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Flocking as a Hunting Mechanic: Predator vs. Prey Simulations

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Abstract

Creating models for simulating real-life situations can be a difficult task because of all the small factors that can impact the outcome of an event. One model aimed to accurately predict flocking behaviour for animals is *Boids flocking model*. In this study, we aim to answer if the model is adequate for modeling a predator vs. prey situation. And if it is not, we aim to conclude what factors is needed to increase the accuracy of the model.

The conclusion is that flocking is mainly a defensive tool, and that the Boids flocking model does not model predator actions accurately. To adequately model predator actions, a factor of teamwork and/or coordination is needed.

Flocking in offensive situations makes predators act too much like a single unit and decrease their effectiveness. The advantages of hunting in a group are lost. The number of dead animals did not change depending on if prey flocked or not.

Sammanfattning

Det är svårt att skapa simuleringar över verkliga händelser eftersom det finns en mängd mindre faktorer som drastiskt kan påverka händelsens utgång. En modell som änmar efterlikna riktigt flockbeteende är *Boids flockningsmodell*. Denna studie undersöker om denna modell är tillräcklig för att modellera en verklighetstrogen jaktsituation mellan rov- och bytesdjur. Vidare undersöks vilka extra faktorer som behövs för att öka modellens realism.

Resultaten visar att flockbeteende främst är ett defensivt verktyg samt att Boids modell inte ensamt kan användas för att simulera ett rovdjurs beteende. Det behövs faktorer såsom sammarbete och koordination för att förbättra rovdjurens situation.

I offensiva sammanhang agerar rovdjuren för mycket som en tät grupp, vilket resulterar i minskad effektivitet då de låser varandra - fördelen av att vara i grupp går förlorad. Antalet levande och döda djur ändrades inte signifikat om bytesdjuren flockade eller ej.

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Chapter 1

Introduction

A simulation is an experiment with a model that is used in order to test a real-life situation or event. A model is a simplified or abstract entity with a set of rules used to approach a close or exact (depending on experiment needs) resemblance of the actual situation or event. The correctness of the model depends on the scope of the experiment and what is needed to satisfy the research question. A model should imitate the behavior of an event to a satisfying degree. A simulation uses this model and operates on it over time in order to either provide a result of the situation, visualize a state of the situation at a given time, and/or generalize a set of behaviors.

A simulation is used when investigating the actual situation is impractical, expensive, impossible, or illegal. It can also be used to test a situation frequently and repeatedly with different factors to get a better understanding the situation or to find an optimal state at the end of the simulation [White and Ingalls, 2009].

Simulations have been used both in entertainment and for making analyses. A well known example of a simulation is the wind-tunnel used by the Wright brothers to optimize and analyze the aerodynamics using scale models. Nowadays, computer simulations are much more common because of their low cost and ease of setup.

Simulations have been used to test animal behavior, and human effects on natural habitats. An example of a common simulation is the balance of fishing vs reproduction rates of fishes. Simulations of these situations are used to predict at what rate humans can fish whilst not destroying the ecosystems where the fishing occurs.

Other areas of use for simulations are to make realistic approximations in animations, research on artificial intelligence, and other forms of virtual entertainment such as video games and artificial fish tanks.

In realtime strategy games, flocking algorithms such as Boids flocking model (described in section 2.2.1), can be employed to provide realistic and efficient troop movement [Palmqvist and Dimberg, 2006] for a great amount of soldiers [Balla and Fern, 2009].

1.1 Research Question

The research questions that this work answers is: How does flocking impact the balance between prey and predator? Is Boids flocking model adequate for simulating prey and predator dynamics?

In order to solve these questions, flocking animals have been simulated using computer algorithms.

1.2 Scope and Constraints

The research question is wide, and has thus been reduced in the following ways:

1. The study is limited to two-dimensional simulations.
2. Animals are modelled with two vectors: position and velocity. They are considered moving dots.
3. Animals have a limited area in which they interact with other animals.
4. There are no external forces acting upon prey and predator. This means that factors of wind resistance and individuality are completely ignored for the simulations.
5. All simulations are performed with fixed time steps.
6. There are no random elements in the simulations. The results are deterministic.

