Artificial Life
Summer 2025

Multi Robotics, DidaBots, Swarms, Boids, PSO Particle Swarm Optimization

Master Computer Science [MA-INF 4201]
Mon 14:15 – 15:45, HSZ, HS-2

Dr. Nils Goerke, Autonomous Intelligent Systems,
Department of Computer Science, University of Bonn

Examination:

After the end of the lecture period (18.7.25) there will be an examination for the module Artificial Life.

To be admitted for the exam , you will need

- to register
- a minimum of **50%** of the possible reachable points
- a minimum **two presentations** of your solutions in the exercises.

Exam date: Tuesday **22 July 2025, 12:00**, Lecture Hall 1+2, HSZ

The examination will be a written exam,
operated in presence, Lecture Hall 1+2, HSZ
exam duration is 100 minutes
up to 100 points are reachable (approx. 1 minute per point).

Some details for the exam

Exam:
Tuesday 22.7.25 12:00 - 15:00
Lecture Hall 1 and Lecture Hall 2

Date for resit exam:
Monday 8.9.25 9:00 - 12:00
Lecture Hall 1

Some details for the exam

Tuesday 22nd July 2025, Lecture Hall 1+2, 12:00 – 14:00

For the exam:

- Please take your students id card (Studentenausweis) with you.
- Documents with a photo, to check your an identity with you (identity card, or passport, or drivers license, …).
- Bring a pen, ball pen, felt-tip pen with you.
- You will not need a calculator for the exam.
- Paper will be provided.

Some important details for the exam

Thursday 22nd July 2025, Lecture Hall 1+2, 12:00 – 14:00

- Exam time is 100 minutes
- up to 100 points are reachable (approx. 1 minute per point)
- only pen, ball pen, felt-tip pen are allowed, NO pencil.
- only blue or black, NO red or green colors.
- NO correction fluid, No white out (Tipp-Ex).
- all answers need an explanation.
- please indicate clearly what you consider to be the solution.
- when you use formulas, all variables must be explained explicitly.
- short sentences and keywords are preferable to long text passages.
- no extra tools or utilities or electronic devices are allowed.

Multi Robotics, Swarms, Boids, PSO

Multi Robotics, Swarms, Boids, PSO

- Cooperating Robots
- The Didabot Experiment
- Swarm, Swarming, Swarm Behavior
- C.Reynolds: Boids
- Particle Swarm Optimization, PSO

Cooperating Robots

During the last years robotics research has made a lot of progress. The capabilities of our modern robots is opening the field to novel areas of application.

Some tasks are still too complicated for a single robot, and will need cooperating robots,
which is a hard challenge nowadays.

While modern robots became more and more sophisticated, they suffer from being rather expensive.

The idea came up to use multiple, cheap robots with limited capabilities of a single robot, but with new capabilities of the group of cooperating robots.

Multi Robotics, Swarms, Boids, PSO

- Cooperating Robots
- **The Didabot Experiment**
- Swarm, Swarming, Swarm Behavior
- C.Reynolds: Boids
- PSO: Particle Swarm Optimization

Didabots, Swiss Robots

- Didabots: shape and purpose
- Using Didabots to investigate reactive obstacle avoidance
- The environment
- Unexpected results from the experiment
- “Emergence” ?
- Explanation: Pushing Boxes
- Explanation: Spontaneous release of boxes
- Explanation: Induced release of boxes
- Explanation: Heaps
- Multiple Didabots

Didabots

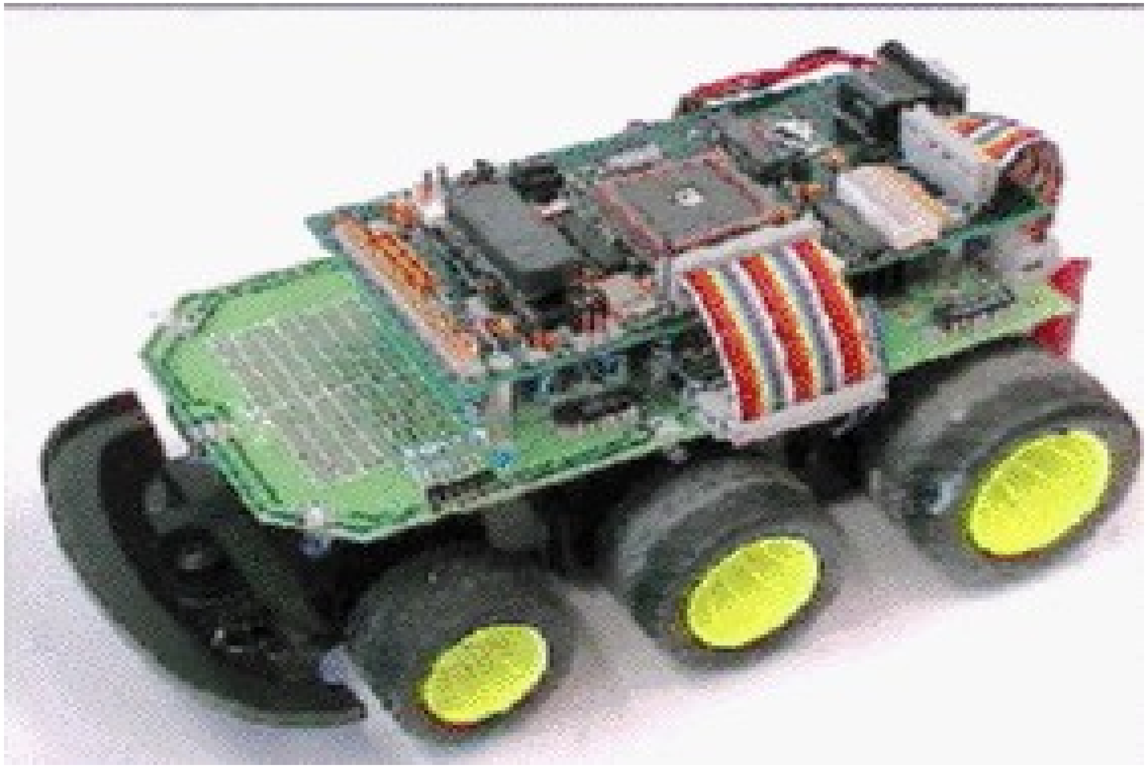
Didabots are a development of the AI Lab of the University of Zürich (Switzerland) for teaching students (**Dida**ctic Ro**bots**) .

“The goal was to create a group of general purpose robots that are small and flexible and can easily be programmed from a host computer”.

Didabot structure:
a chassis with two motors (differential steering), 6 wheels, a uProcessor board, six infrared (IR) proximity sensors, six ambient light sensors, nine touch sensors, a beeper, a light bulb, and two wheel encoders.

From: The Didactic Robots, AILab Technical Report 95.09, M.Maris, R.Schaad, Artificial Intelligence Laboratory, Computer Science Department, University of Zürich, Winterthurerstrasse 190, 1995

Didabots



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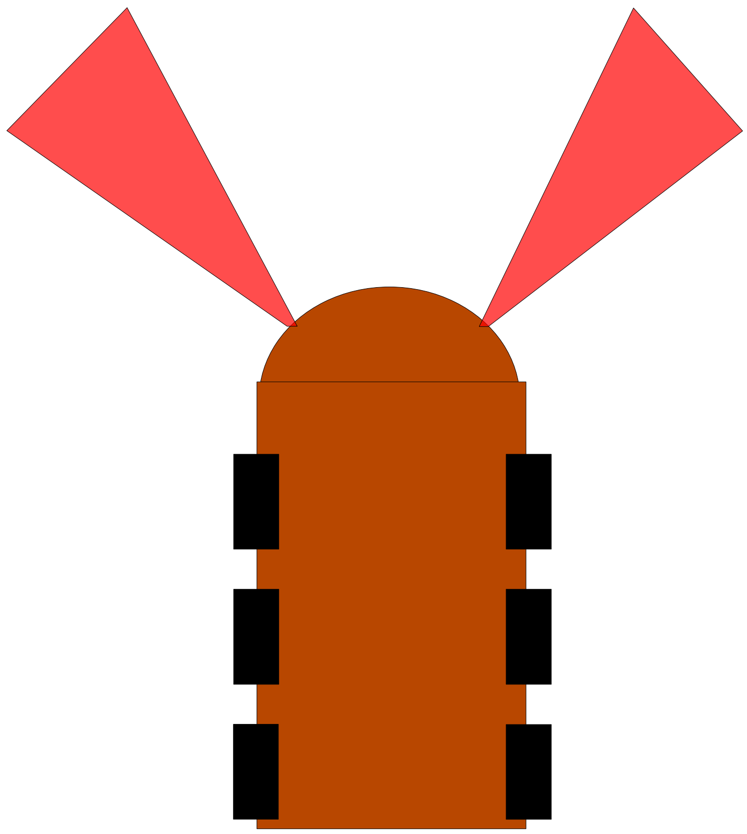
http://www.ifi.uzh.ch/ailab/robots/robots-a.html

Didabots

In the *Didabot Experiment* only those two of the infrared proximity sensors are used that point diagonal to the front.



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Didabots obstacle avoidance

In one experimental setup, the Didabots were used to investigate the obstacle avoidance capabilities in an environment (arena) with a lot of rectangular obstacles, boxes.

