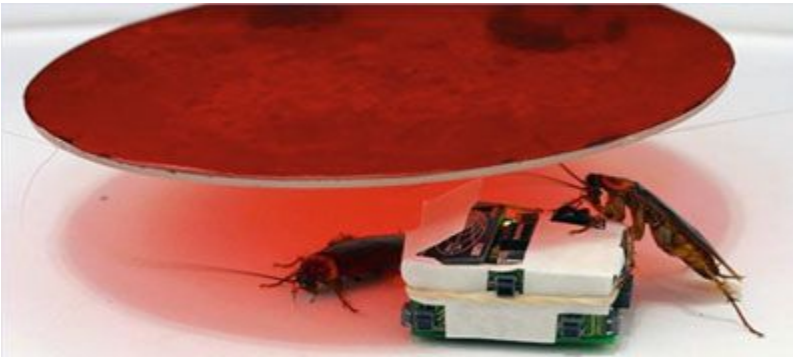


Toy Stories



So, why do we think it possible?





Swarm Robotics

Multi-Robot Systems

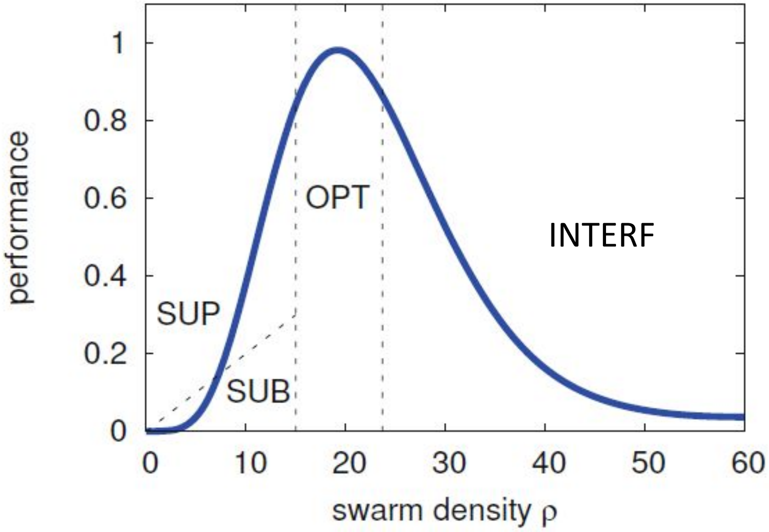
- H. Hamann (2018). Swarm robotics: A formal approach. Springer
- M. Brambilla, E. Ferrante, M. Birattari, M. Dorigo (2013). Swarm robotics: a review from the swarm engineering perspective. Swarm Intell 7:1–41
- M. Dorigo, M. Birattari, M.Brambilla (2014). Swarm robotics. Scholarpedia, 9(1), 1463
- A. Kolling, P. Walker, N. Chakraborty, K. Sycara, M. Lewis (2016), Human Interaction With Robot Swarms: A Survey, IEEE THMS 46(1): 9-26
- J. Sánchez-García et al. (2018), A survey on unmanned aerial and aquatic vehicle multi-hop networks: Wireless communications, evaluation tools and applications, Computer Communications 119: 43-65
- S. Chung, A. A. Paranjape, P. Dames, S. Shen and V. Kumar (2018), A Survey on Aerial Swarm Robotics, IEEE TRO 34(4), 837-855

Basic questions

- What is a swarm?

  Swarming ***behavior***
- How big is a swarm?

  $10 << N << 10^{23}$?



Basic questions

- What is a swarm?
- How big is a swarm?
- What is swarm robotics?

(The study of how to get) A **large number** of relatively **simple** physically **embodied** agents (to) exhibit a desired **collective behavior** that **emerges** from the **local interactions** among agents and between the agents and the **environment**

(Excuse me, you said environment?)

Stigmetry

Indirect coordination through “something” in the environment:

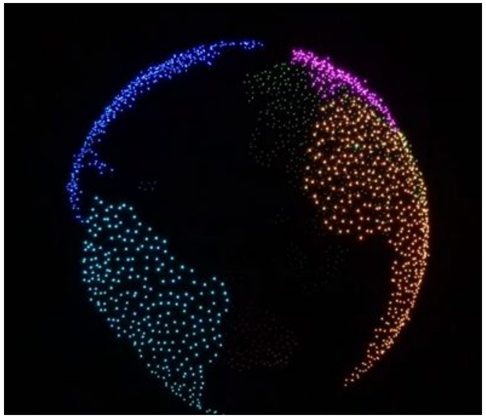
- Objects, e.g., cleansing
- Trails (involuntary), e.g., chase
- Pheromones (on purpose), e.g., guidance, even area measurement: $2L^2/(n\pi)$ is a good estimate, where n is the number of intersections of two arbitrary paths of length L

Basic questions

- What is a swarm?
- How big is a swarm?
- What is swarm robotics?
- Why swarm robotics?
  – Robustness (and Resilience)
  – Flexibility and Adaptability
  – Scalability

Basic questions

- What is a swarm?
- How big is a swarm?
- What is swarm robotics?
- Why swarm robotics?
- What is not swarm robotics?



Basic questions

- What is a swarm?
- How big is a swarm?
- What is swarm robotics?
- Why swarm robotics?
- What is not swarm robotics?
- Homo or hetero?

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Methods

- Design
- Analysis
- Simulation
- Experimentation

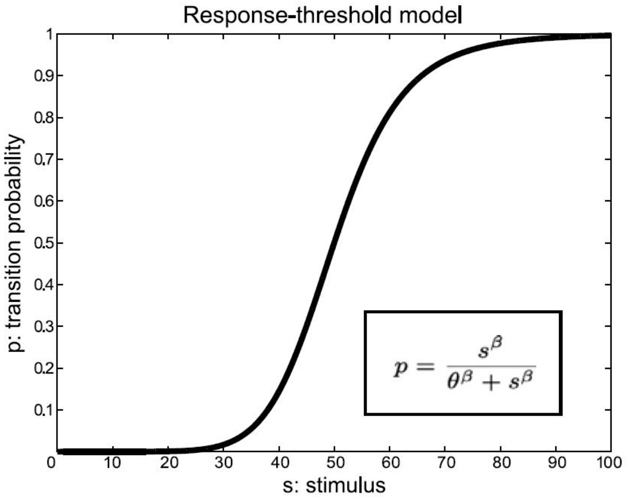
Methods: Design

Intuition is still the main ingredient.

Behavior-based design:

Individual behavior of each robot implemented and improved (trial-error) until desired collective behavior obtained (bottom-up)

- Probabilistic finite state machines
- Virtual physics



Automatic design:

- Evolutionary
- Reinforcement learning

Methods: Analysis

Microscopic models and simulations

- Level of detail (points, point-masses, physics, sensors, ...)
- Scalability? How to simulate very many robots in RT?

Macroscopic models and equations

- Rate and differential equations. The micro-macro link. Langevin & Fokker-Plank [Hamann]
- Classical control and Lyapunov's stability theory

Other mathematical frameworks (multidisciplinary)

From logic, multi-physics, populations, social, ...

Methods: Simulation

Many options:

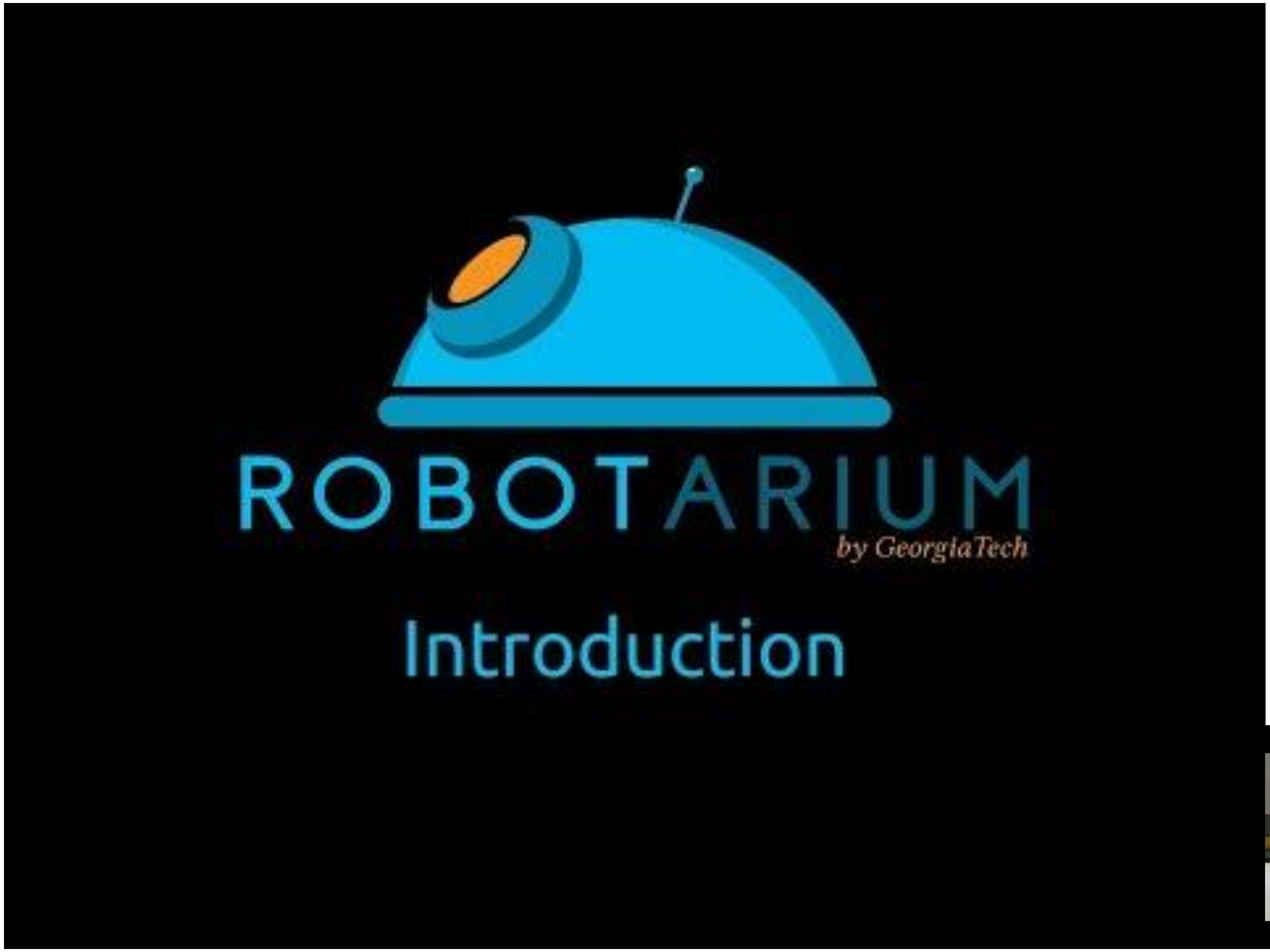
- Matlab
- C++, **Python**
- ROS, ROS+Gazebo
- Some “serious” (academic) ad-hoc simulator