These constraints have been set in order to assure reliable results that can be reproduced in the future. By removing external forces and randomness, the performed simulations are deterministic. Thus, repeatable results are given.

An extended version of the boids algorithm [Reynolds, 1999] was used for simulating the animals as dynamic obstacle avoidance is a must.

1.3 Relevance

As a study of expected outcomes in real-life situations, computer simulations provide an alternative to actual observations as they can be run quickly and in large scale. Furthermore, they provide a great test for the currently used algorithms for flocking behavior.

Computer simulations also avoid the difficult ethics surrounding animal testing and experimentation as no life is risked. Therefore, substituting studies that relies on the killing of animals should prove to be beneficial to everyone.

With the advent of autonomous drones, flocking provides a great means of hiding in flock-like structures. Furthermore, for full automation, drones could combat each other in a variety of ways. Finding the optimal way of engaging another party - or defending against hostiles - is therefore crucial for drone survivability.

Chapter 2

Background

2.1 Theoretical Background

2.1.1 Flocking In Nature

Flocking is a behavior found in nature among some animals. The flocking behavior is exhibited through cooperating animal groupings. This confuses attacking predatory animals. Furthermore, each individual animal spends less time watching out for predators as only animals at the edge of the flock are threatened. This results in higher survivability for both the individual and the group [Caraco et al., 1980].

Another positive aspect of flocking birds is the reduced wind resistance experienced by the trailing birds. This is especially notable for birds staying in a *V-formation*. Researchers have also found that V-formation flight leads to lower wing flap rate - and by extension lower average heart rate amongst the flying bird population [Cavagna et al., 2015].

Flocking is very similar to schooling amongst fish. The main purpose of schooling is "protection against predators" [Pitcher, 1986]. Tight animal groupings experience fewer attacks than loose bodies of fish [Nøttestad and Axelsen, 1999].

Figure 2.1: Birds flying in V-formation. An example of flocking in nature.
Credit: Huffington Post

Figure 2.2: Schooling fish. Another example of flocking in nature.
Credit: OpenStax College

2.1.2 Flocking In Military Use

In military use, flocking is mimicked by military flying in a V-formation. For a formation of two planes, the leading plane cannot benefit from the configuration. The following plane, however, experiences an increase in efficiency (around 15%) due to reduced air drag [Hummel, 1995].

Figure 2.3: Three military Saab Gripen fighters flying in tight formation. The line resembles half a V, and the wind resistance is reduced for all but the first plane.
Credit: Saab AB

Unmanned aerial vehicles, UAVs, can also benefit from flocking when running sensory operations. In military use, it has been proven that fixed wing aircraft in a group reduce sensor errors when performing "vision based target tracking operations" [Quintero et al., 2013].

One common method used when flocking UAVs is to assign a leader role to one UAV and then let all other UAVs follow it. The leader can either be controlled using automation or manual controls.

Sensing tasks can be distributed across the different UAVs, allowing for more different sensors to be used, or for increased system accuracy and robustness. The same Boids algorithm, that has applications in general animation, can be used in conjunction to prevent drone crashes and to keep the following UAVs direction in line with that of the leader.

2.1.3 Flocking In Animation

Flocking algorithms have been used in computer games and animations since the first publication about simulated flocking. Simulated flocking can be run effectively with a large number of animals while remaining rather realistic. The computational complexity is rather low as a basic implementation can run in $O(n^2)$ time where n is the number of simulated animals, and improvements can reduce this toward a linear function given some limitations on the simulation. This allows a large amount of animals to be animated in a short amount of time.

In film, simulated flocking was used to render flocking bats in Tim Burton's *Batman Returns* from 1992. One base model was used to create one digital bat with animations for basic movement. The bat was later copied multiple times with the same base animation and positioned with some spacing around it to allow its flapping wings to move freely. Finally, the bats were given real movement using a flocking algorithm. This produced a realistic effect [Gabbai, 2005].