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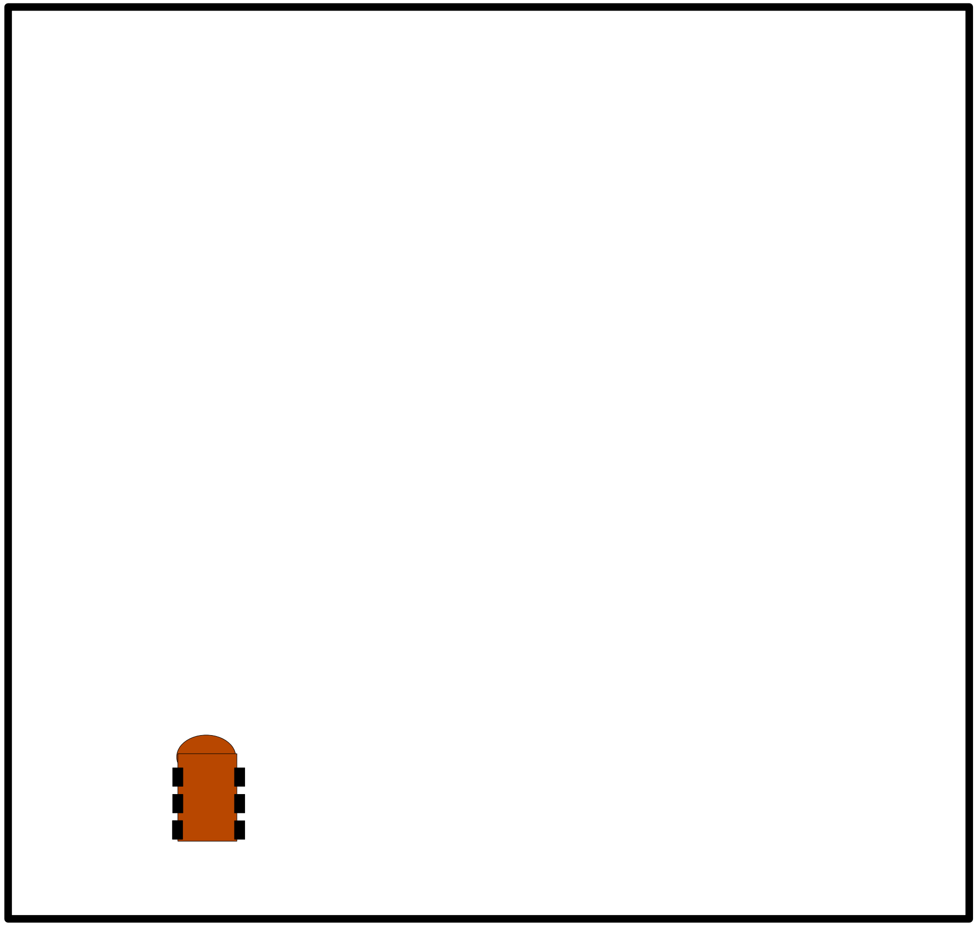

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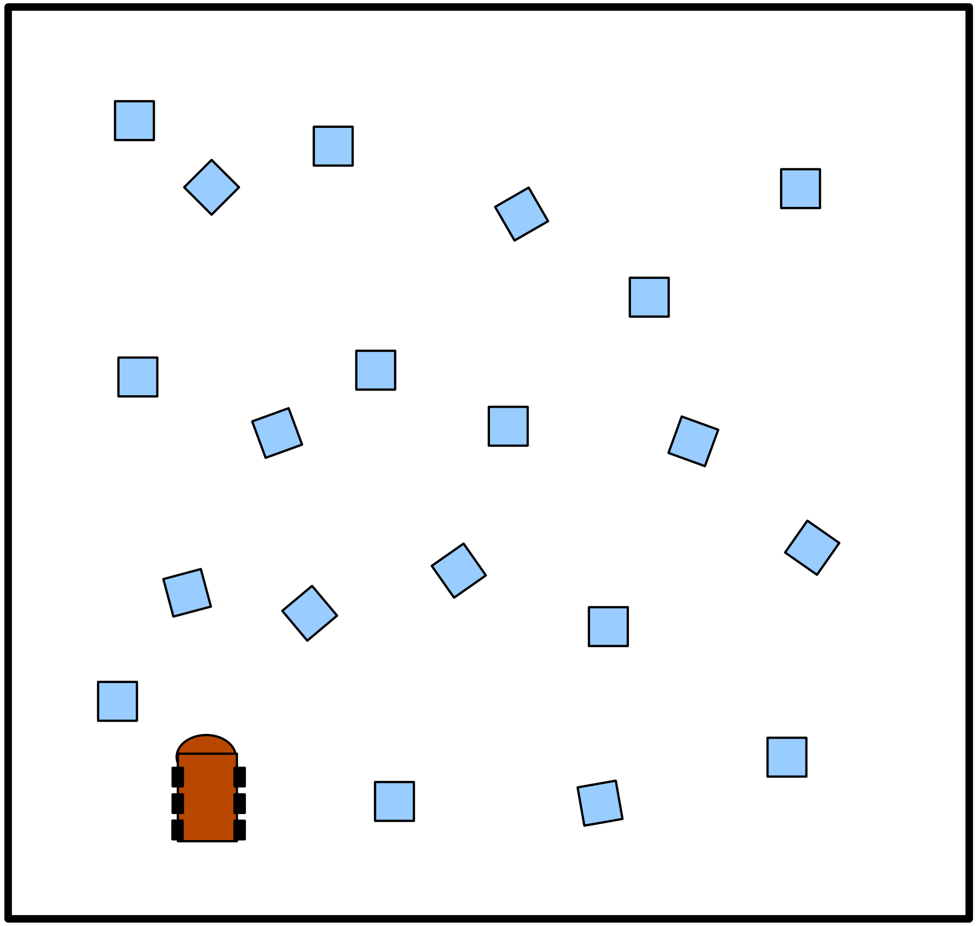

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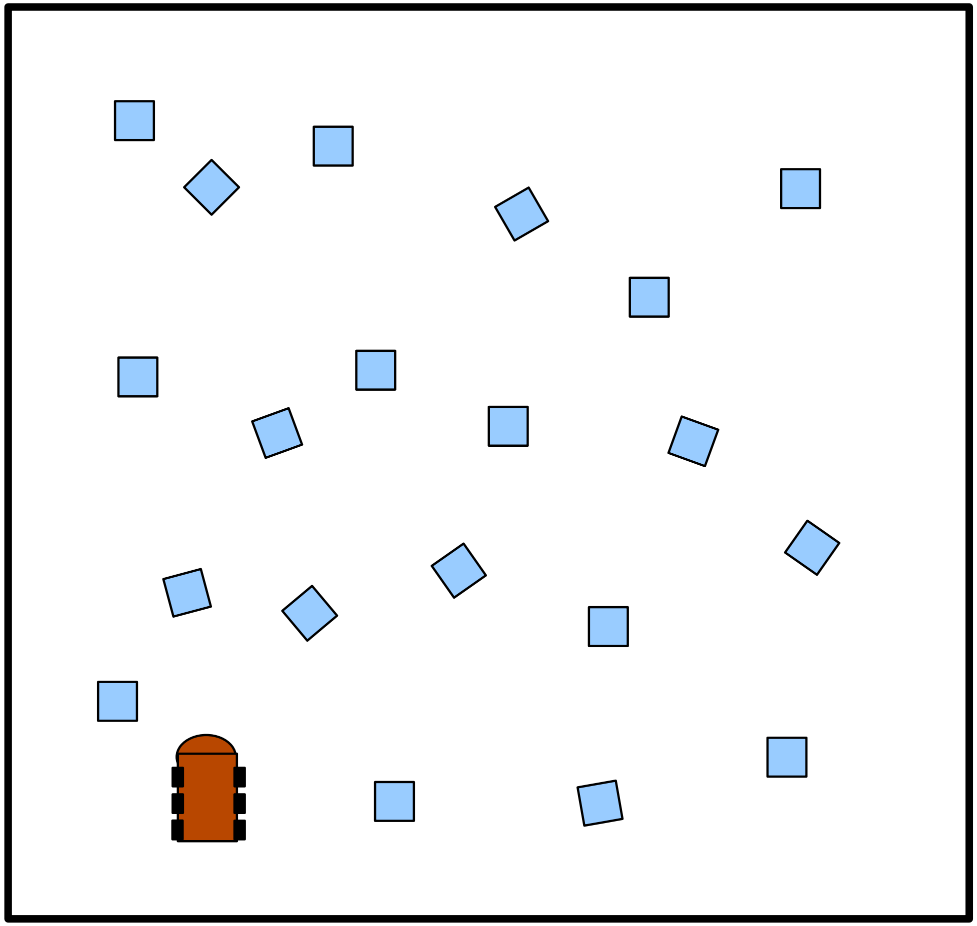


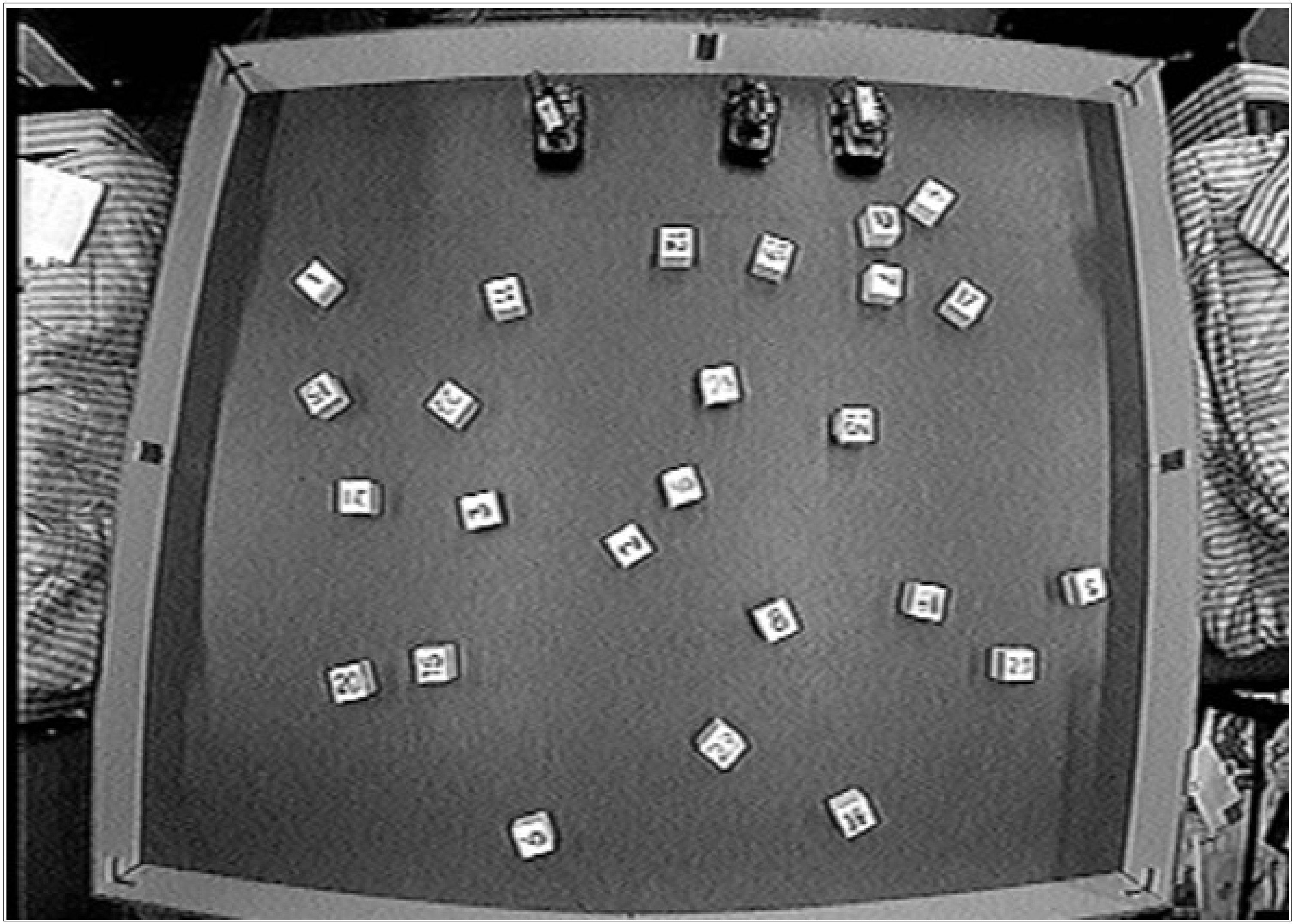
The robot is using 2 proximity sensors, and is controlled in a Braitenberg type 3b manner:

“ if there is a sensory stimulation on the left, turn (a bit) to the right,

if there is a sensory stimulation on the right, turn (a bit) to the left ”

Didabot Experiment

Experimental setup with obstacles and several Didabots.



