Boids Model

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Multi-Agents - IA310

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Abstract:

This work aims to present, discuss and modify the Boids model, commonly used for the description of aggregate dynamics of natural agents. Among the proposed implementations are the presence of a leader; the addition of obstacles and the disruption caused by predators. Notably, we present simulations with indirect communication between leader and flock in order to escape the predator. To study the system in a quantitative way, different metrics are used to compare the various scenarios.

Keywords: boids model; swarm intelligence; emergence, multi-agents; artificial intelligence

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This document has pedagogical purposes and its objective is to use the knowledge acquired from the lectures in a practical context.

1 Introduction

1.1 Context

Boids (from *bird-oid*, or bird-like) is an artificial life simulation originally developed by Craig Reynolds [2]. The aim of the simulation was to replicate the behavior of aggregate natural motion; such as flocks of birds, schools of fish or herds of land animals. Instead of controlling the interactions of an entire group, however, the Boids model only specifies the behavior of each individual agent. With only a few simple rules, the program manages to generate a result that is complex and realistic enough to be used as a framework for computer graphics applications such as computer generated behavioral animation in motion picture films.

Additionally, it is a perfect example of emergent behavior in artificial life simulations; that is, the complexity of Boids arises from the interaction of individual agents following a set of simple rules. For example, the group can separate into two or more components and eventually reunite, or reach situations of total or quasi-periodic stability. In modified models of Boids containing predators [4], some behavioral patterns described solely from the point of view of biology were simulated for the first time; such as the Schelling Segregation Law [3].

1.2 Original Boids Model

The original approach by Craig Reynolds assumes that the flock is simply the result of the interaction between the behaviors of individual birds. To simulate a flock, we simulate the behavior of an individual bird (or at least that portion of the bird's behavior that allows it to participate in a flock). To support this behavioral "control structure" 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 peers.

The set B of n boids b_i involved in the flock is denoted by:

$$B = \{b_i, i = 1, 2, ..., n\} \tag{1}$$

Each boid b_i has a position vector $\vec{p}_i$ and a velocity vector $\vec{v}_i$ that describe its motion in space at a time t. The force which adjusts the speed of the boid is typically an impulse generated by the same, so that impulse is limited in a scalar of maximum force denoted as f_m. In addition, boids are restricted to a maximum speed expressed as s_m. This speed limit is imposed by a gating of the velocity vector of the boid.

The local space associated with each boid b_i is described by $\vec{f}_i(t)$, $\vec{l}_i(t)$ and $\vec{u}_i(t)$ which refer respectively to the vectors "forward" (x axis), "side" (z axis) and "up" (y axis). Where each boid has a local view of its environment called "area of perception" related to a steering behavior. The area of perception is determined by a radius r and a angle θ (field of view) where only neighbors who are in the area of perception are selected for calculating certain steering behavior (Figure 3).

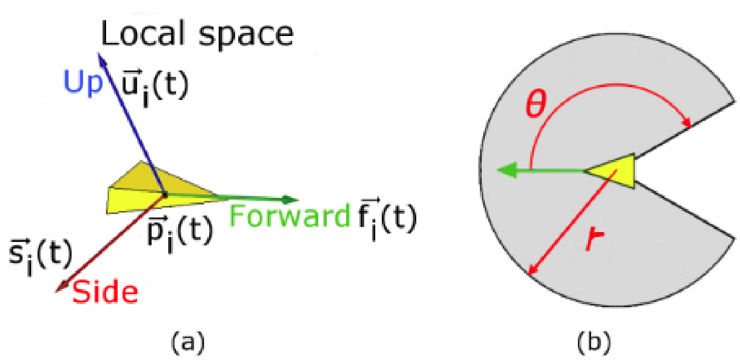

Figure 1: (a): Local space of a boid. (b): Area of perception of a boid. [1]

The steering behaviors of a boid b_i executed at time t are cohesion, $\vec{c}_i(t)$; separation,$\vec{s}_i(t)$; and alignment, $\vec{a}_i(t)$. In addition, the steering behaviors cohesion, separation and alignment are associated with the sets of boids b_j perceived C_i, S_i and A_i, respectively. The purpose of cohesion behavior is to move a boid towards the center of a group perceived within its neighborhood. If this steering behavior were uniquely applied, the formation would be gathered together in a region. The formula of cohesion, $\vec{c}_i(t)$ is expressed in the equation below, where m_c is the cardinality of the set C_i.