Another early animation using simulated flocking is a large-scale wildebeest stampede in *Disney*'s *The Lion King* from 1994. The animated scene is six minutes long, but took three years to create. A similar approach to that in *Batman Returns* was used. Flocking algorithms was used to prevent the wildebeests from colliding [Walt Disney Company, 2014].

Figure 2.4: Wildebeest stampede with flocking birds above in *The Lion King*. A great technological accomplishment 1994 and one of the earliest examples of flocking algorithms in animation.

Credit: *Walt Disney Company*

2.2 Technical Background

2.2.1 Boids Flocking Model

A commonly used method for simulating flocking is the *Boids* model devised by Craig Reynolds in 1987.

His model was the first published way of simulating fairly realistic algorithm for simulating fairly realistic flocks of animals - hereby known as agents. The algorithm depends on three simple rules: separation, alignment, and cohesion [Reynolds, 1987].

Agents

An agent refers to a single unit in the flock. For example, an agent could be a single bird in a flock of birds or an individual fish in a large school. The properties of one agent is perfectly equal to another so each agent is thus indistinguishable from every other agent of its kind.

Alterations are allowed as prey and predator agents may be given different behaviors. They do both, however, still follow the same three rules when flocking.

In simulations, agents are represented by two vectors: position and velocity. Thus, agents are treated as single dots in simulation despite being represented differently in graphics. In graphics they are shown as isosceles triangles with its position being in the center and its velocity (direction) pointing towards the direction of the vertex between the two longer legs.

Neighborhood

A computer controlled agent can know everything in the entire simulation, but for a real creature this is not true. In order to simulate this, agents are given an area in which they can interact with other agents. This area is known as their neighborhood.

A neighborhood is given by a view distance and an angle that denotes the agent's field of view.

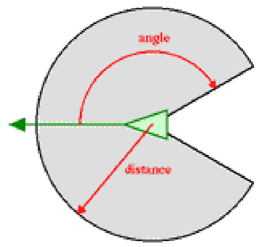


Figure 2.5: An agent's neighborhood.
Credit: Craig Reynolds

Separation

An agent needs to avoid collisions with other nearby agents. To avoid collisions, a factor of *separation* is added. An agent will keep a certain distance to every other agent in its neighborhood. If the agent finds another agent too close, it will attempt to steer away from it to avoid collision.

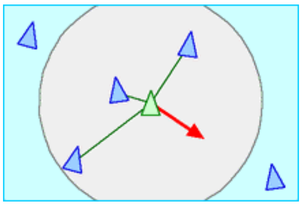


Figure 2.6: Separation
Credit: Craig Reynolds

Alignment

All agents travel in the same direction as neighboring agents - or at least fairly close to this direction. To achieve this, an *alignment* rule is added. Thus, an agent will gradually steer to align itself with the general direction of other agents in its neighborhood. The general direction is the average of all direction vectors in the neighborhood.

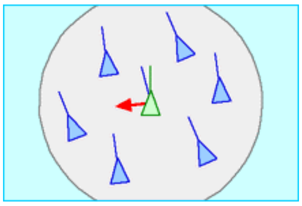


Figure 2.7: Alignment
Credit: Craig Reynolds

Cohesion

An agent needs to stick to the flock. To ensure this, a factor of *cohesion* is added. An agent will move towards the mean position of neighboring agents. When other agents are found within the neighborhood, the agent will attempt to move towards the middle point of all the others.

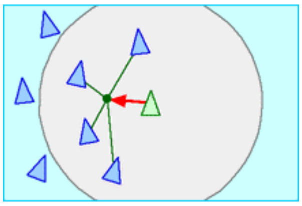


Figure 2.8: Cohesion
Credit: Craig Reynolds

Resultant

The three rules separation, alignment, and cohesion will all result in different vector forces which should act on the agent to whom they belong. Given that animals cannot turn instantaneously in real life, a resultant force is calculated by summing the three vector forces.