Artificial Intelligence Lab, University of Zurich, Switzerland

Didabot Experiment

Running the experiment with the described setup
(Didabot, type 3b behavior, environment) an unexpected effect occurres.

After a while the box distribution has changed in a very specific way:

The boxes are building clusters,

heaps of several boxes close together plus some boxes close to the boundary of the arena.

Maris, M. and Boekhorst, R te. (1996). Exploiting Physical Constraints: *Heap formation through behavioral error in a group of robots*. In proc. of IROS `96, Nov. 4-8, Osaka, Japan

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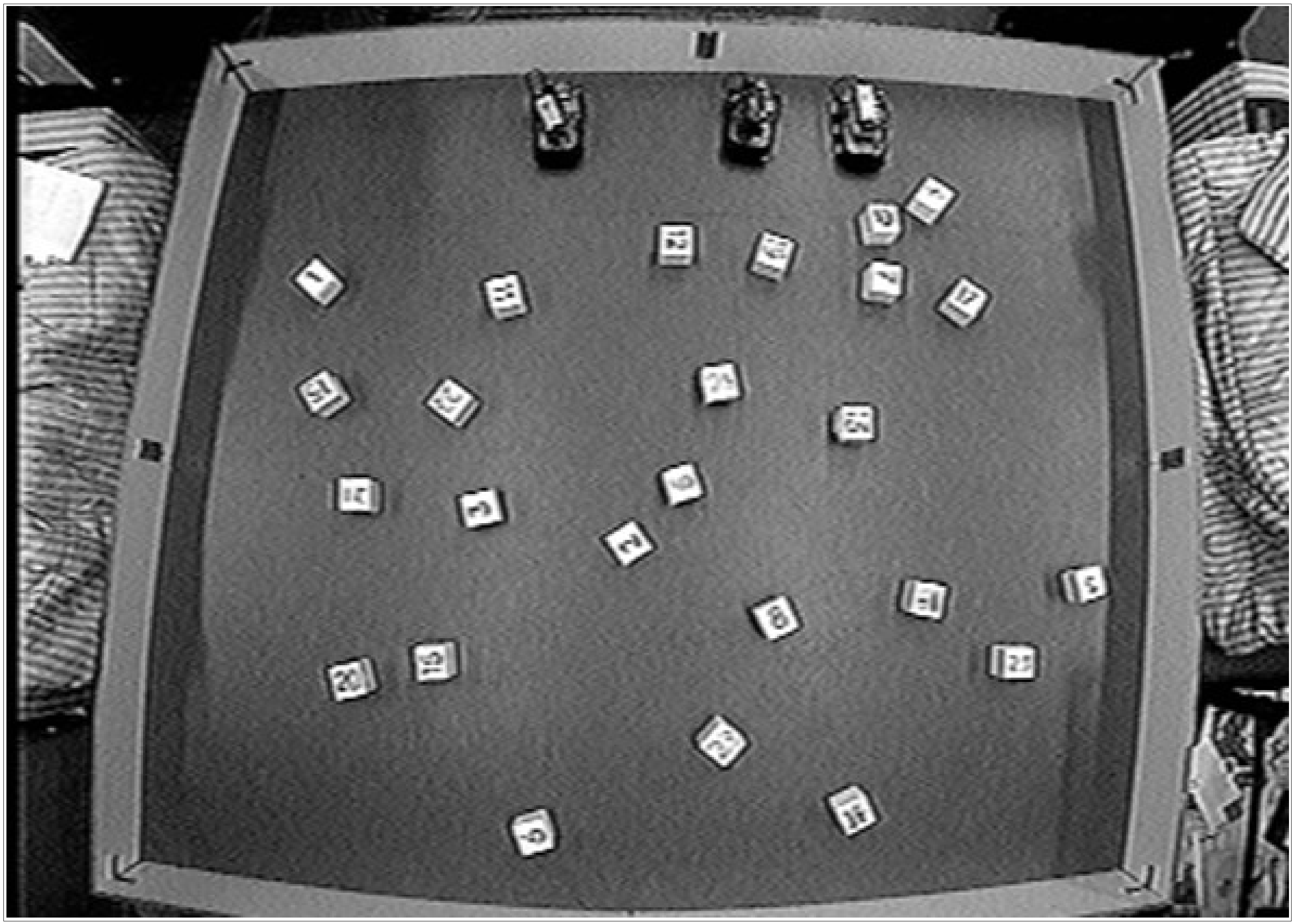

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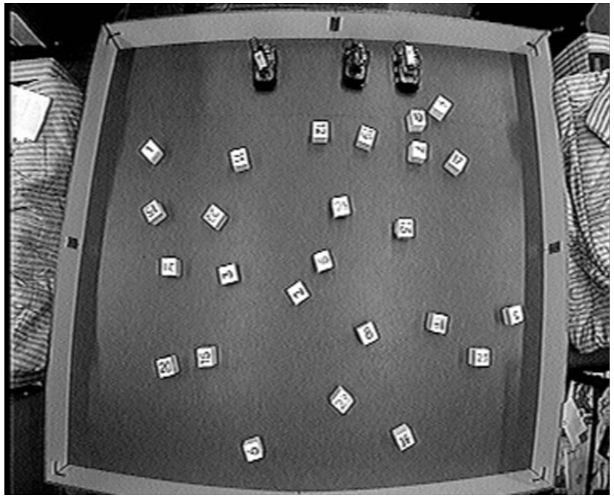

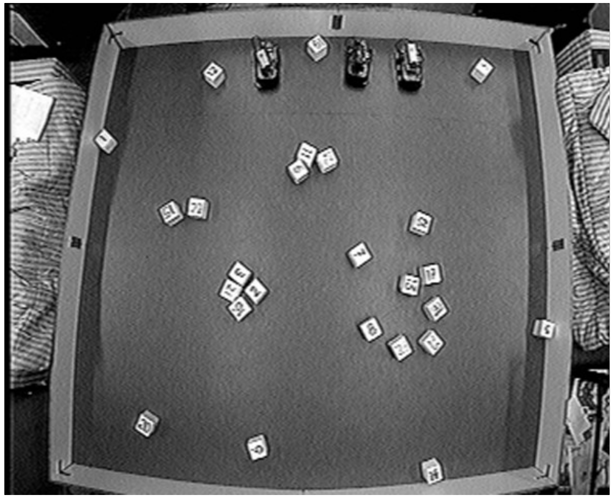

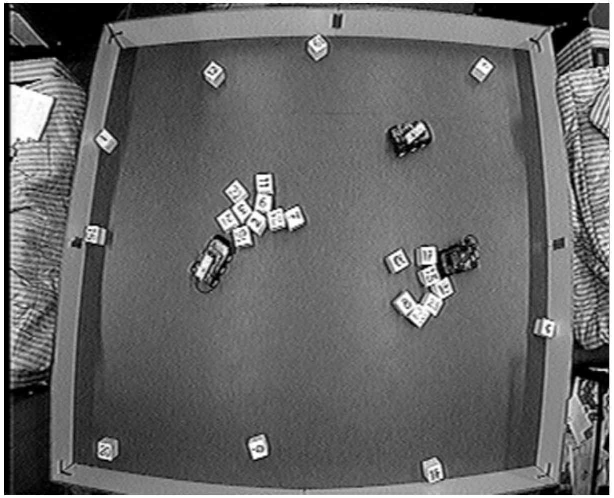

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Emergence

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From Wikipedia, 26.6.2011:

“ In philosophy, systems theory, science, and art, emergence is the way complex systems and patterns arise out of a multiplicity of relatively simple interactions.

Emergence is central to the theories of integrative levels and of complex systems. “

Didabot Experiment

A closer look to the Didabot morphology, the robot control scheme and the resulting Didabot behavior reveals the reason for the cluster production.

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A closer look to the Didabot morphology, the robot control scheme and the resulting Didabot behavior reveals the reason for the cluster production.

The following properties are essential for the observed effect:

- The boxes can be pushed around by the robot.
- The boxes are smaller than the distance between the two sensors used.
- The front of the robot is not flat, but curved.
- Braitenberg type 3b, obstacle avoidance behavior.