$$\vec{c}_i(t) = \left(\frac{1}{m} \sum_{\forall b_j \in C_i} \vec{p}_j(t) \right) - \vec{p}_i(t) \tag{2}$$

The purpose of separation behavior is to move a boid to avoid a collision with their neighbors and prevents agglomeration of formation. If only this behavior is applied, the formation dissipate.

$$\vec{s}_i(t) = - \sum_{\forall b_j \in S_i} (\vec{p}_j(t) - \vec{p}_i(t)) \tag{3}$$

The purpose of alignment behavior is to move a boid in the same direction as their neighbors. The alignment behavior acts as a first heuristic to avoid collision, because when all boids of a formation move at the same velocity the risk of collision between them is reduced. The formula of alignment, $\vec{a}_i(t)$ is expressed below, where m_a is the cardinality of the set A_i:

$$\vec{a}_i(t) = \left(\frac{1}{m_a} \sum_{\forall b_j \in A_i} \vec{v}_j(t) \right) - \vec{v}_i(t) \tag{4}$$

When each boid b_i applies the basic behaviors of cohesion $\vec{c}_i(t)$, separation $\vec{s}_i(t)$, and alignment $\vec{a}_i(t)$ in combination, as result the formation is held together and moves coordinately. The formula for flocking, $\vec{f}k_i(t)$ is expressed below:

$$f\vec{k}_i(t) = \alpha\vec{c}_i(t) + \beta\vec{s}_i(t) + \delta\vec{a}_i(t) \tag{5}$$

Where each behavior is multiplied by the weights α, β and δ, and the range of values of these weights is $[0, \infty)$. In the experiments, the standard values used were $\alpha = 0.05$, $\beta = 0.05$ and $\delta = 0.005$, even though such parameters can be manipulated by the user on the simulation.

With this force, the speed and acceleration of each agent will be updated. This description already supports a basic understanding of the framework for the Boids model.

2 Methodology

In order to study in more detail the dynamics of the Boids model, this work proposes different additional functionalities that will complicate the development of the system. We note that these implementations do not aim to radically change the original framework, seen in the previous section, being therefore additions linked to the environment and the dynamics of leaders and predators. In this section, we'll detail each proposed modification and discuss the metrics we'll use to get a quantitative perspective on the impact on the system. We note that our implementation of the Boids model will solely use two dimensions instead of three.

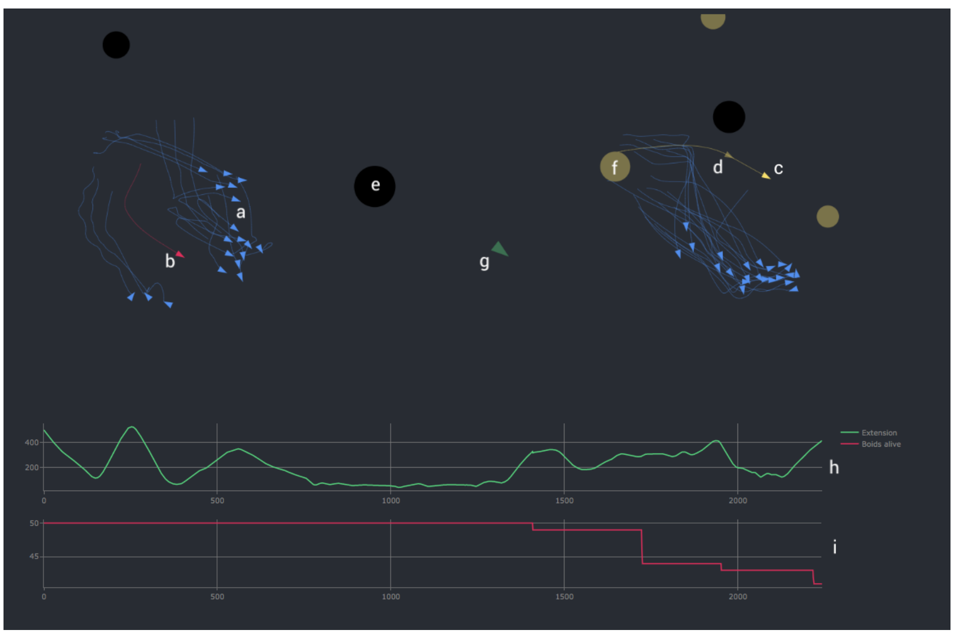

Figure 2: The custom simulation interface created. (a) common boids; (b) predator; (c) leader; (d) arrow left by leader (indirect communication); (e) obstacle; (f) turbulence zone; (g) the flock's center of mass and average speed vector; (h) extension curve through time; (i) number of boids through time;

Figure 3: The controls for the custom simulation.