The three forces can be applied differently by normalizing the individual vectors and then multiplying them with appropriate weights. Hence, agent specific behavior could be induced by slightly altering one aspect of flocking.

The resultant force is added to the agent's velocity vector. The velocity is then normalized or limited to a maximum allowed speed. Lastly, the agent's velocity is added to its position vector resulting in movement.

The previous velocity can also be used as a base vector for the resultant, giving agent movement a more realistic flow.

1999 Extension

The Boids algorithm was extended by Reynolds [1999] twelve years from the first documentation. His new work provided a simple way of avoiding obstacles as well as other basic locomotion and task solving strategies. Furthermore, Reynolds provided a basic hierarchy of motion behaviors for agents:

1. *Action Selection*: Choose strategy, goals and plan.
2. *Steering*: Determine a path.
3. *Locomotion*: Animate and articulate.

In the same article, Reynolds [1999] also describes a four crucial steering behaviors:

Seek Radially align velocity vector toward a stationary target.

Flee Radially align velocity vector away from a stationary target.

Pursuit Radially align velocity vector toward the predicted position of a moving target in a certain future.

Evasion Radially align velocity vector away from the predicted position of a moving target in a certain future.

The four steering behaviors are really two sets of opposites. Seek and flee are opposites that do not use any future prediction (stationary target), whereas pursuit and evasion are the same opposites in which future target position is considered (moving target). These rules provide a base for modelling prey and predators.

The following two images are from the work of Reynolds [1999].

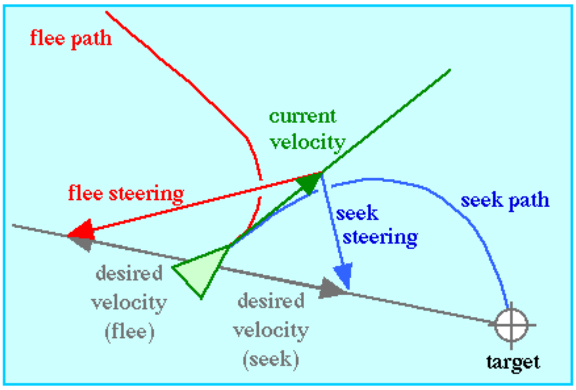


Figure 2.9: Seek and flee

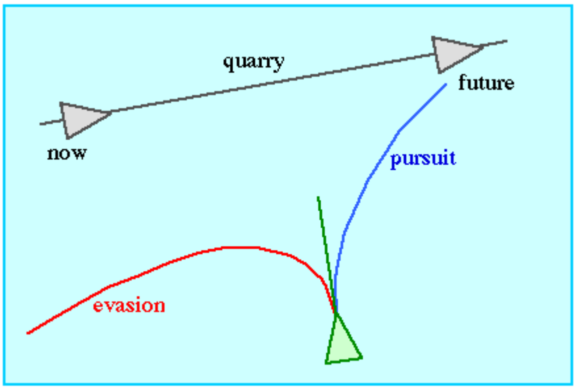


Figure 2.10: Pursuit and evasion

Chapter 3

Method

3.1 Software

The software was written and created using *Java 8*. The program creates both preys and predators, both of which extends the same base class: Agent. This mean all agents are created equally with some minor property changes for each type of agent. Speed and action are some examples of these differences.

The program creates 100 prey agents and 4 predators and loops their actions step by step for the entire length of the simulation's scope (5000 steps). The program also stores a visual representation of the state for each step so each event could be closely examined.

The program also outputs the current amount of preys that are still alive for each time step which was used for visualizing, and generating a concrete result.

3.2 Setting rules and restrictions

Initially, a set of simulation restrictions were determined in order to scope down the research question. It was decided that all agents should be treated as two vectors: position and direction. Agents do not have a size other than in visual representations. Furthermore, all individuals are able to move at the same speed, and follow the same rules with the exception of predatory agents being able to move slightly faster than its prey counterpart. This was made in order to prevent stalemates.