Didabots

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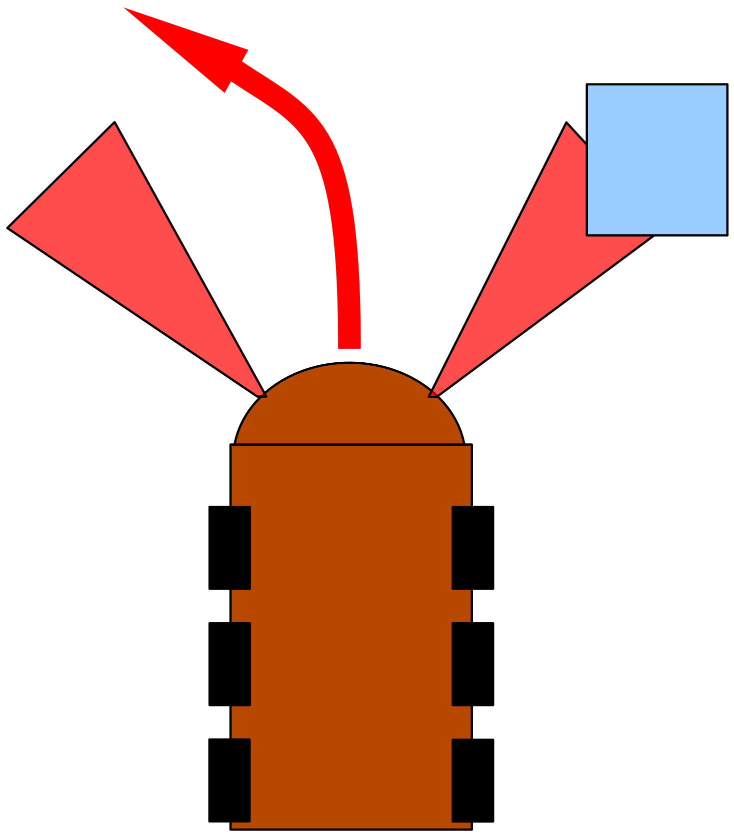

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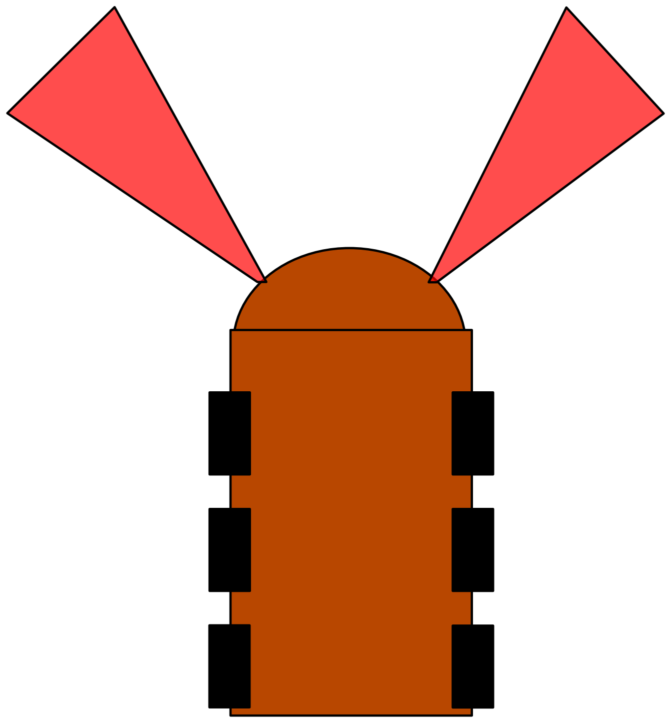
The Braitenberg type 3b generates a normal obstacle avoiding behavior when a box is somewhere in reach of the sensors.

In case the box is directly in front, it will be between the two sensors and thus “invisible” for the robot.



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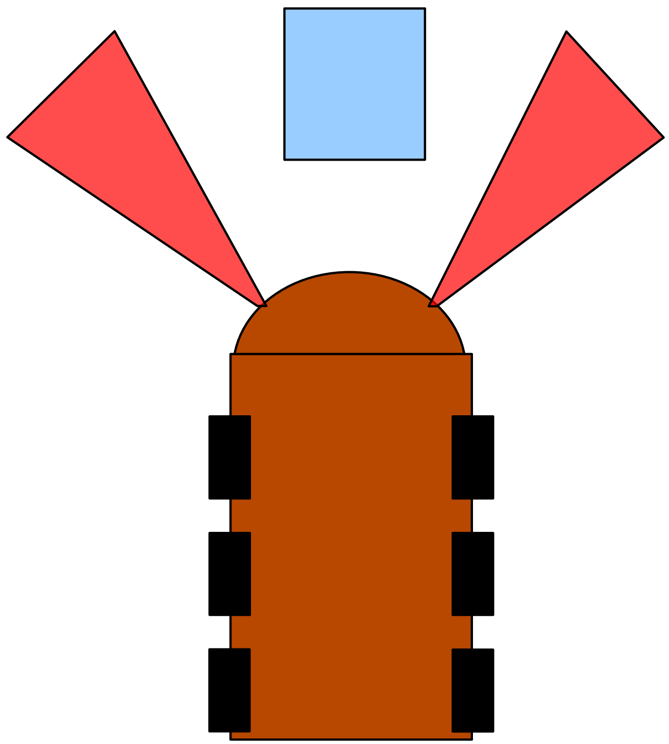

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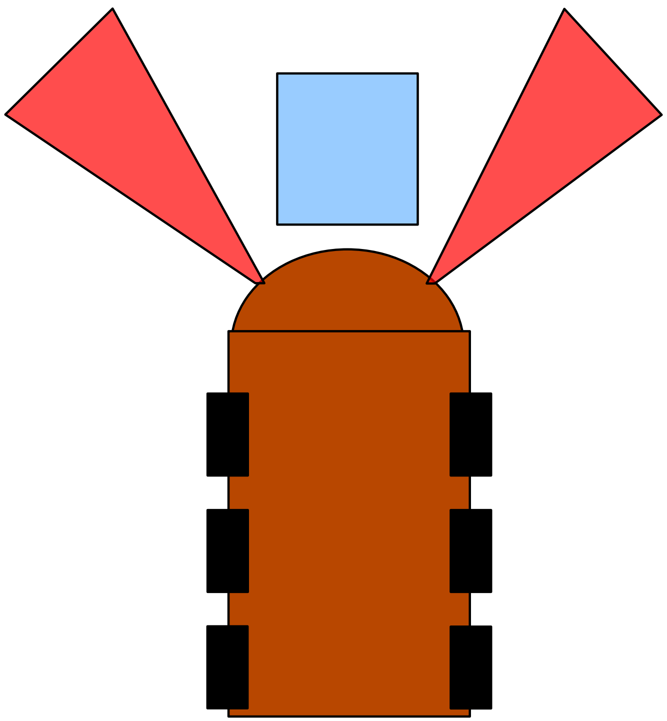

Thus, it will “sit” on the “nose” of the Didabot and will be pushed around by the moving, type 3b behaving robot;

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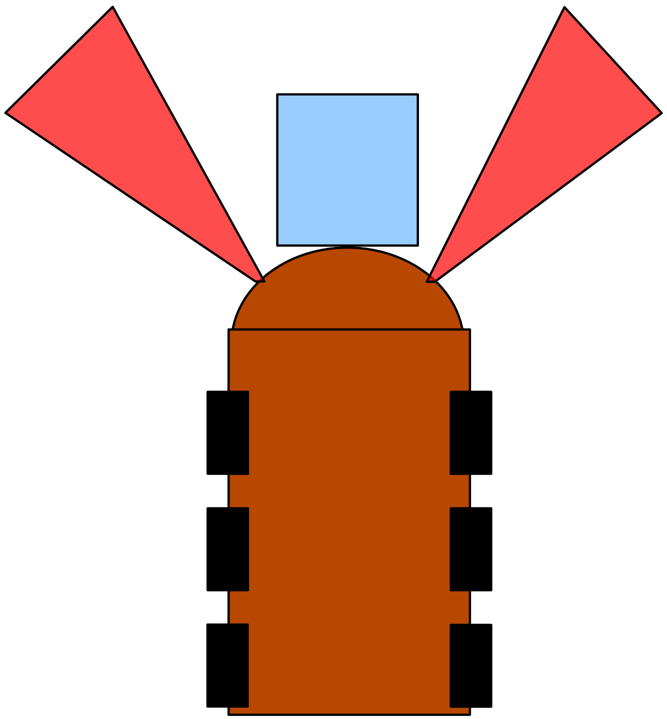

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Then, following the 3b behavior, the robot will turn, and release the box at an arbitrary position.

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Induced release:
when the robot encounters an obstacle, or another box with its sensors, the 3b behavior will make the robot turn, and the box on the nose is released.

This time, the release point is close to an obstacle, or another box, and thus heaps are formed.

Didabots

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The size, and the number of heaps depends on the density of objects, the probability of spontaneous release (and thereby on the shape of the robot) on the characteristics of the sensors, and on the details of the Braitenberg type 3b implementation.

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The behavior of the Didabots has sometimes been called: "*Cleaning up*", "*Making free space*", "*Try to build clusters*",

But in fact the programmed micro-behavior is just reactive, obstacle avoidance following Braitenberg's principle of antagonistic inhibition.

Multiple Didabots

How will the result change, if multiple, identical Didabots are in the arena at the same time?

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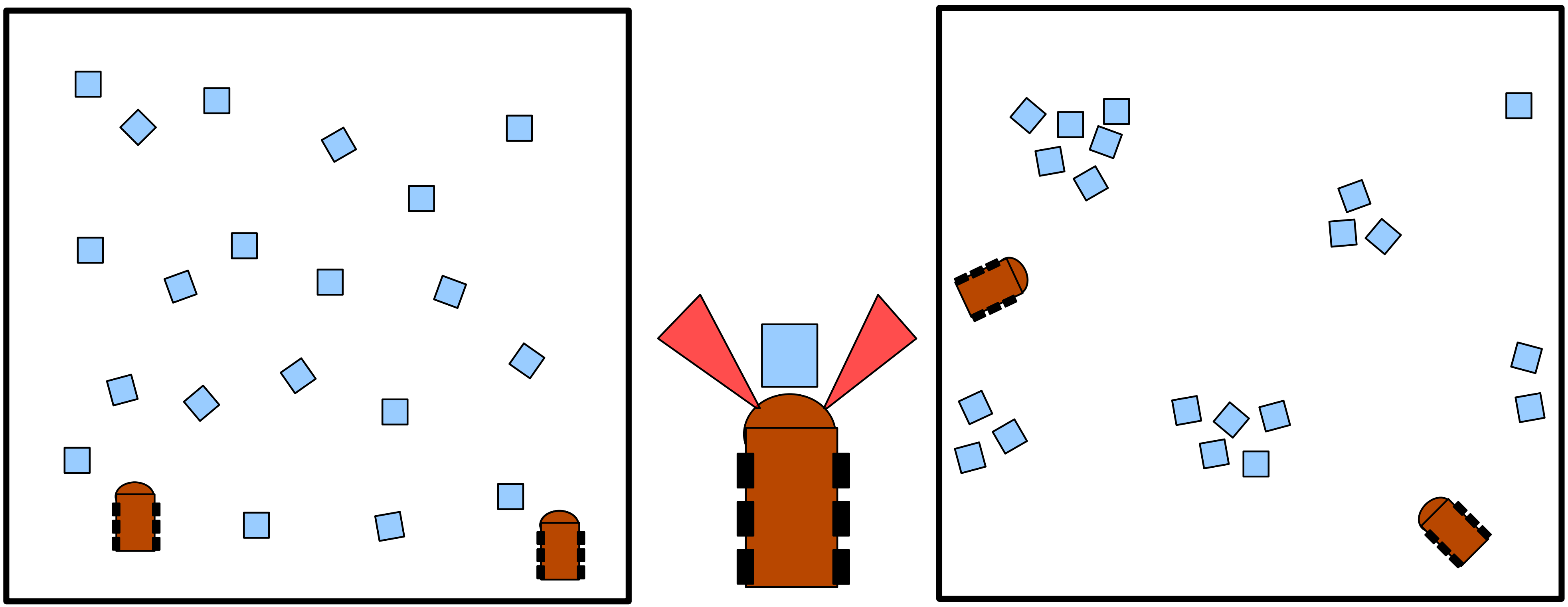
Induced release type 2,

two Didabots approaching each other will perform an avoiding movement (type 3b behavior),
and will thus release any boxes they are carrying.