The scalability problem. Three options:

- **Time scale**
- High-performant code (low level Sw eng + Hw accel)
- Distributed simulation

Is it possible to “prove by simulation”?

Methods: Experimentation



Some Scenarios

- Aggregation
- Clustering
- Pattern and Chain Formation
- Self-Assembly
- Coordinated Motion (or Flocking)
- Collective Transport
- Decision-Making (e.g., Division of Labor)
- Decision-Making (e.g., Path Selection)

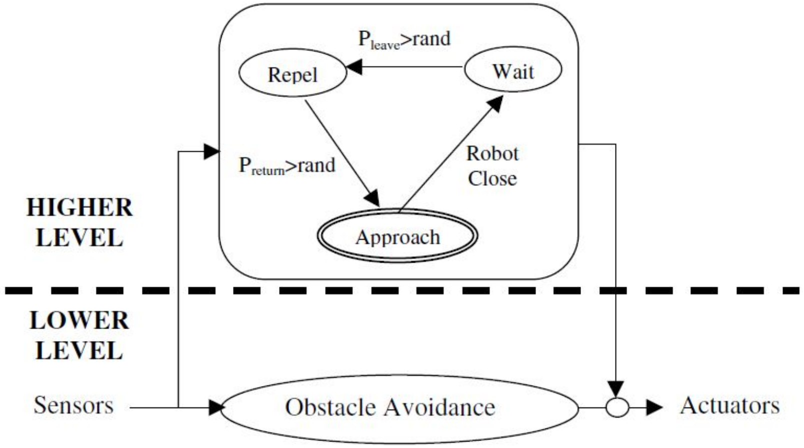
Aggregation

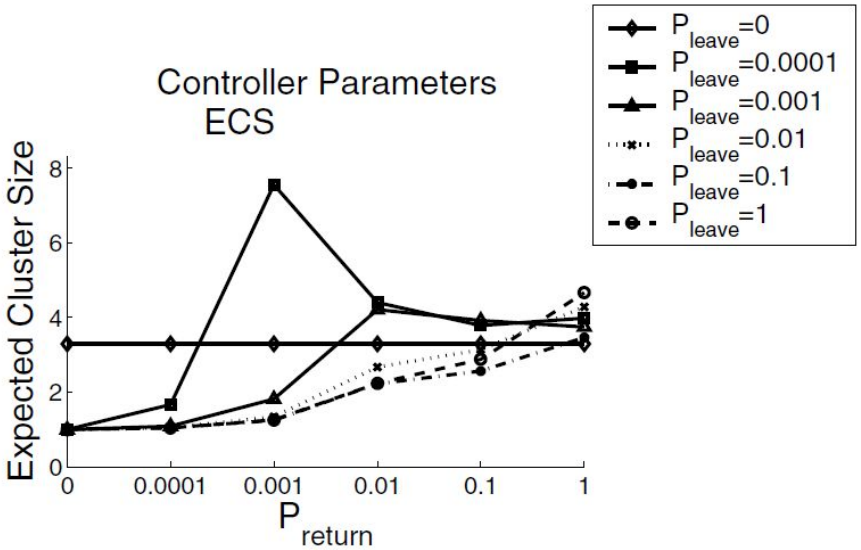
Group all robots in a region

Very useful building block, and very common in nature: unity makes strength

PFSM approach: when a robot finds others it decides whether to join or leave; probabilities (join large groups, leave small groups that don’t grow) and anti-agents (e.g., leave large groups) have diverse effects

O. Soysal, E. Sahin (2005)





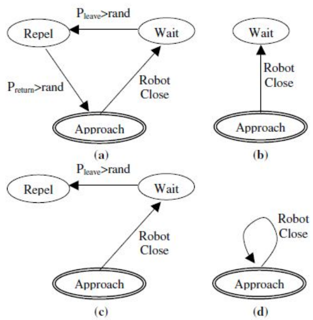
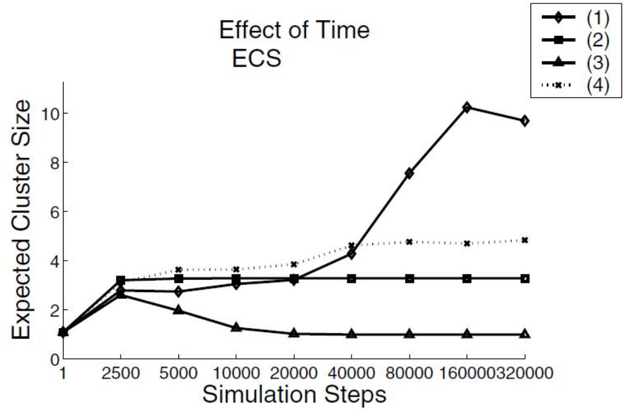
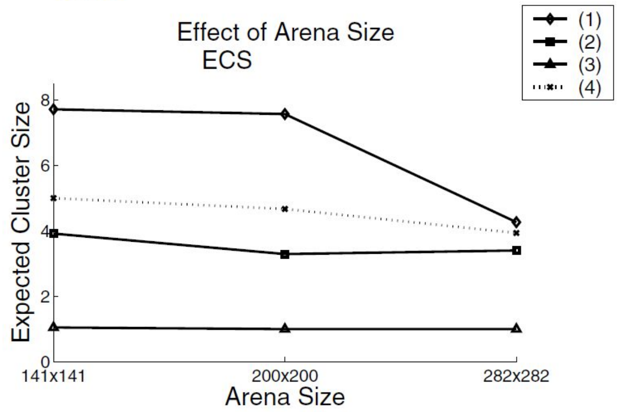
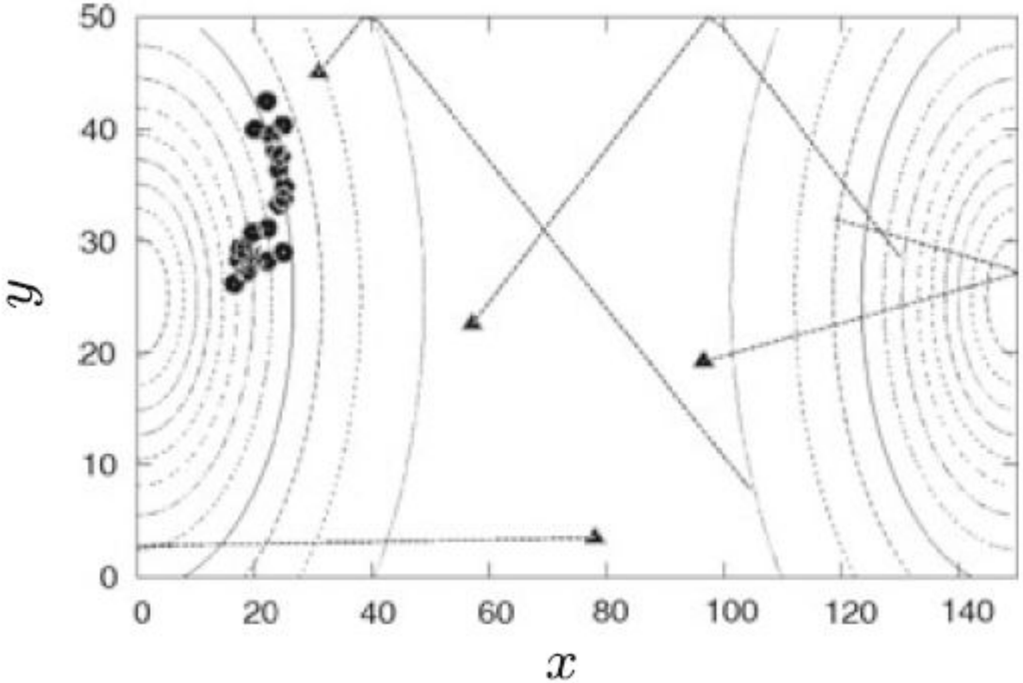