Once this was done, the basic set of rules described by Reynolds [1987] was then implemented with these restrictions. This implementation was tested and tweaked until Reynolds' rules were clearly followed by the computer simulated agents. This was done using visual inspection.

Four different scenarios were then tested:

Prey flock	Predators flock
No	No
Yes	No
No	Yes
Yes	Yes

3.3 Running the simulation

All simulations ran in 5000 steps with each step being available for visual inspection. All prey is spawned randomly in a 2048x2048 starting area using a random number generator with a static seed. The seeds can be found in appendix A. All simulations ran on the same stationary computer with the same hardware connected.

At time step 1000, four predators were released in the center of the simulated starting area. Predator starting positions were statically symmetrical and thus predefined. Time step 1000 was also chosen as the starting point for recording results.

No agents could leave the simulated area. This was achieved by adding an extra linear force onto the resultant vector for each agent close enough to the edge of the room. This force was dependant on the distance from the center, increasing as the agent travelled closer to the edges. The central area was therefore preferred by agents and could be seen as an important animal nesting or feeding area.

For each scenario the result is counted as the average of ten different tests. The same random number seeds were used for each grouping, resulting in a total of ten unique seeds. This means that starting positions were the same in each group.

3.4 Agent Specific Method

Simulated agents were given a field of view specific to their role. Prey were given a $360°$ field of view, whereas predators could see in a $140°$ arc. This was modeled with the American woodcock [Jones et al., 2007] in mind for prey and the predators after an eagle [Martin and Katzir, 1999]. Neither species can turn their head around in the simulations, meaning that they can only look in their direction of movement.

Movement speed was also determined by agent role. Prey were able to move five distance units per simulation frame, and predators were able to move six in the same amount of time.

The predators could only kill one other agent each per simulation step, and they could only kill agents that they would reach in the next simulation step.

Chapter 4

Results

The following graph shows simulation steps 1000-5000. The population of pray remain at 100% up until this point since predators are first introduced to the simulation at time frame 1000.

The graph is a composite of the number of average agents alive for each simulation step and all simulations. The horizontal axis indicates the simulation time step, and the vertical axis indicates the corresponding number of alive non-predator agents.