2.1 Modifications

2.1.1 Leader

At first, we propose a system configuration with the addition of a **leader**. This special agent (yellow triangle in the simulation) differs from regular boids in the following ways: it does not avoid nor tries to match its velocity to that of other boids, meaning their separation and alignment are zero.

$$\vec{s}_{leader}(t) = \vec{a}_{leader}(t) = 0 \tag{6}$$

Since alignment is zero, the leader does not adapt its movement to that of other boids – it rather influences other boids to follow its movement. Separation would also hurt leaders' capacity to actually lead the flock, by making it keep its distance – which is why this parameter is also zeroed.

Cohesion ($\vec{c}_{leader}(t)$), however, is kept.

Regular boids were modelled to be specially sensible to a leader, so they can see one from a longer distance (three times the common visual range), and are also specially attracted to a it – if a boid sees a leader, their direction will be also aligned with the leader's position, according to a weight ψ ($\psi = 0.5$ in the experiments).

$$\vec{a'}_i(t) = \delta \vec{a}_i(t) + \psi \vec{v}_{leader}(t) \tag{7}$$

Leaders also leave a trace of their path through the simulation. Every second, they leave behind an arrow pointing at the direction they were taking.

This has an effect of **indirect communication**, since regular boids try to align to these markers, helping them reach the leader even if they are behind the flock, or were going in a different direction (refer to Figure 4).

Leaders' behaviour regarding predators is also different from regular boids – this will be dealt with in the corresponding section.

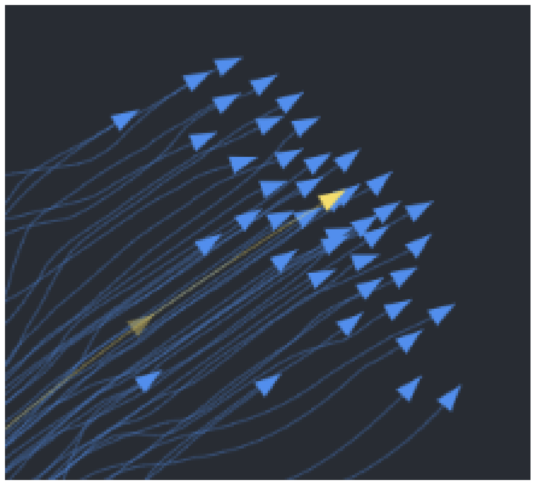

Figure 4: The yellow leader amid a flock, and the last arrow it left behind (in transparent yellow). The boid right next to the arrow was probably attracted by it, rather than by the leader or other flock members.

2.1.2 Obstacles and Turbulence

The second implemented modification was the presence of randomly spawned **turbulence areas** (transparent yellow circles – refer to Figure 5) and **obstacles** (black circles – Figure 6), of various sizes.

When a boid goes through a turbulence area, it suffers an acceleration towards a given direction (chosen randomly). When a boid sees an obstacle, however, it is forced to change direction not to collide with it.

2.1.3 Predator

Predators are also based on the boids model, with some modifications to induce predating behavior. They do not have separation,

$$\vec{s}_{pred}(t) = 0 \tag{8}$$

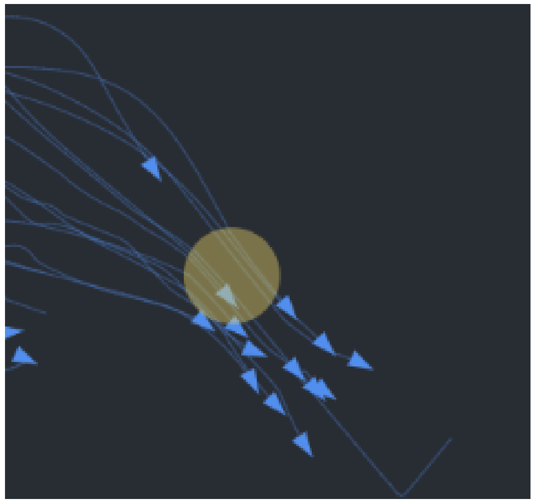

Figure 5: A group of boids go through a turbulence area, being rapidly pushed out of it.