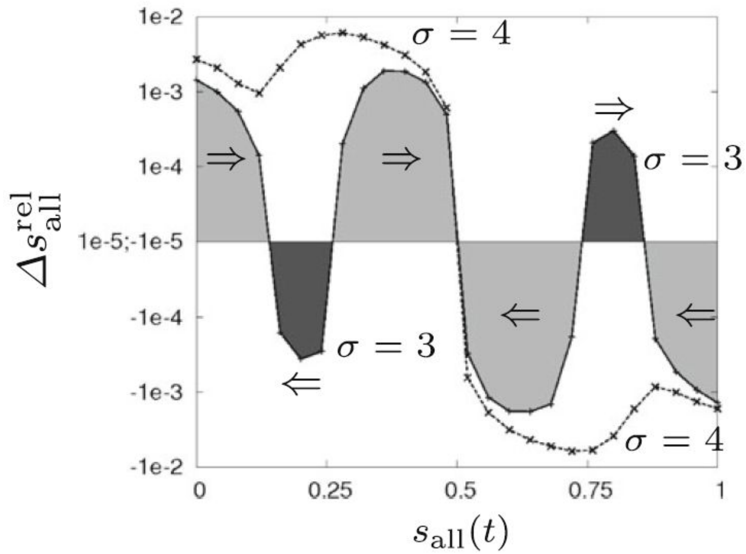
Figure 7. Finite State Machine representations of the aggregation behaviors studied are shown. (a) strategy 1, (b) strategy 2, (c) strategy 3, (d) strategy 4. See text for detailed description.