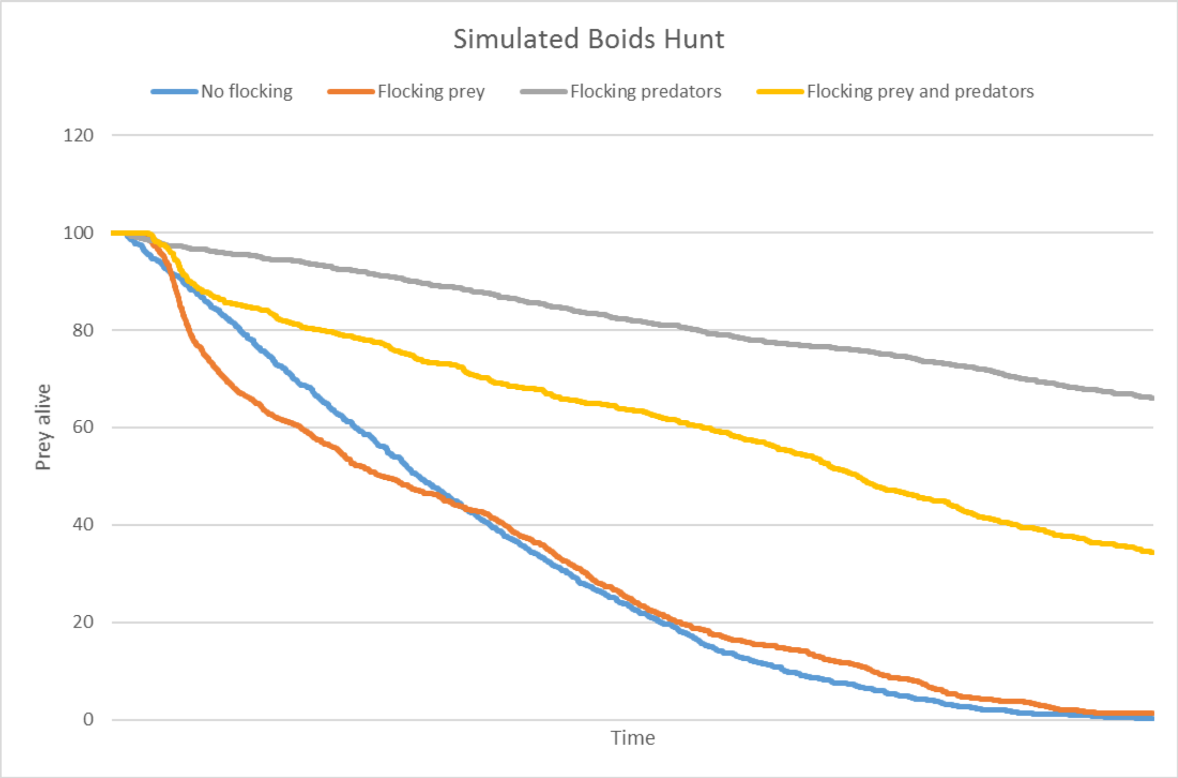


Figure 4.1: All results in one graph

Individual graphs for each random number seed used can be found in appendix B.

4.1 Simulation Screenshots

The following figures are screenshots taken from the simulation. Frames are ordered left to right, and top to bottom.

4.1.1 Agent Distribution

Two screenshots of agent distributions from the first 1000 steps of animations.

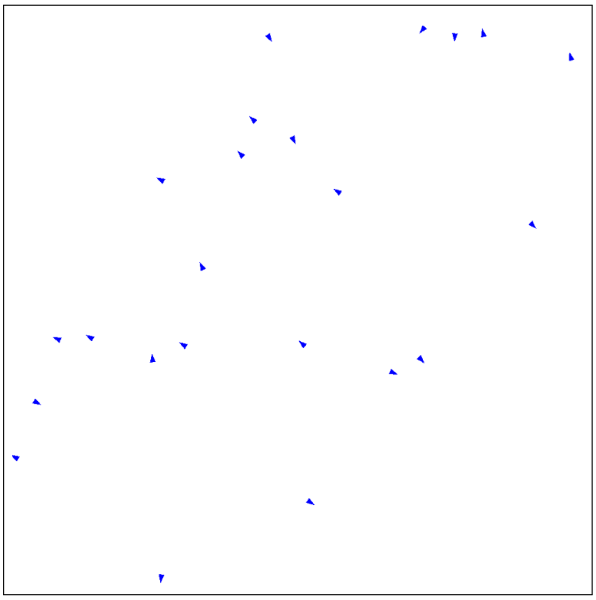


Figure 4.2: No flocking. Distribution seems rather uniform along the diagonal.