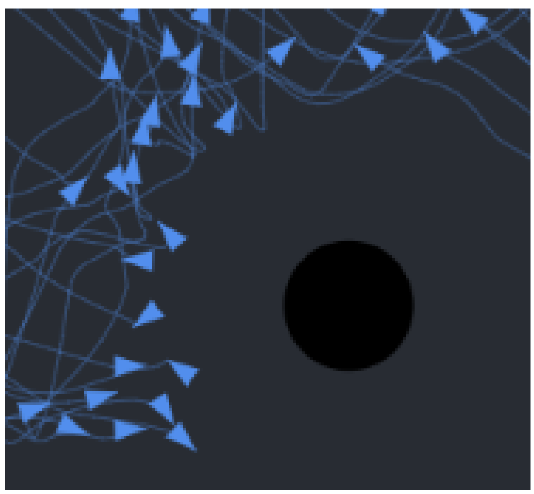

Figure 6: A group of boids changes their path after seeing an obstacle ahead.

and their alignment is corrected by a parameter ζ ($\zeta = 0.5$ in the experiments). This is needed because, as regular boids run away from predators in different directions, if the predator were to align too starkly to the preys' average velocity vector, it would stand still.

$$\vec{a'}_{pred}(t) = \zeta \vec{a}_{pred}(t) \tag{9}$$

Also, predators' visual range is slightly better than that of regular boids (it is multiplied by $\theta = 1.5$ in the experiments). This is needed to give an advantage to the predator, and would be justified by the predator's species having better sight.

As said before, with the addition of predators, other boids have a new behavior allowing them to flee from a predator from the moment they see it. To grant the leaders with an advantage point, they can spot predators at a distance three times greater than that of regular boids.

A predator can also eat regular boids, if it manages to get sufficiently close. The simulation includes a chart that shows, in red, how the number of living boids varies through time.

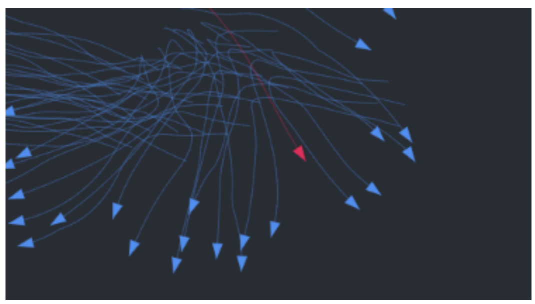

Figure 7: A group of boids is chased by a predator (red triangle).

2.2 Proposed Metrics

As the studied system is based on the interplay of a group of agents that react individually to their surroundings, we can propose two types of performance analysis: local or general.

In a local analysis, we could focus on the performance of a single agent, or on a specific spatial region of the system (i.e.: close to obstacles or turbulence zones). A general analysis, on the other hand, takes into account the holistic behavior of the system; contemplating an average effect of the different configurations to be tested. In the work done by Gershenson et al. [1], different metrics for Boids analysis were proposed. Here, we implement two general metrics: the **extension of the system** and the **number of agents alive**.

The model extension is given by the average distance of the agents in relation to the flock centroid. The centroid is easily calculated by equation (10):

$$\vec{\text{cen}}(t) = \frac{1}{n}\sum_{i=1}^{n}\vec{p}_i(t) \tag{10}$$

Then the computation of the extension naturally follows:

$$\text{ext}(t) = \frac{1}{n}\sum_{i=1}^{n}\|\vec{\text{cen}}(t) - \vec{p}_i(t)\| \tag{11}$$

This is a representative metric for the configurations that will be implemented, since we expect that they will directly change the flock's clustering capacity, or the stability of the groups formed.

A second metric of interest for the case where predators are present is, naturally, the number of live agents. Different configurations and parameters will be tested in order to study the scenarios that favor predation success, such as the presence or absence of a leader.

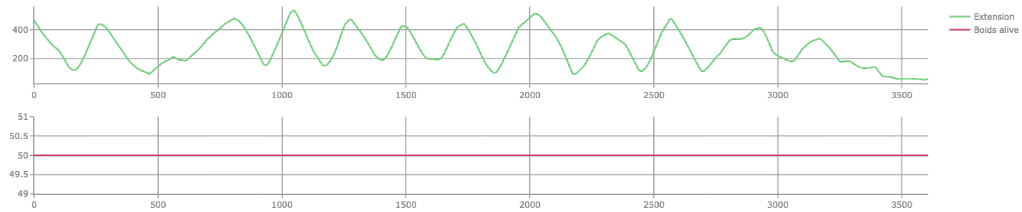

Figure 8: Extension evolution over time steps for a simulation with no leader

3 Results

In this section, the results of the different additional configurations implemented in this work will be discussed. For each result discussed below, ten simulations were performed in order to capture an average behavior of the phenomenon.