H. Hamann et al. (2012)





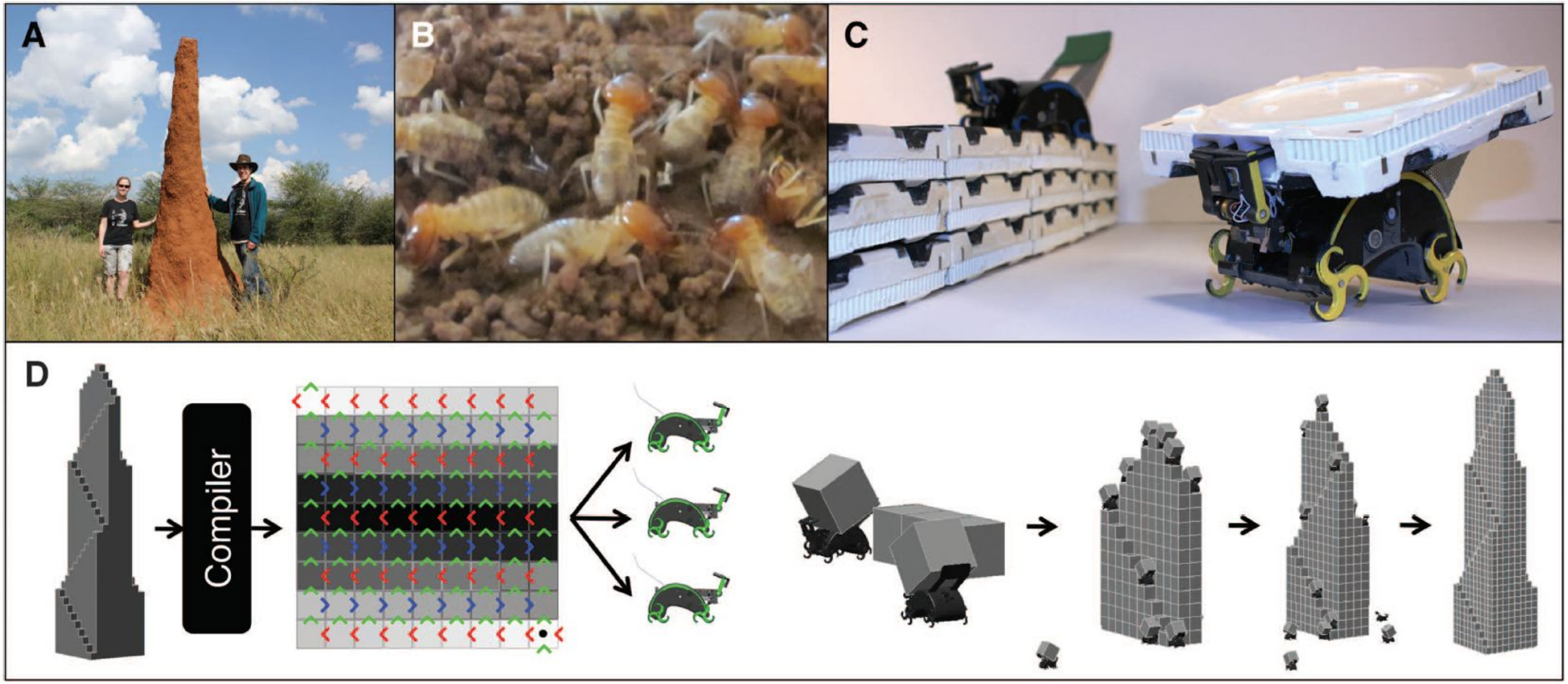
Clustering

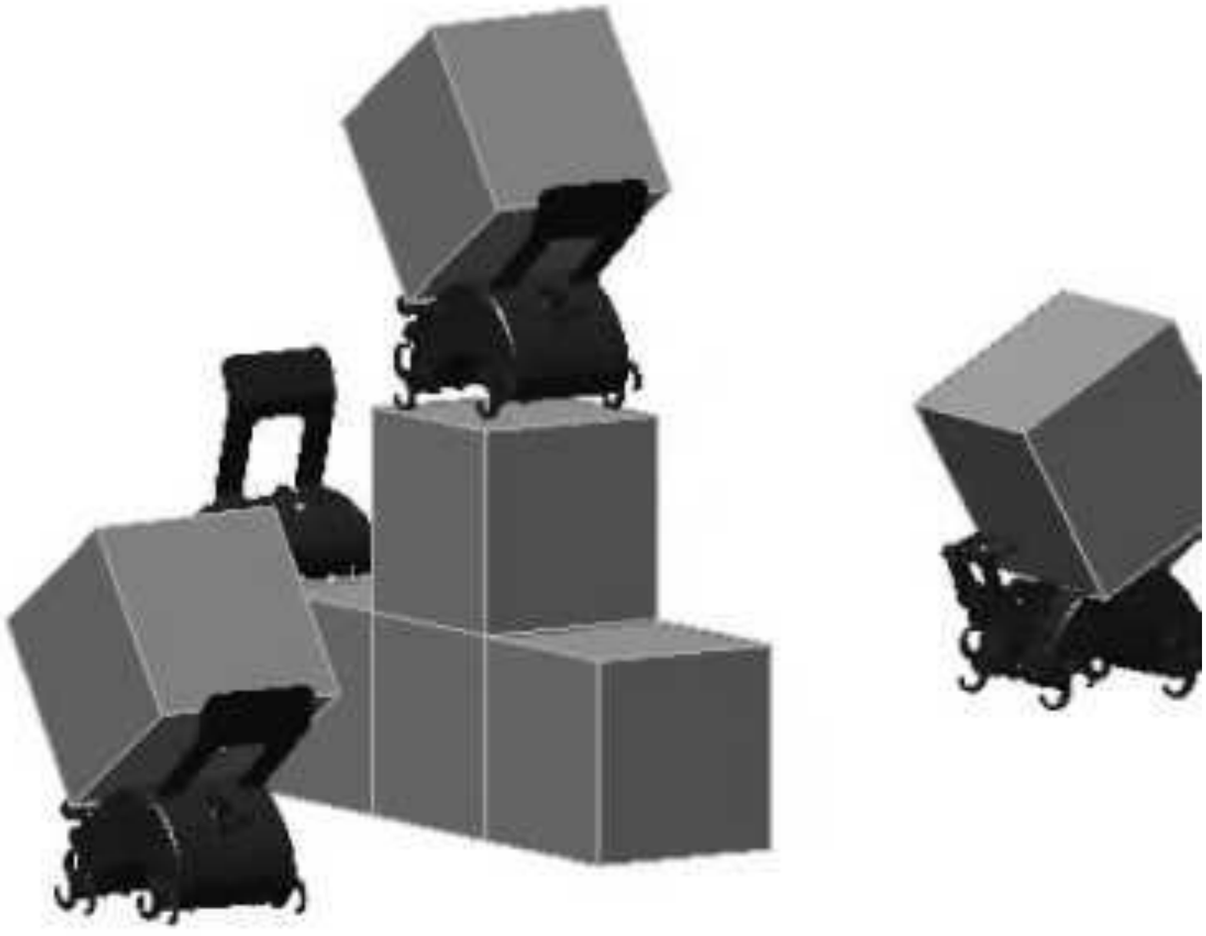
Put objects together in a region

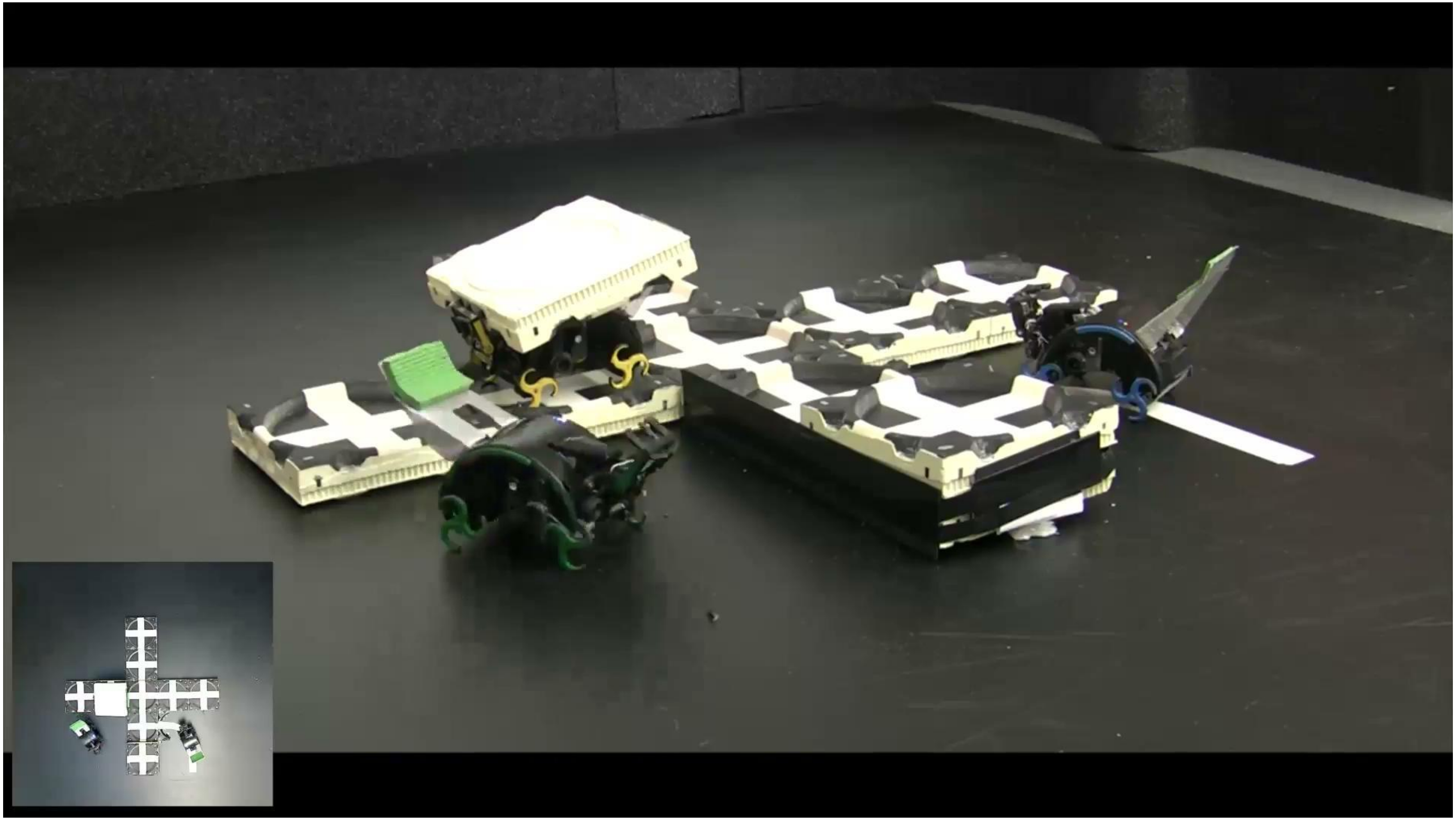
Another very common and useful building block, e.g., foraging and construction applications

PFSM approach: if you don't have an object, pick one; if you have an object, leave it near another; probabilities (don't pick when object near others, leave better near many) and anti-agents have diverse effects

J. Werfel, K. Petersen,R. Nagpal (2014)







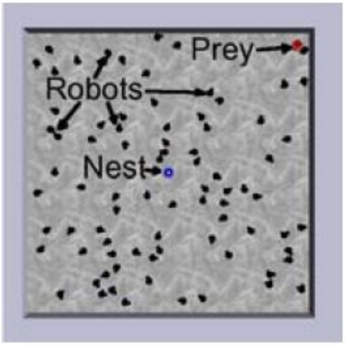
Pattern and Chain Formation

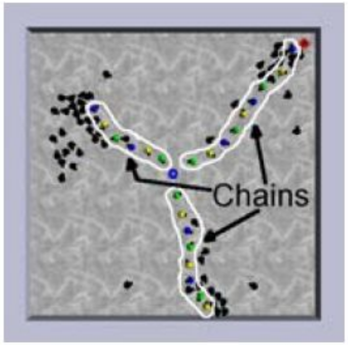
Robots deploy in a regular fashion, e.g., connecting two points (chain)

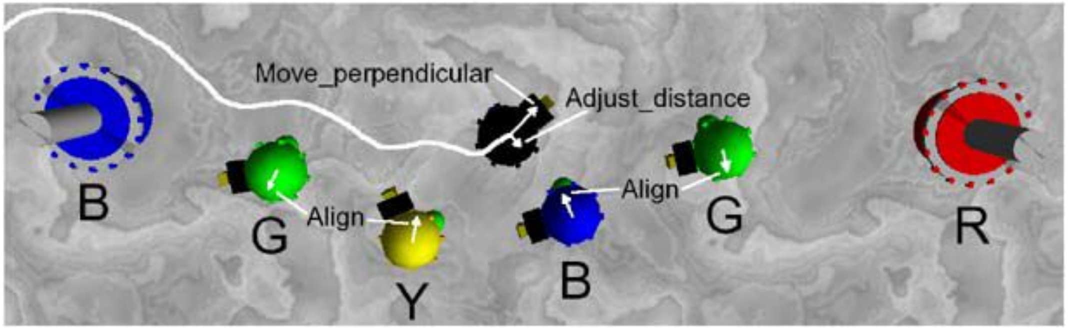
(Even mineral) Nature often favors regularity, and it is useful for many missions (area coverage, bucket brigades, foraging, navigation infrastructure)

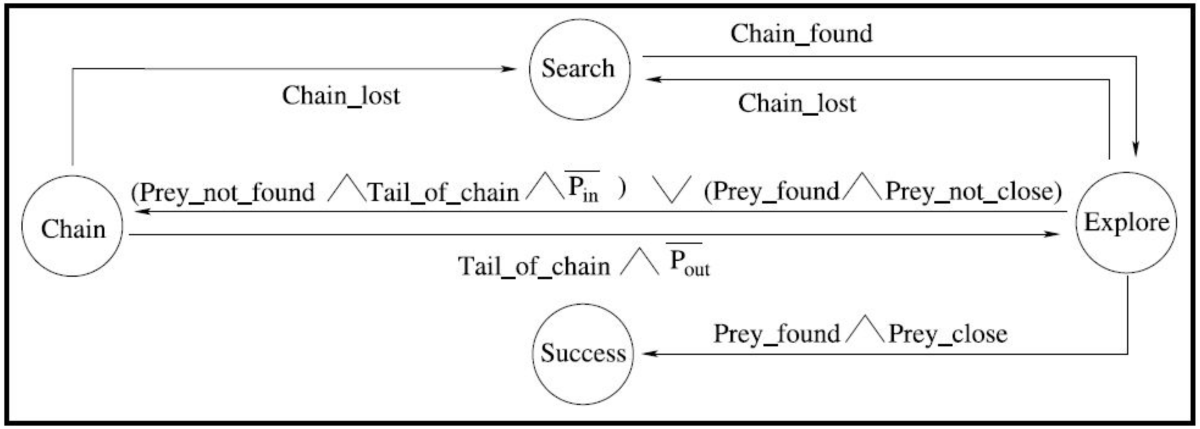
Virtual physics approach: different choices of attraction/repulsion forces to peers and obstacles; Voronoi and Delaunay lattices

S Nouyan, A Campo, M Dorigo (2008)