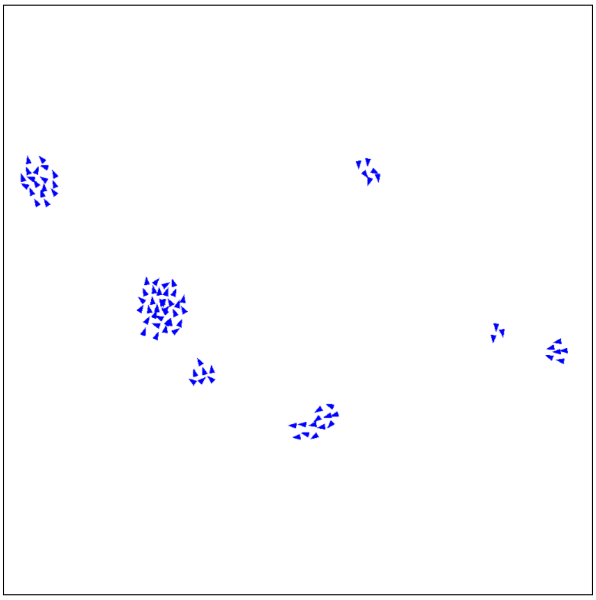
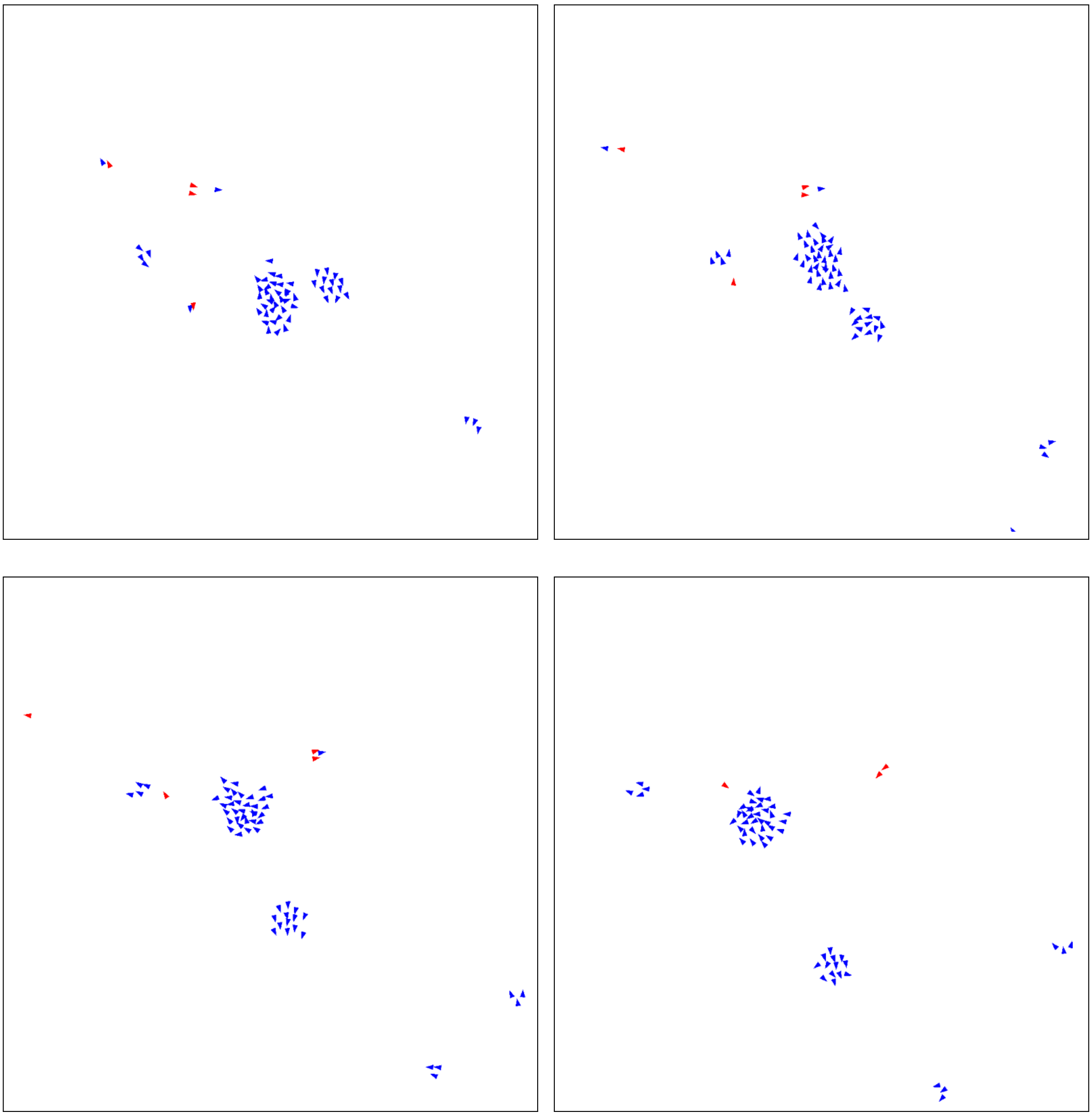


Figure 4.3: Flocking. Dense flocks with a lot of empty space between.