3.1 Leader Dynamic

As described in section 2.1.1, the leader has an effect over the other boids, they will try to follow it and match its velocity. The leader can be seen from a longer distance and can communicate indirectly by leaving a marker where it passed.

	Time steps for $ext < 50$	
Experiment	Mean	Standard Deviation
Without leader	2838.4	1417.1
With leader	1324.2	671.3

Table 1: Statistical information taken from 10 simulations for the experiments done with or without a the presence of a leader.

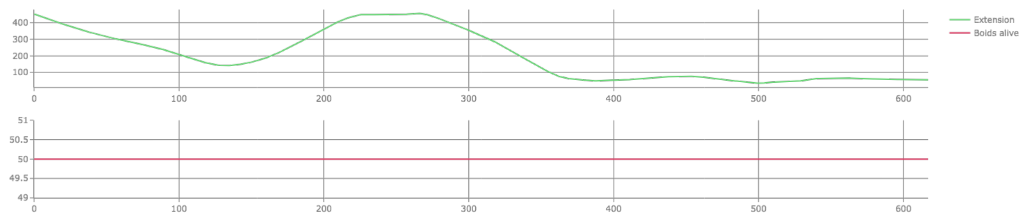

Figure 9: Extension evolution over time steps for a simulation with a leader

The extension metric (11) was used to measure the clustering of the flock with or without a leader. The results are presented in Table 1. Figures 8 and 9 show the extension metric evolution over the simulations steps. The results show that the leader help the model converge faster to a united flock, when the extension is lower.

3.2 Turbulence Zones and Obstacles

With the inclusion of turbulence zones and obstacles (Figure 10), the flocks of boids do not tend to converge into one flock, and are force into a rather erratic behavior. This is expected, because the obstacles and turbulence areas affect directly the agents' capacity to find each other and stay together.

The result is an Extension chart that is very noisy, and doesn't really converge (Figure 11). Therefore we have taken, for 10 runs of the experiment, the minimal and maximal extension achieved after a threshold of 3000 steps, and the resulting statistical description can be seen in Table 2.

We can see that the minimal extension is rather high, in comparison to the extension levels achieved in section 3.1, confirming our expectations.

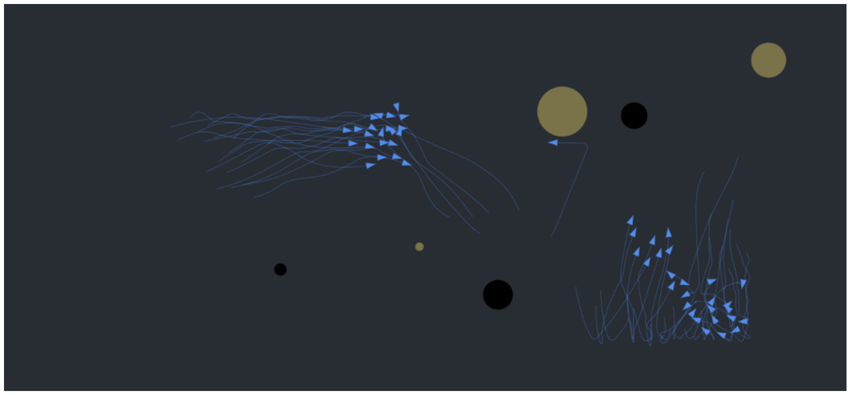

Figure 10: A frame of the simulation with regular boids, turbulence areas and obstacles.

	Statistics	
Metric	Mean	Standard Deviation
Min Extension	155.6	37.4
Max Extension	575.4	59.27

Table 2: Statistical information taken from 10 simulations for with turbulence areas and obstacles, without the presence of a leader.

3.3 Predator Dynamics

3.3.1 Without Leader

Considering the aforementioned predator implementation, detailed in the section 2.1.3, we have the following results for the leaderless case:

One can note that the presence of the predator alone can be seen as a disturbance device in the system, since the extension of the system with predator is greater than the scenario without it.

Additionally, we noticed that for the observed temporal scope, there is an average loss of 5 agents due to the presence of the predator.