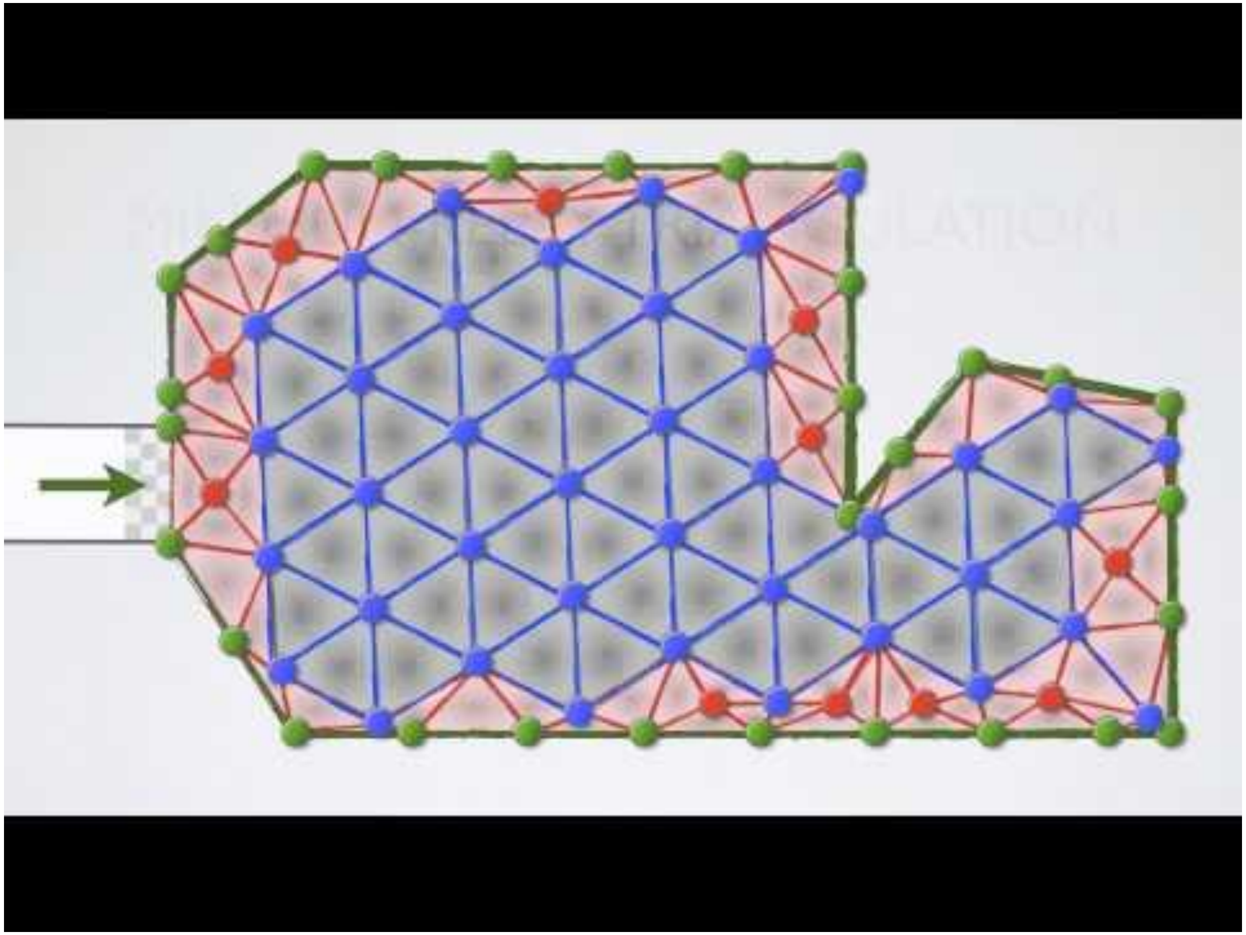








A. Becker et al (2013)



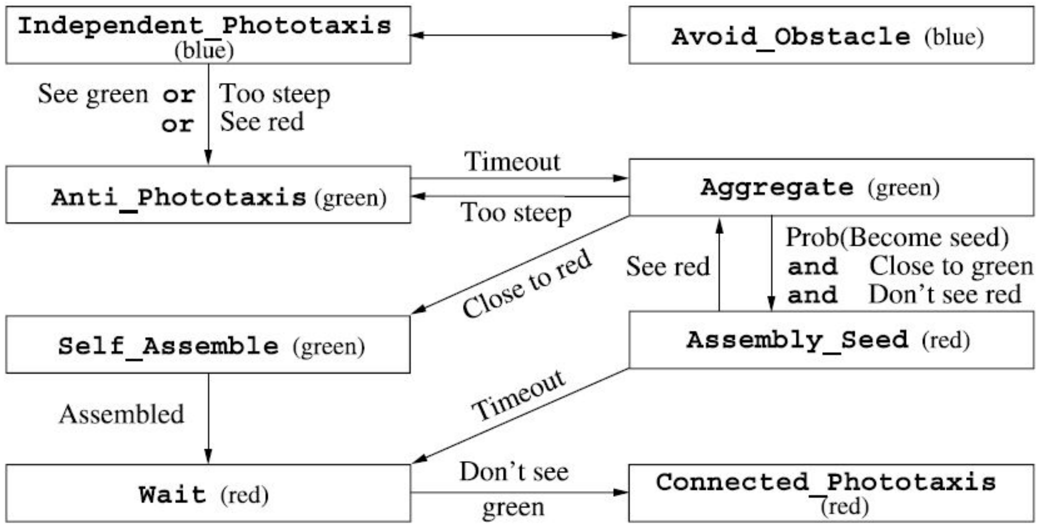
Self-Assembly

Robots physically connect each other for diverse purposes, such as easier navigation

Most common in nature: Symbiogenesis (and yes, army ants)

PFSM approach: when challenge detected switch to self-assembly mode, possibly signalling to peers suitable docking points; collective decision that the assembly is completed to switch to next challenge (move together, dis-assembly, etc)

R. O'Grady et al (2010)



Coordinated Motion (or Flocking)

Robots move in a flexible formation (while doing something else, such as exploring)

Saves energy and increases safety and precision when going from one place to another, so all social animals (and robot swarms) do it

Virtual physics approach: keep distances and align movements, by means of steering forces or lattices; destination? leaders?

Collective Transport

- Move together a large object
- Cooperation is mandatory
- A silly PSFM approach: when object found, attach to it, and try (for a while) pull, push, change orientation, re-attach, until object moves
- Combine ideas from aggregation, clustering and coordinated motion, with more or less (local) sensors

Decision-Making (e.g., Division of Labor)

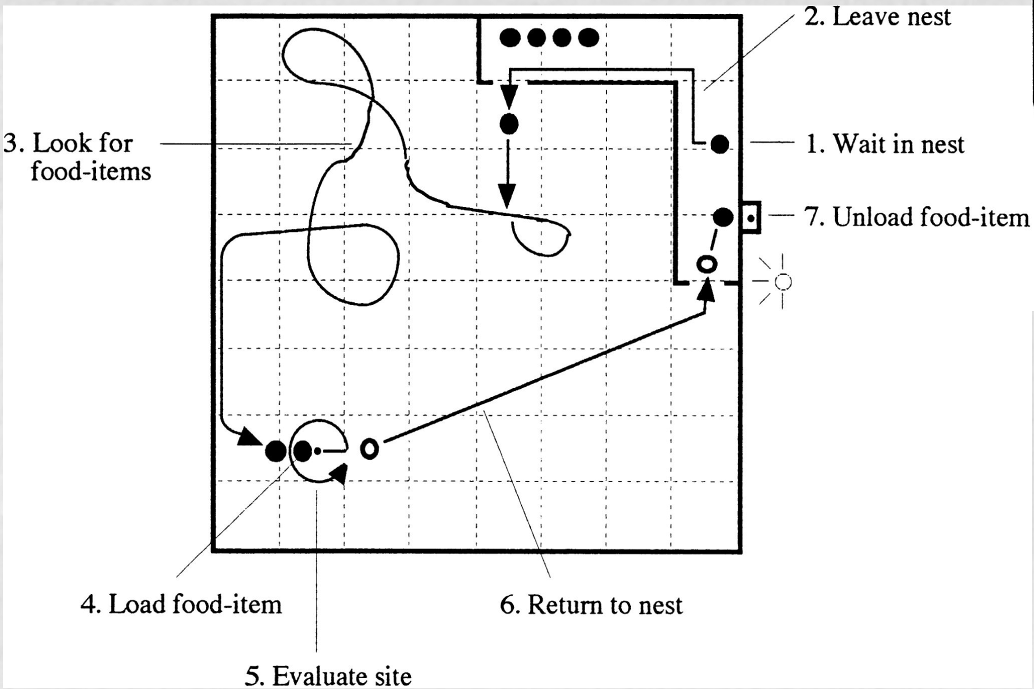
Robots distribute themselves over different tasks, to maximize performance

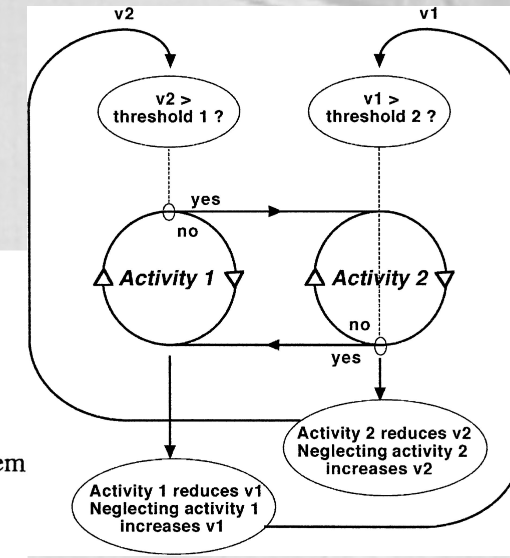
Inherently collective decision-making, frequent in foraging and construction missions

PFSM approach: probabilities can be different among (better or worse suited) robots, and in response to the state of oneself, the peers, and the environment