Didabots

Several Didabots are building clusters of boxes.



Multi Robotics, Swarms, Boids, PSO

- Cooperating Robots
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Swarm Behavior

- What is a Swarm?
- Swarm, Flock, School, Herd, ...
- Examples from Biology
- Evolution of swarms (D.Kriesel)

  http://www.dkriesel.com/en/science/distributed_evolution_of_swarms

Swarm, Swarming, Swarm Behavior

The research on swarming or swarm behavior has increased during the last years.

Understanding the collective phenomenon of swarms is an interesting subject of current research in biology, biocybernetics, bionics, psychology, social sciences, cognitive robotics, or computer science.

Swarm Intelligence

Swarm intelligence (SI) is the collective behavior of decentralized, self-organized systems, natural or artificial. The concept is employed in work on artificial intelligence. The expression was introduced by Gerardo Beni and Jing Wang in 1989, in the context of cellular robotic systems.

SI systems consist typically of a population of simple agents or boids interacting locally with one another and with their environment. The inspiration often comes from nature, especially biological systems.

The agents follow very simple rules, and although there is no centralized control structure dictating how individual agents should behave, local, and to a certain degree random, interactions between such agents lead to the emergence of "intelligent" global behavior, unknown to the individual agents.

Examples in natural systems of SI include ant colonies, bird flocking, animal herding, bacterial growth, fish schooling and microbial intelligence.

From: wikipedia, Swarm Intelligence, 13.7.2017
https://en.wikipedia.org/wiki/Swarm_intelligence

Swarm, Swarming, Swarm Behavior

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It is a common observation, that a lot of species live together in groups. Some of these groups are permanent, some are temporary.

Swarm, Swarming, Swarm Behavior

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It is a common observation, that a lot of species live together in groups. Some of these groups are permanent, some are temporary.

We talk about a *herd of gnus*, a *shoal of herring*, a *school of dolphins*, a *pod of whales* and a *flock of geese*, ...

“ *group, collective, swarm, flock, shoal, herd, pod, hive, school, …* “

Swarm, Swarming, Swarm Behavior

Different type of groups have different properties and can have different structure; e.g.
they can be homogeneous or different (size, color, type, ...)
they can be permanent or can be temporary,
they can be uniform or can be structured,
they can have a hierarchical organization or not, ...

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Some of these groups consist of animals that are all alike.

In other groups the individuals are alike, but their individual position within the group is different from each other.

Still other groups have even different shape, physiognomy and task for the different individuals.

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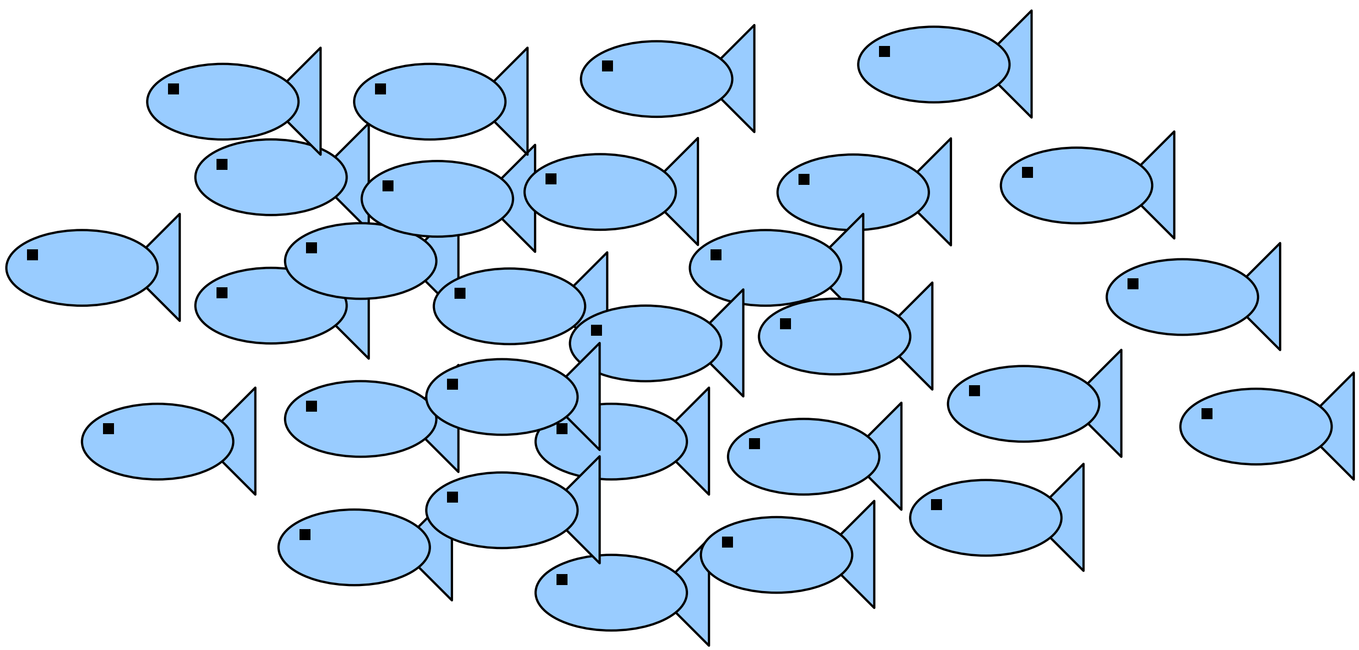

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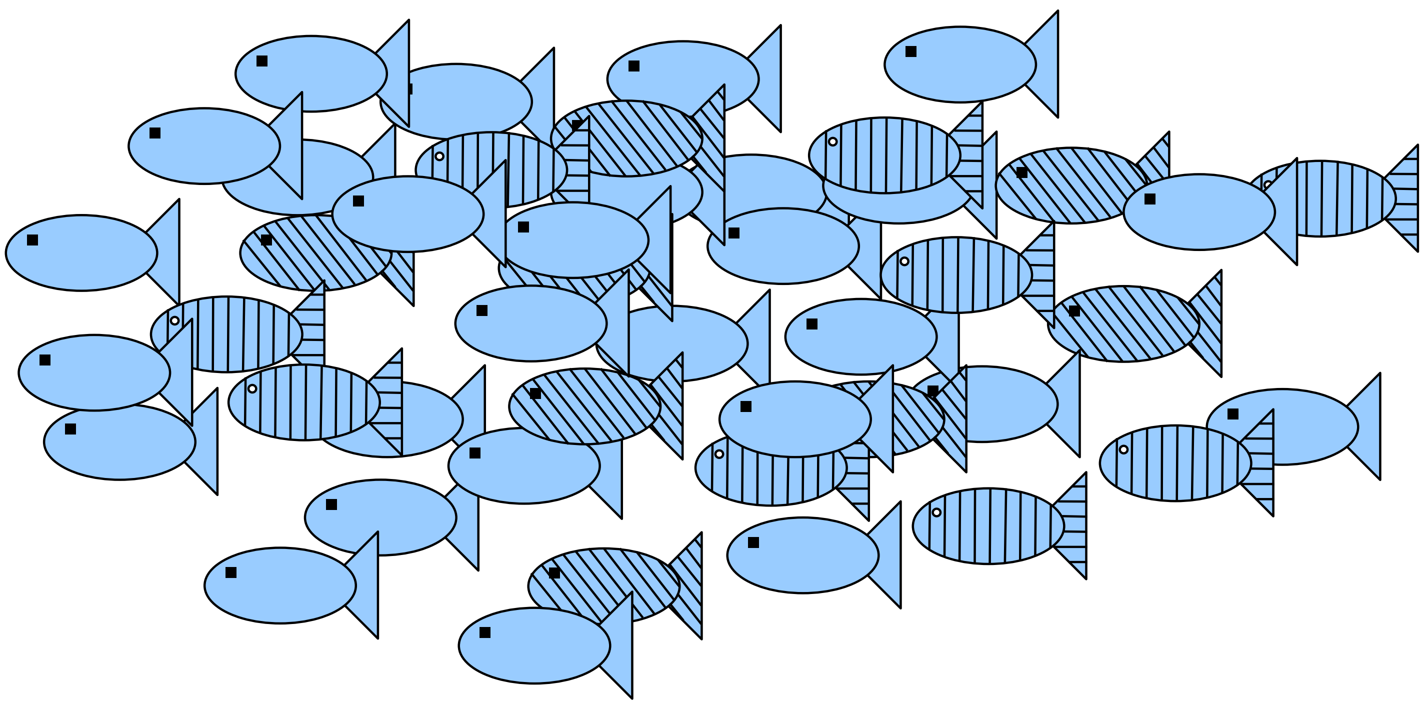