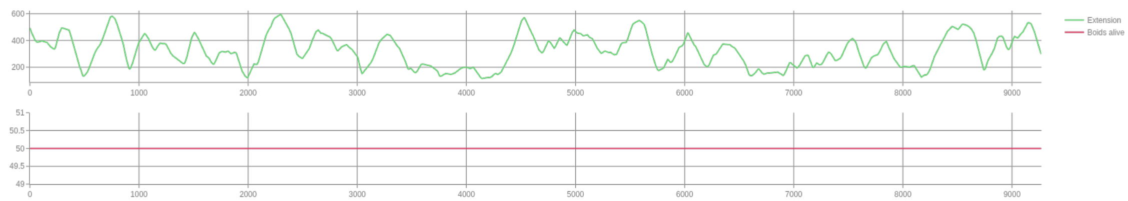

Figure 11: Extension (in green) and number of boids (in red) for a scenario with turbulence zones and obstacles (without leader nor predator), after 3000 iterations.

	Statistics	
Metric	Mean	Standard Deviation
Min Extension	91.2	22.16
Max Extension	555.4	51.08
Alive Boids	45.3	3.1

Table 3: Statistical information taken from 10 simulations without the presence of a leader.

3.3.2 With Leader

We now observe the case of predation with leader, which will indicate, through indirect communication with the other agents, a strategic direction to escape the predator. We therefore have the following results:

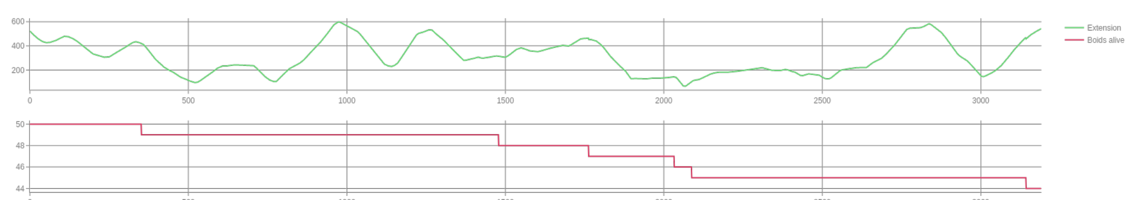

Figure 12: Extension (in green) and Number of Boids Alive (in red) for predator dynamics with leader, after 3000 iterations.

A starting point of comparison with the leaderless case is the smoothness of the extension curve. One may notice that the presence of the leader smooths out the dynamics of extension, that is, it makes the flock prone to stay together regardless of predation.

In a naive initial analysis, we could assume that this behavioral tendency would be an interesting strategy to reduce the effects of the predator. However, for the selected parameters of action of the leader and the predator, this phenomenon occurs in the opposite way: the fact that the leader groups the rest of the agents makes it easier for the predator to attack a flock. This notably occurs when a flock is cornered by the predator.

	Statistics	
Metric	Mean	Standard Deviation
Min Extension	77.5	15.8
Max Extension	560.1	39.4
Alive Boids	42.7	3.1

Table 4: Statistical information taken from 10 simulations for predator dynamics with the presence of a leader.

4 Conclusion

Regarding the characterization of Agents, Environment and Interaction seen in class, we characterize the system as follows:

Agents are **reactive**, since boids do not have an internal state – they simply react to the environment and other agents following simple rules, according to what is visible to them.

The **Environment** is:

- **Non-accessible** - limited range of view;
- **Deterministic** - there are no stochastic components at play;
- **Episodic** - each step is fully defined by the previous one;
- **Static** - the environment does not change – the agents do;
- **Continuous** - the movement and actions take place in a continous canvas;

Also, regarding the **Interaction**, there is a case of **Indirect Communication**, via the markers left by the leader along its path. These markers serve to nudge more boids towards the leader, and play a big role on the system's dynamics, as seen on the Results section.

Summarizing the experiments' results, we have verified that the leader's presence (with indirect communication) has increased the boids' clustering, minimizing the global extension. Obstacles and turbulence areas have shown to prevent system stability, in such a way that it almost never converges to a low extension value. Moreover, predators were more deadly in the presence of a leader – this was not anticipated, but is easily explainable, since the leader tends to group the boids, who become easy prey for the predator.

4.1 Contributions

- Caio Lang - Problem modeling, discussion, implementation.
- Bruno Sanches - Problem modeling, discussion, implementation.
- Pedro Rosa - Original idea, research, problem modeling, discussion.

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