The Call of Duty

[M.J.B. Krieger, J.B. Billeter (2000)]





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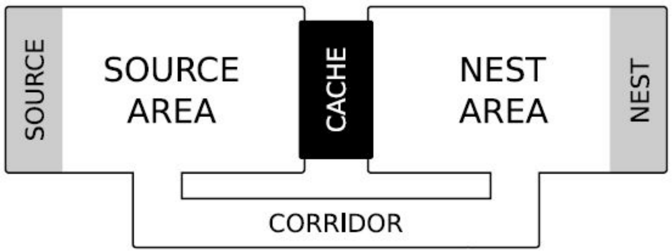
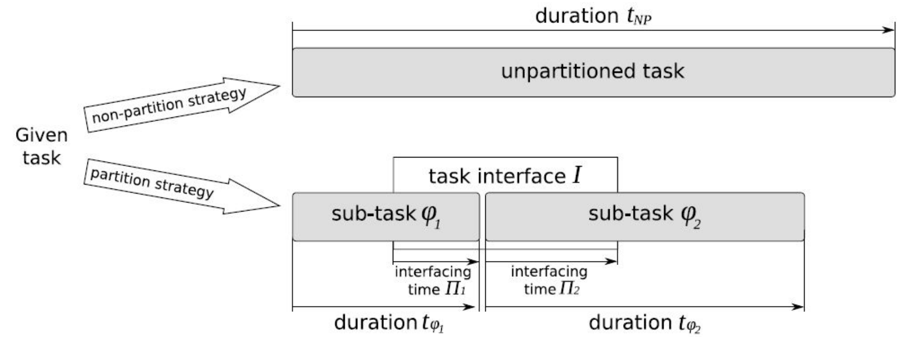
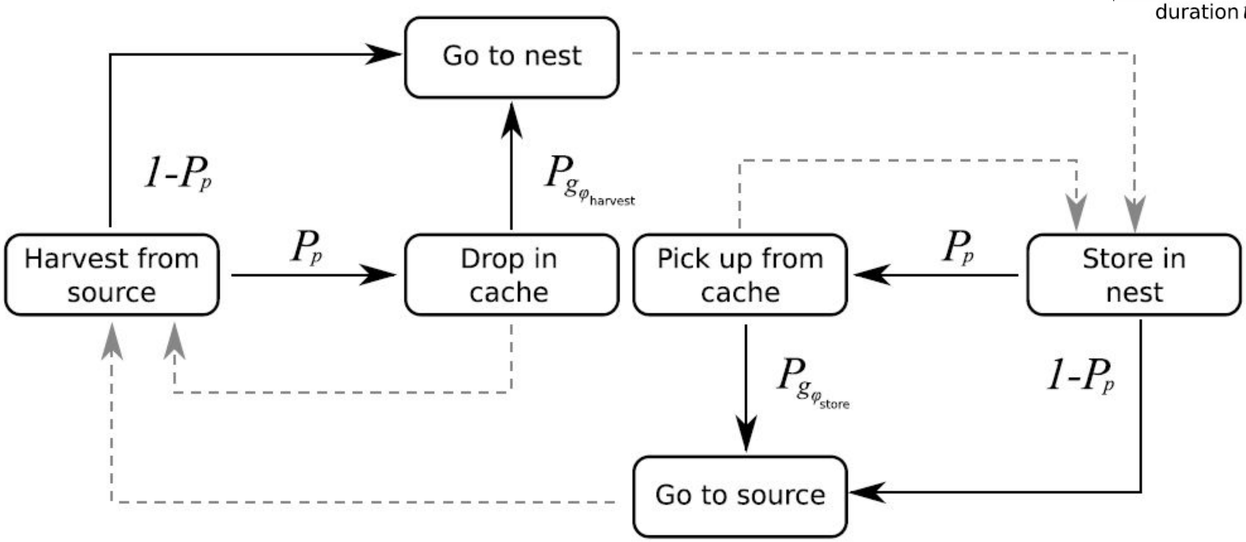
Divide et Impera (or not)

[G. Pini et al (2011)]







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Decision-Making (e.g., Path Selection)

Robots “measure” the quality of different paths, and they end up selecting collectively the best one.

Diversity of mechanisms:

- Pheromones
- Majority opinion
- Commitment and cross-inhibition

Some Scenarios

- Aggregation
- Clustering
- Pattern and Chain Formation
- Self-Assembly
- Coordinated Motion (or Flocking)
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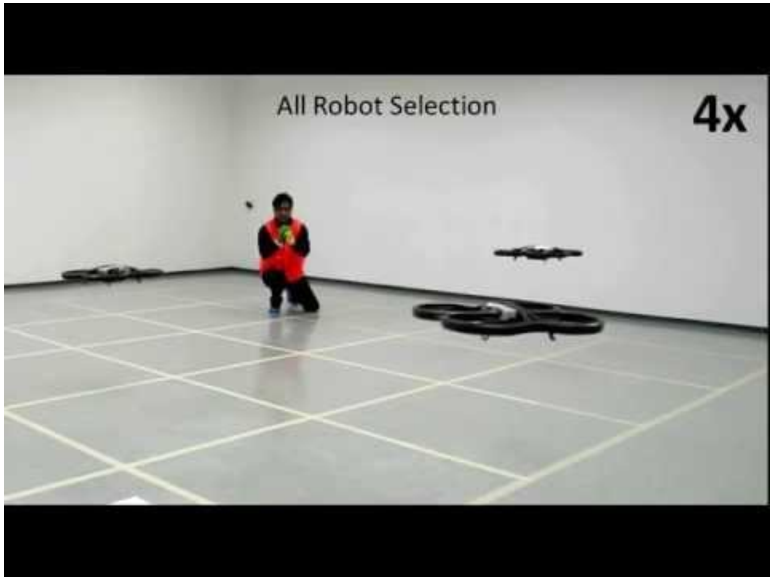
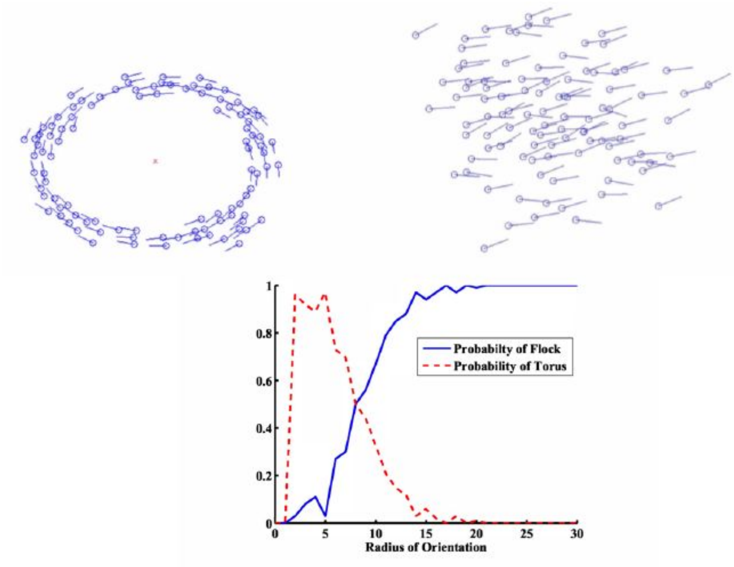
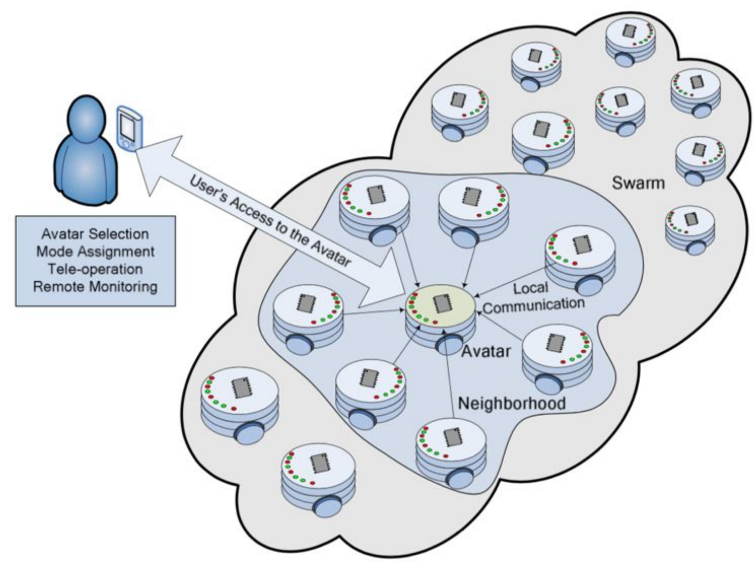
- Decision-Making (e.g., Division of Labor)
- Decision-Making (e.g., Path Selection)

Human-Swarm Interaction

- Cognitive complexity, or "effort":
  - O(1 robot) = human effort to operate one robot
  - O(N robots) = N·O(1 robot)+overhead(N,Space)
  - Goal for O(swarm of N robots) = O(1)
- Human-swarm (proximal or remote) interaction :
  - Changing parameters
  - Control through environmental influence (stigmetry)
  - Control through proxy agents (avatars, leaders)
- Levels of automation