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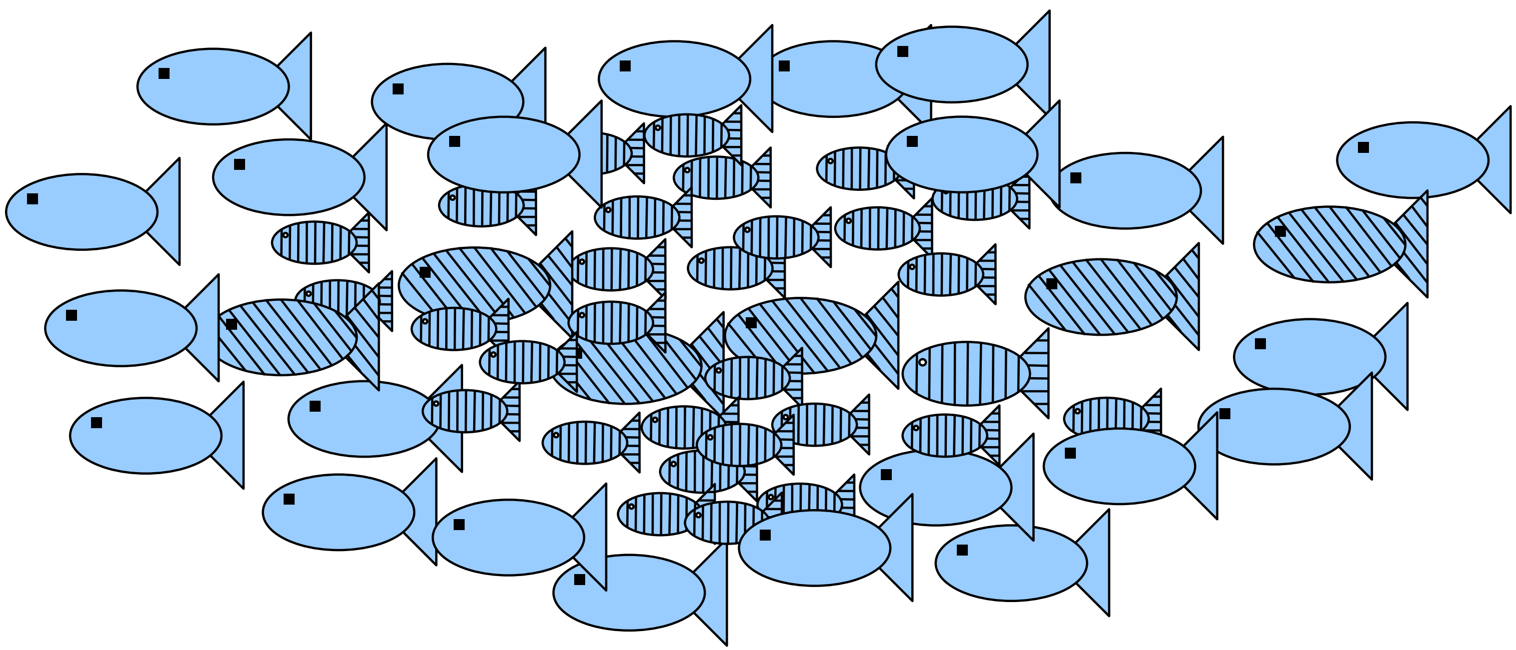

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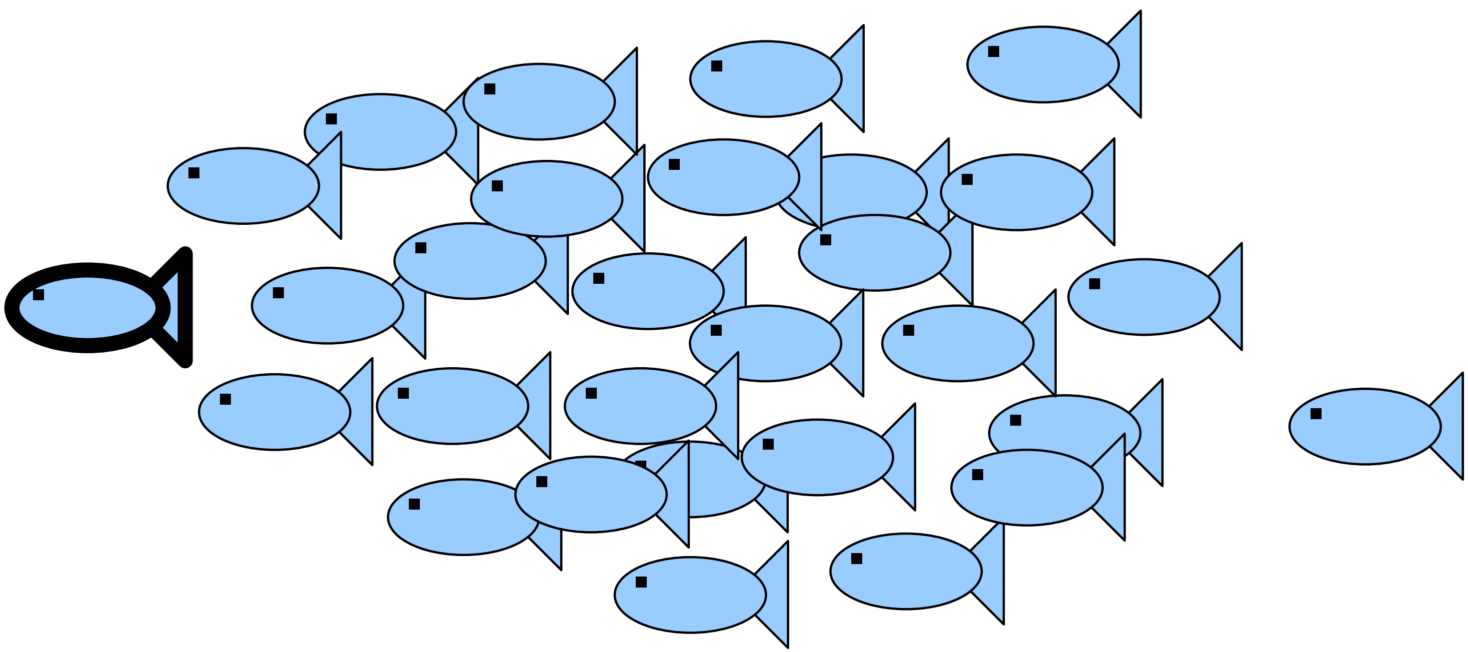

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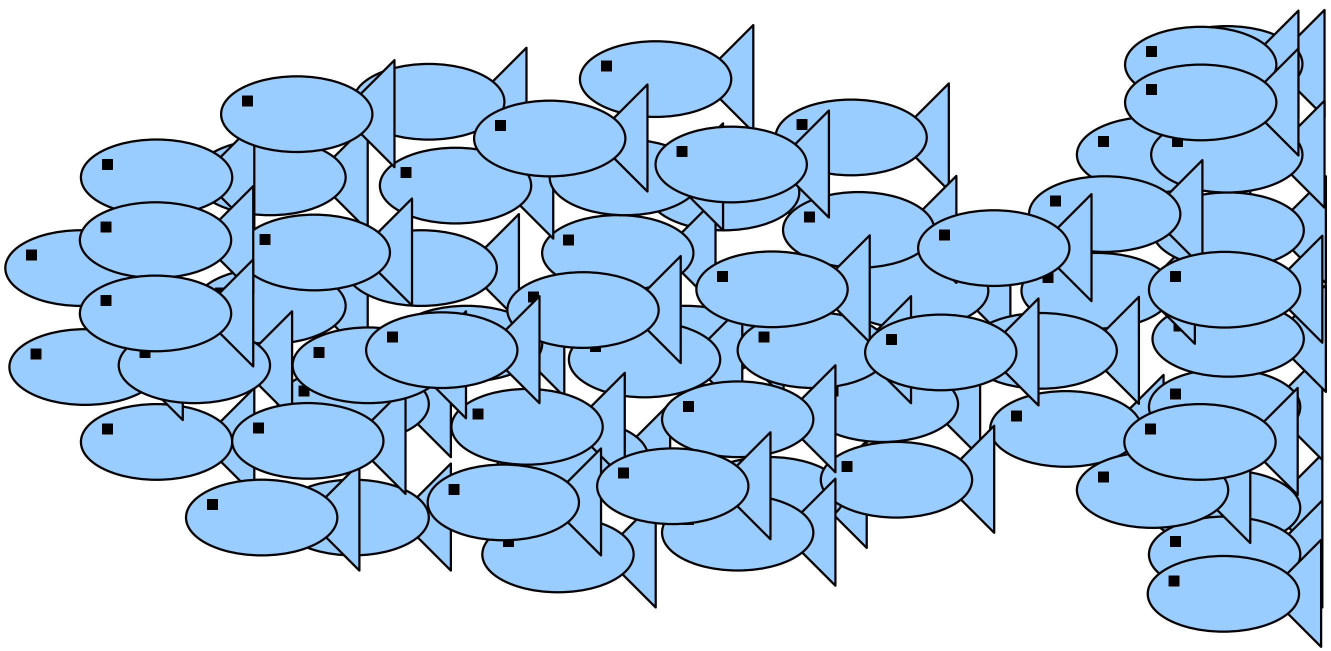

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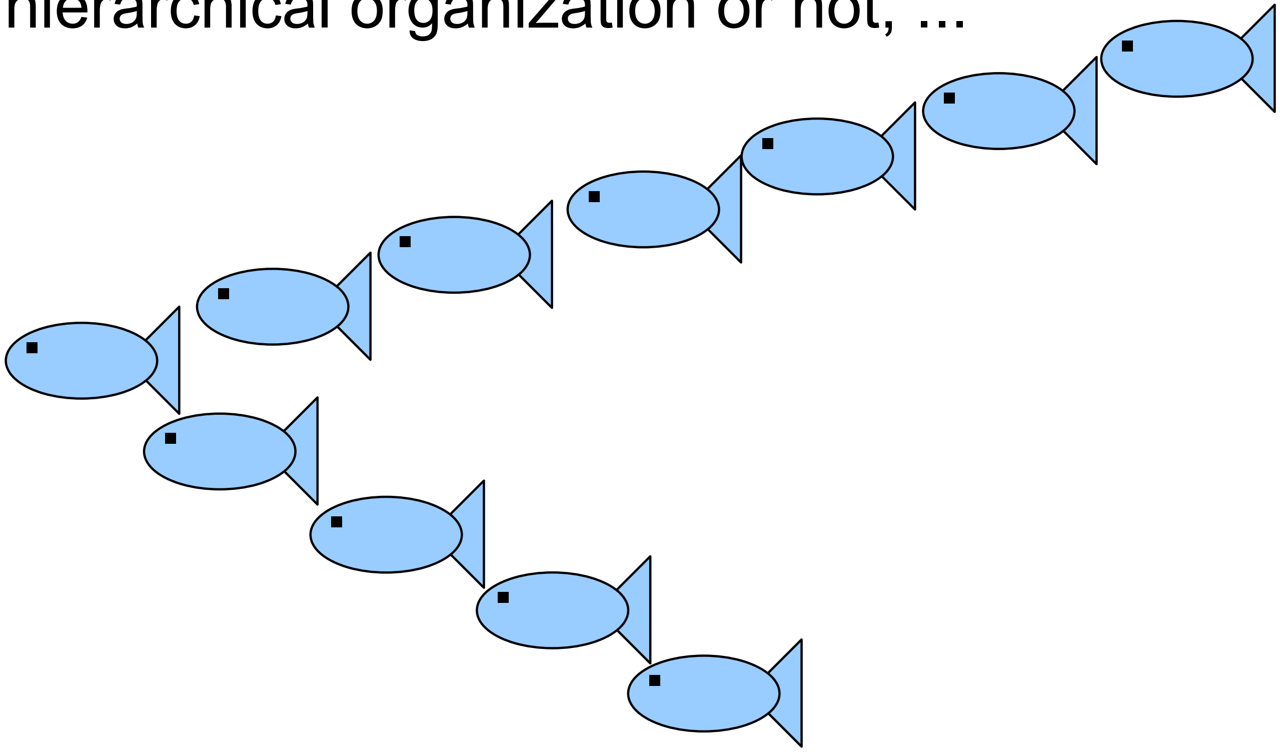