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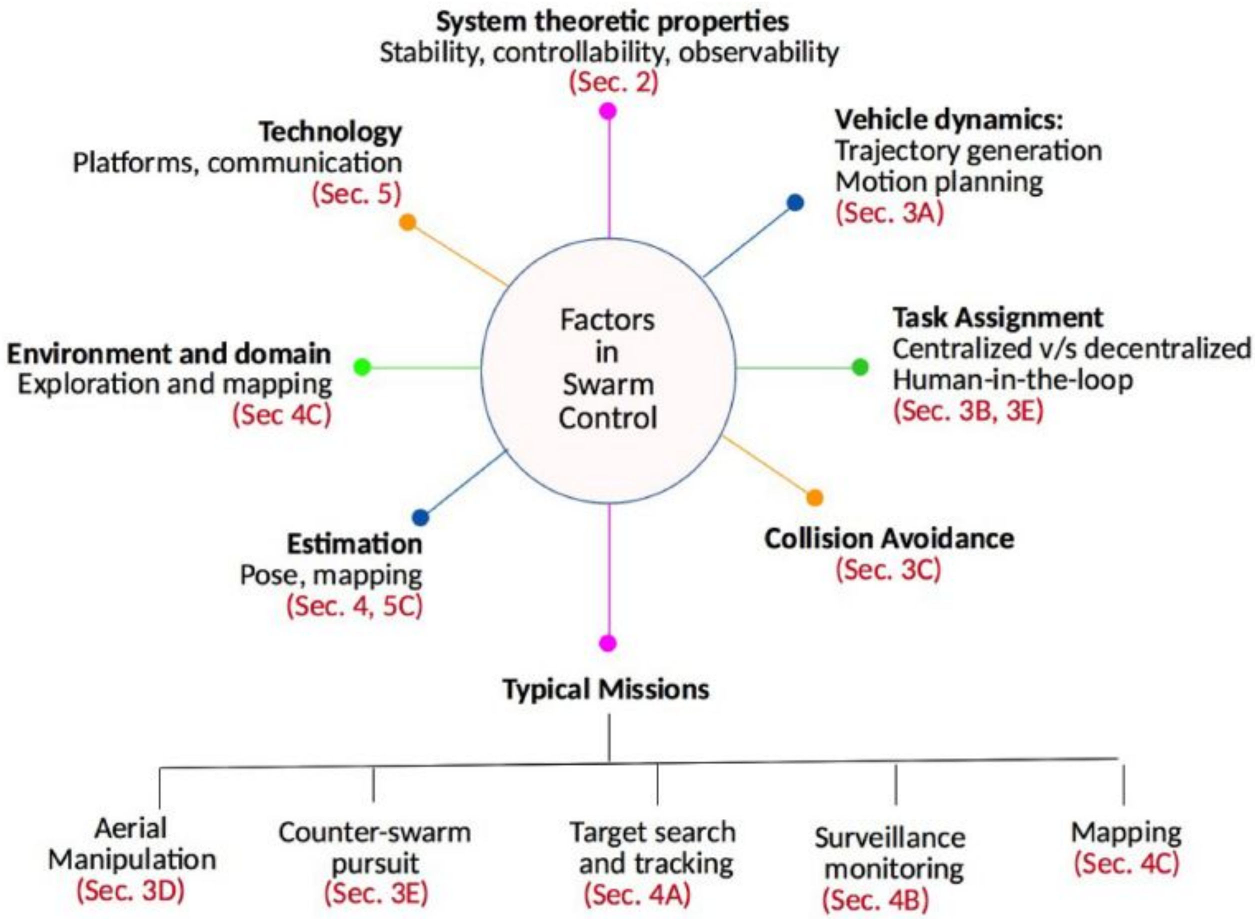
With feet on the ground

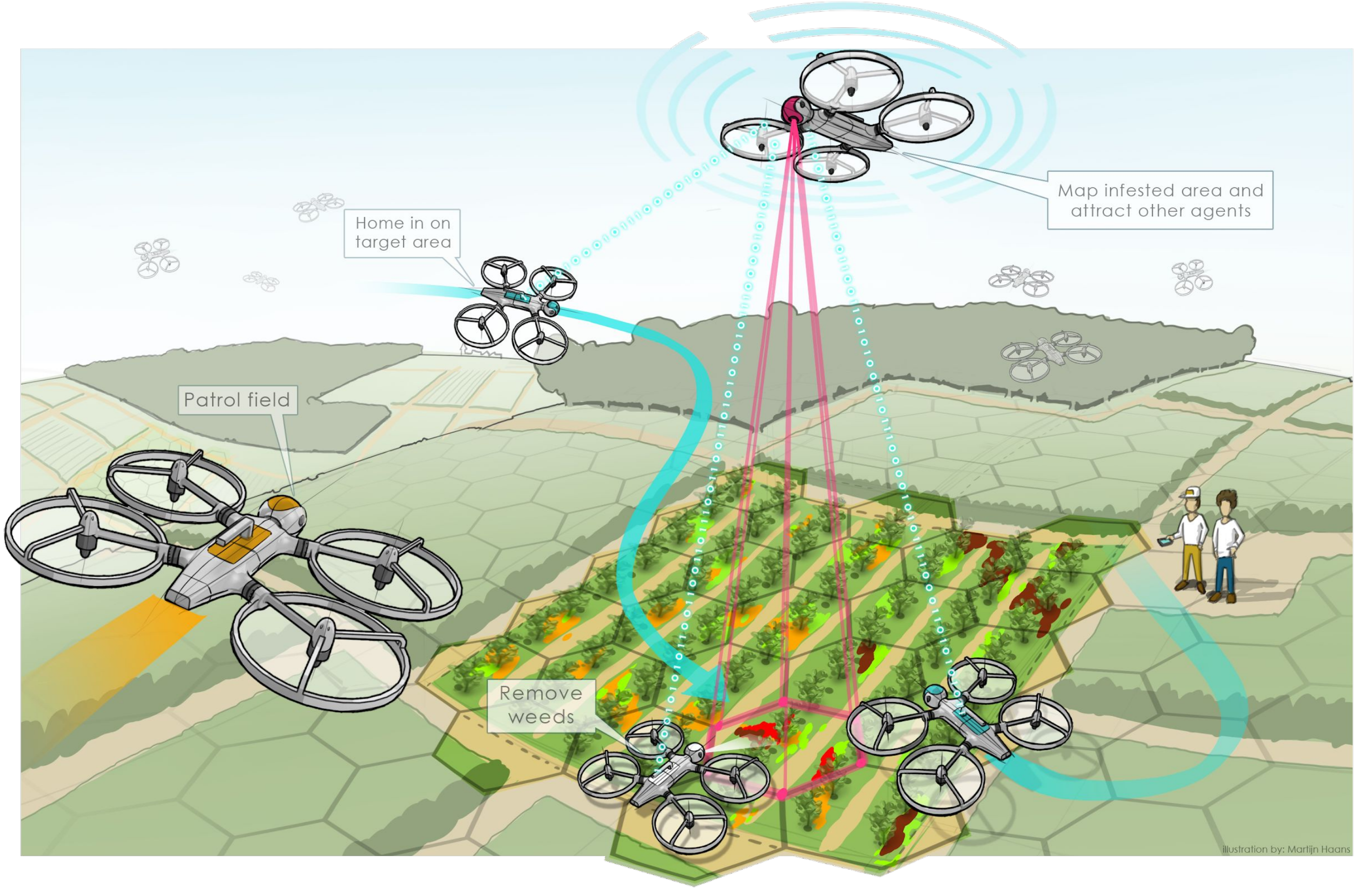
(not quite exactly, though):

What is expected to happen “soon”?