Swarm Behavior

A flock of auklets exhibit swarm behaviour

from: http://en.wikipedia.org/wiki/Swarm_behaviour

Swarm Behavior

Birds flocking, as an example for swarming behavior.

from: http://en.wikipedia.org/wiki/Swarm_behaviour

Swarm Behavior

Great cormorant flock flying in Vee formation

from: http://en.wikipedia.org/wiki/Swarm_behaviour

Swarm Behavior

These bluestripe snapper are schooling.
They are all swimming in the same direction in a coordinated way.

from: http://en.wikipedia.org/wiki/Swarm_behaviour

Swarm Behavior

Schooling predator fish size up schooling anchovies

rfom: http://en.wikipedia.org/wiki/Swarm_behaviour

Swarm Behavior

Herd of thousands of king penguins with their youngs (brown)

from: http://www.guardian.co.uk/

Swarm Behavior

Swarm of jellyfish

By Brocken Inaglory - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=2141765 http://en.wikipedia.org/wiki/Jellyfish

Swarm Behavior

Herd of zebra

from: http://de.wikipedia.org/wiki/Zebra

Swarm Behavior

Migratory locust (Locusta migratoria), grasshoppers in a migratory phase of their life

from: https://en.wikipedia.org/wiki/Locust

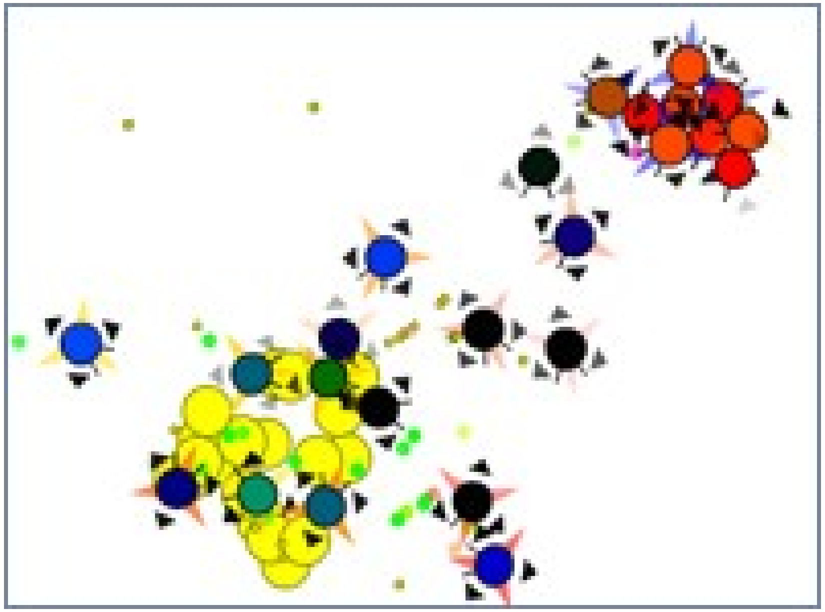
Swarm Behavior

Swarm near Satrokala, Madagascar during a 2014 outbreak,
Swarm sizes of 100-200 Billion animals have been reported.

from: https://en.wikipedia.org/wiki/2019-2022_locust_infestation

Evolving Swarm Behavior

A recently published work has focused on implementing an evolutionary process to generate swarm behavior:



“ The variety of evolved behaviours includes several behavioural patterns observed in nature, such as mutual inhibition of reproduction in order to budget food, sophisticated aggregation behaviour, marking food sources with pheromones, and exploration. Forms of communication were evolved, simple, though essential for the swarm. Behaviours were evolved which can be observed everywhere in nature – however, in a synthetical and, therefore, completely transparent analyzable way.“

from: http://www.dkriesel.com/en/science/distributed_evolution_of_swarms

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Boids: Craig Reynolds

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In 1986 Craig Reynolds developed a simple model consisting of three rules for each individual, that is capable of generating a swarm like behavior.

He called the individuals: Boids (Birds, Androids) to implement coordinated animal motion such as bird flocks and fish schools.

Reynolds, C. W. (1987) *Flocks, Herds, and Schools: A Distributed Behavioral Model, in Computer Graphics*, 21(4) (SIGGRAPH '87 Conference Proceedings) pages 25-34.

https://www.youtube.com/watch?v=86iQiV3-3IA

http://www.red3d.com/cwr/boids/

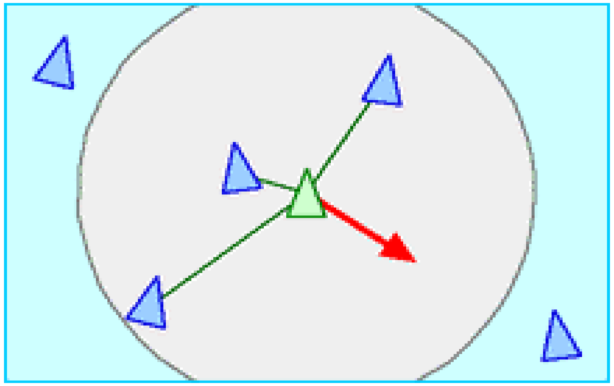
Boids: Craig Reynolds

The basic flocking model consists of three simple **steering behaviors** which describe how an individual **boid** maneuvers, based on the positions and velocities of its nearby flockmates.

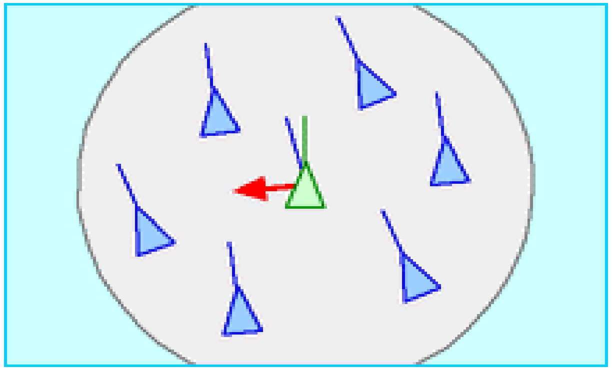
- **Separation:**
  steer to avoid crowding local flockmates
- **Alignment:**
  steer towards the average heading of local flockmates
- **Cohesion:**
  steer to move toward the average position of local flockmates

Boids: Craig Reynolds

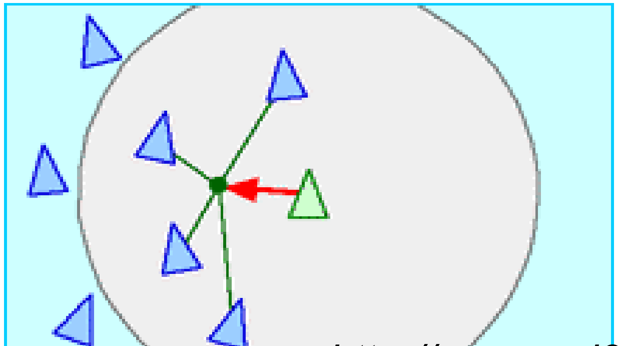
Separation:
steer to avoid
crowding local flockmates