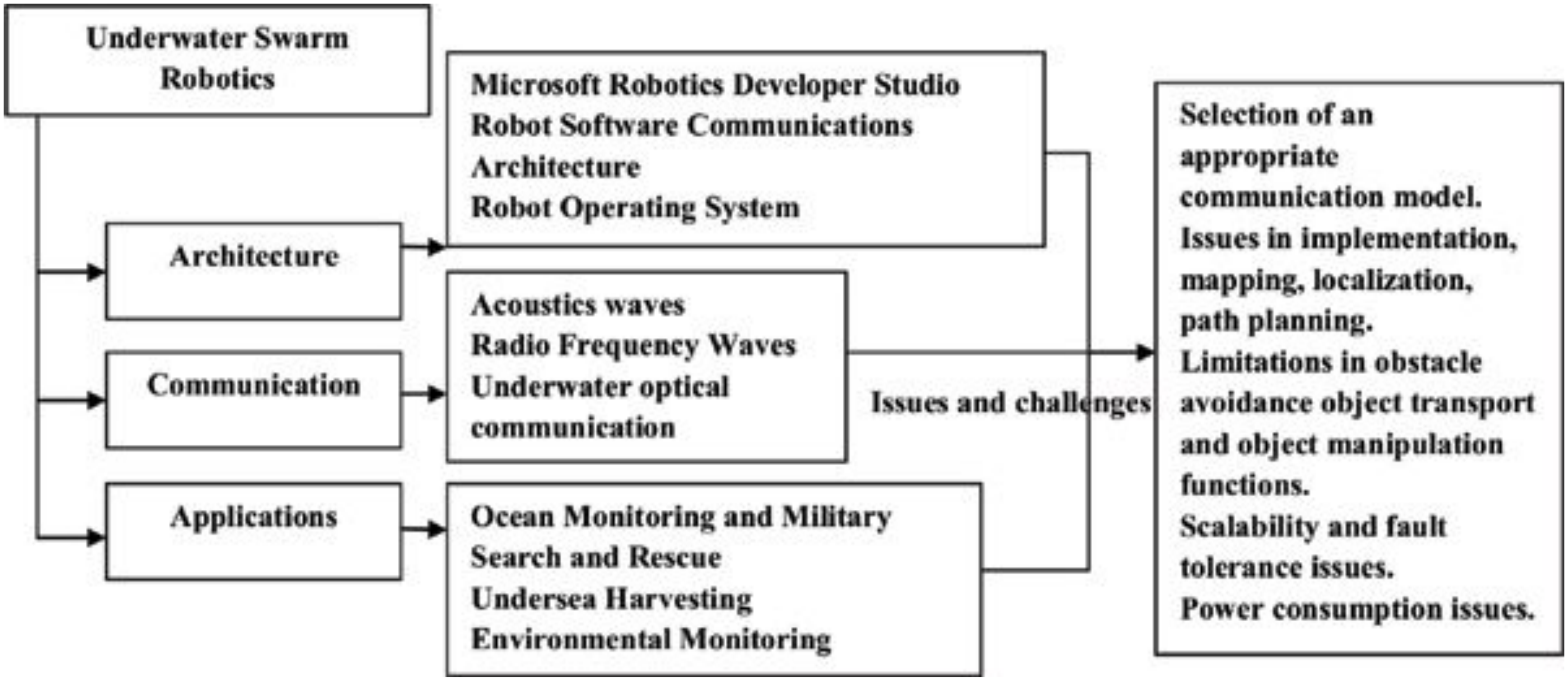
Aerial Swarm Robotics



Agricultural Applications



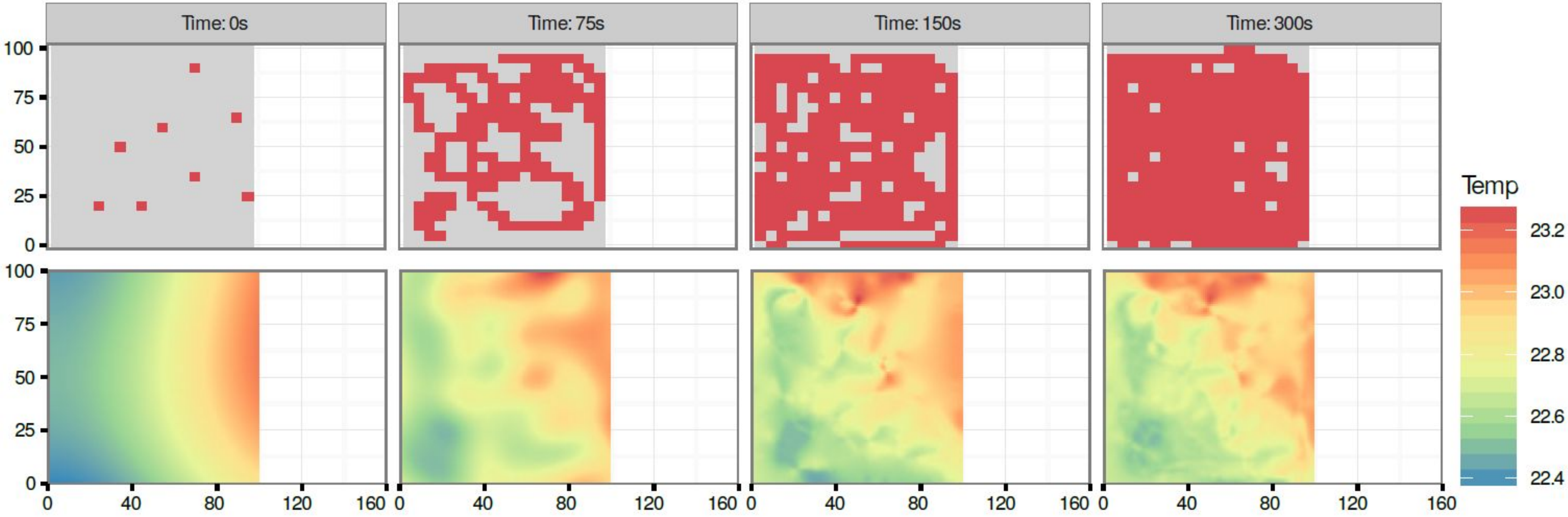
Aquatic Swarm Robotics



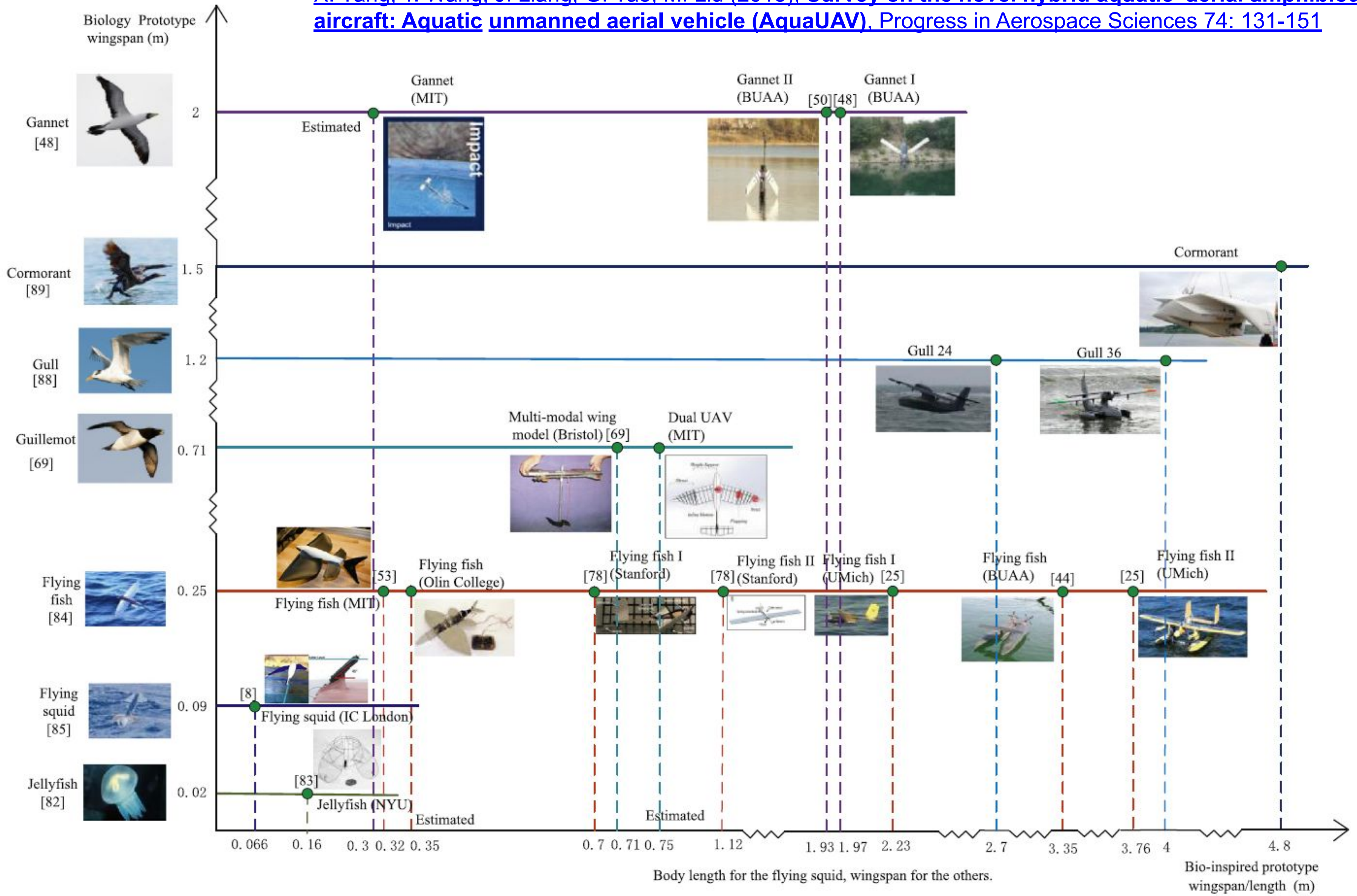
K. Satheesh Keerthi, B. Mahapatra, V. Girijan Menon (2020), Into the World of Underwater Swarm Robotics: Architecture, Communication, Applications and Challenges, Recent Advances in Computer Science and Communications 13(2)

Marine Environmental Monitoring

Duarte, M. et al. (2016). Application of swarm robotics systems to marine environmental monitoring. In OCEANS 2016



[X. Yang, T. Wang, J. Liang, G. Yao, M. Liu (2015), **Survey on the novel hybrid aquatic–aerial amphibious aircraft: Aquatic unmanned aerial vehicle (AquaUAV)**, Progress in Aerospace Sciences 74: 131-151]



What Comes Next?

Coordinated Motion (virtual physics)

- Boids (steering forces)
- Voronoids (lattices)

Lab sessions