Alignment:
steer towards the average
heading of local flockmates



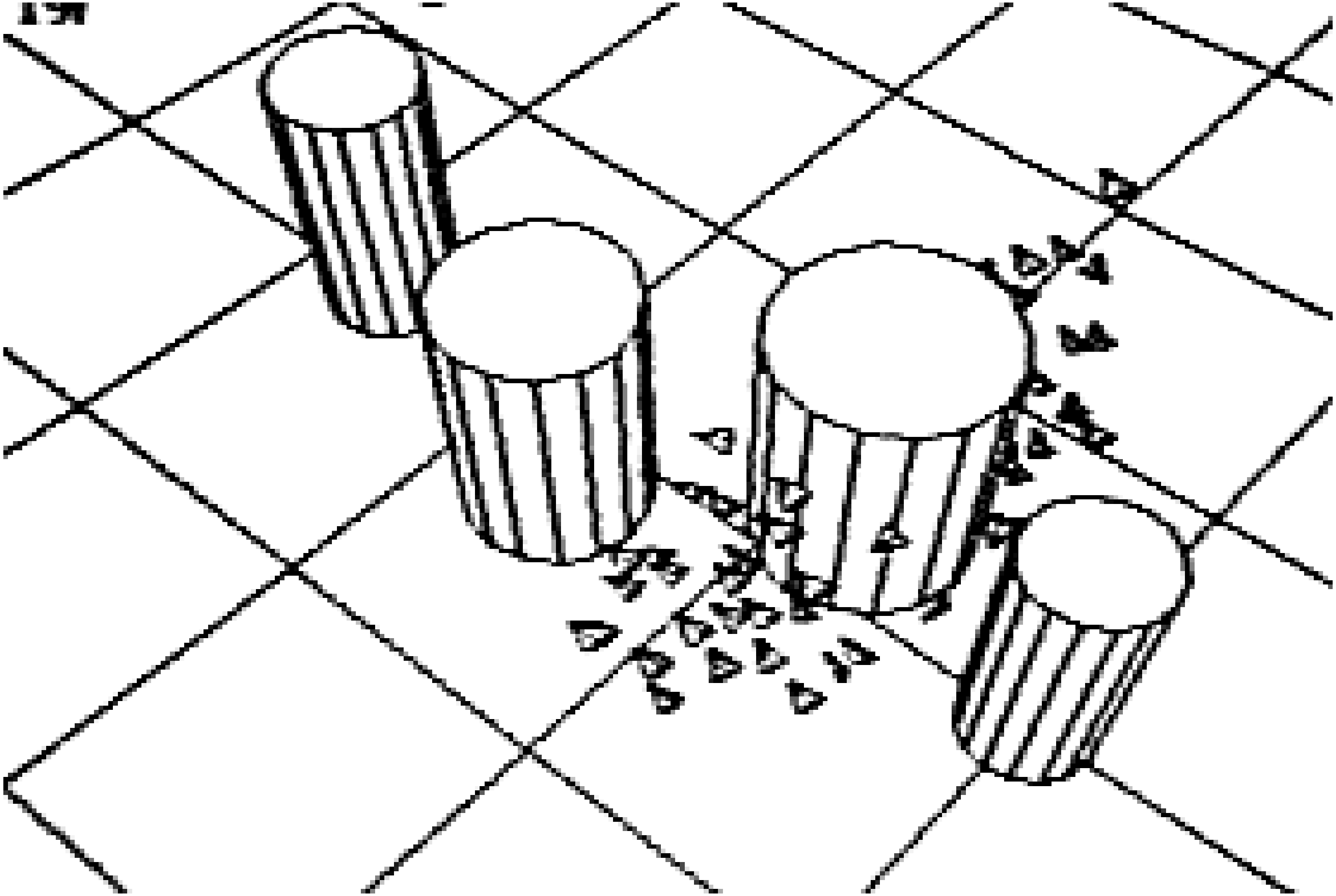
Cohesion:
steer to move toward the
average position of local
flockmates



http://www.red3d.com/cwr/boids/

Boids: Craig Reynolds

Simulated boid flock avoiding cylindrical obstacles (1986)



http://www.red3d.com/cwr/boids/

Boids: Craig Reynolds

Since the publication of the boids by C.Reynolds, the idea to generate natural like swarming behavior by sets of (simple) steering rules has been adopted within a lot of applications:

- Computer Animation
- Games, Interactive graphics and virtual reality
- Robotics
- Aerospace
- Biology
- Physics
- Search, optimization and visualization techniques

http://www.red3d.com/cwr/boids/

Multi Robotics, Swarms, Boids, PSO

- Cooperating Robots
- The Didabot Experiment
- Swarm, Swarming, Swarm Behavior
- C.Reynolds: Boids
- **Particle Swarm Optimization, PSO**

Multi Robotics, Swarm, Boids, PSO

- Cooperating Robots
- The Didabot Experiment
- Swarm, Swarming, Swarm Behavior
- C.Reynolds: Boids
- **PSO: Particle Swarm Optimization**

Remark:

Please **do not mix up** the two paradigms: Boids and PSO

Although Particle Swarm Optimization has been inspired by Boids these are **different paradigms**, and they have a **different purpose**.

PSO: Particle Swarm Optimization

Particle Swarm Optimization is an Artificial Life inspired, multi hypothesis, meta heuristic method for optimization.

Based on C.Reynolds approach of the Boids,
J.Kennedy, R.Eberhart and Y.Shi developed an approach to generate and to simulate social behavior.

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Particle Swarm Optimization is an Artificial Life inspired, multi hypothesis, meta heuristic method for optimization.

Based on C.Reynolds approach of the Boids, J.Kennedy, R.Eberhart and Y.Shi developed an approach to generate and to simulate social behavior.

Their approach included an objective (position) that should be reached by the simulated individuals.

The results obtained while including the objective function were so successful, that **PSO** became a well accepted optimization method.

The concept of **Particle Swarm Optimization** is related to Evolutionary Algorithms, Particle Filters and Boids.

J. Kennedy, R.C. Eberhart, "*Particle Swarm Optimization*", in: Proceedings of IEEE International Conference on Neural Networks, Perth, Australia, pp. 1942–1948, 1999

PSO: Particle Swarm Optimization

The **PSO** consists of:

Each **particle** **j** has:

PSO: Particle Swarm Optimization

The **PSO** consists of:

- a population of P particles, j=1:P
- a search space ***S***, with positions **X** in ***S***
- an objective function f(**X**)
- a memory to store the best result in the population so far
  global best: $\mathbf{X}_{gb}$, $f(\mathbf{X}_{gb})$
- (several sub-groups of particles)

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Each **particle** **j** has:

- a position $\mathbf{X}_j$ in search space **S**
- a *velocity* $\mathbf{V}_j$, (change in position)
- a memory to store the best result for the individual so far personal best: $\mathbf{X}_{j,pb}$, $f(\mathbf{X}_{j,pb})$
- (group of particles it belongs to, group best $\mathbf{X}_{j,grb}$, $f(\mathbf{X}_{j,grb})$)

PSO: Particle Swarm Optimization

Init PSO, $\mathbf{X}_j$, $\mathbf{V}_j$, groups

Main loop:

- calculate new *velocity* $\mathbf{V}_j$
- calculate new position $\mathbf{X}_j$
- calculate new performance $f(\mathbf{X}_j)$, evaluate particle
- store new best performances
  - personal best
  - global best
  - group best
- **Finish?**

PSO: Particle Swarm Optimization

The *velocity* $\mathbf{V}_j$ is calculated as a weighted combination of 4 different aspects, comparable to the steering rules of Boids:

$$\mathbf{V}_j \leftarrow \omega * \mathbf{V}_j + \alpha * R * (\mathbf{X}_{j,pb} - \mathbf{X}_j) + \beta * R * (\mathbf{X}_{gb} - \mathbf{X}_j) + \gamma * R * (\mathbf{X}_{j,grb} - \mathbf{X}_j)$$

$\omega * \mathbf{V}_j$	keep the old direction
$\alpha * R * (\mathbf{X}_{j,pb} - \mathbf{X}_j)$	steer towards personal best
$\beta * R * (\mathbf{X}_{gb} - \mathbf{X}_j)$	steer towards global best
$\gamma * R * (\mathbf{X}_{j,grb} - \mathbf{X}_j)$	steer towards group best

ω, α, β, γ are control parameters, with $0.0 \leq \omega \leq 1.0$, and $0.0 \leq \alpha,\beta,\gamma \leq 4.0$

R is a random value, [0 … 1], (exploration)

PSO: Particle Swarm Optimization

Init PSO, $\mathbf{X}_j$, $\mathbf{V}_j$, groups

Main loop:

- calculate new *velocity* $\mathbf{V}_j$

  $\mathbf{V}_j \leftarrow \omega \ast \mathbf{V}_j + \alpha \ast R \ast (\mathbf{X}_{j,pb} - \mathbf{X}_j) + \beta \ast R \ast (\mathbf{X}_{gb} - \mathbf{X}_j) + \gamma \ast R \ast (\mathbf{X}_{j,grb} - \mathbf{X}_j)$
- calculate new position $\mathbf{X}_j$

  $\mathbf{X}_j \leftarrow \mathbf{X}_j + \mathbf{V}_j$
- calculate new performance $f(\mathbf{X}_j)$, evaluate particle
- store new best performances

  personal best $\mathbf{X}_{j,pb}$, $f(\mathbf{X}_{j,pb})$

  global best $\mathbf{X}_{gb}$, $f(\mathbf{X}_{gb})$

  group best $\mathbf{X}_{j,grb}$, $f(\mathbf{X}_{j,pb})$
- **Finish?**

PSO: Particle Swarm Optimization

Usually no special group is defined for the particles, and only personal best and global best are used (γ=0.0).

Sometimes the group is defined as the neighborhood in space, and global best is omitted (β=0.0).

Typical values for the parameters are:

P= 20 … 40, ω=1.0, α=2.0, β=2.0, γ=1.0

$$\mathbf{V}_j \leftarrow \omega \ast \mathbf{V}_j + \alpha \ast R \ast (\mathbf{X}_{j,pb} - \mathbf{X}_j) + \beta \ast R \ast (\mathbf{X}_{gb} - \mathbf{X}_j) + \gamma \ast R \ast (\mathbf{X}_{j,grb} - \mathbf{X}_j)$$

$$\mathbf{X}_j \leftarrow \mathbf{X}_j + \mathbf{V}_j$$

PSO: Particle Swarm Optimization

Position Bounds:

For most applications an area within the search space can be determined a priori where the results are expected.
In this case, it is reasonable to restrict the positions of the particles to remain within this predetermined area.
Different philosophies how to handle particles that "try to escape" can be chosen with respect to the application:
(bounce, reset to start, reset randomly, reset to stored best, ...) .

Velocity Bounds:

To restrict the movement of the particles upper bounds for the velocity can be defined.

PSO: Particle Swarm Optimization

Swarm / Group Topology:

It has been proposed to structure the swarm of particles into groups, or sub-swarms, that obey a special topology.

Within the group only the information from the particle itself (personal best) and from a local neighborhood is used to calculate the new velocity.

PSO: Particle Swarm Optimization

Swarm / Group Topology:

It has been proposed to structure the swarm of particles into groups, or sub-swarms, that obey a special topology.
Within the group only the information from the particle itself (personal best) and from a local neighborhood is used to calculate the new velocity.

Typical (Sub-)Swarm topologies:

- Singletons (no special topology, just single particles)
- Ring (cyclic, one dimensional)
- Grid (N-dimensional regular structure, including torus)
- Mesh (Random connected particles)
- Fully-connected

PSO: Particle Swarm Optimization

Particle Swarm Optimization

is a rather young meta heuristics for optimization, that showed some very promising results during the last years.

It is extremely easy to implement, and can be very fast.

To reveal what really is happening inside an **PSO** system is a subject of current research.

Artificial Life
Summer 2025

Multi Robotics, DidaBots, Swarms, Boids, PSO Particle Swarm Optimization

Master Computer Science [MA-INF 4201]
Mon 14:15 – 15:45, HSZ, HS-2

Dr. Nils Goerke, Autonomous Intelligent Systems,
Department of Computer Science, University of Bonn

Artificial Life
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Thank you for your patience

Dr. Nils Goerke, Autonomous Intelligent Systems,
Department of Computer Science, University of Bonn