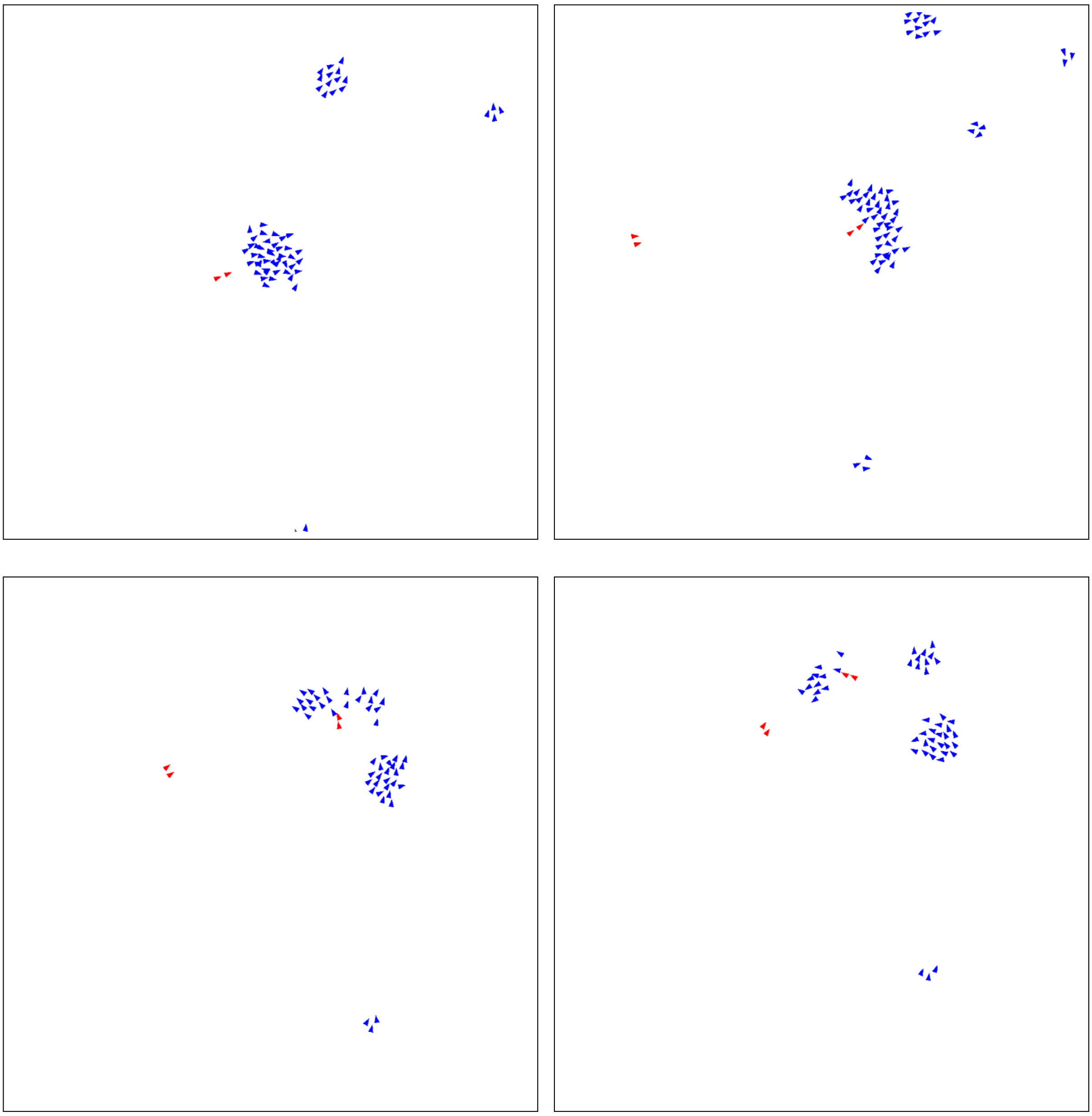
4.1.2 Ineffective Predator Flocking

Figure 4.4: Four simulation frames from seed 3 with flocking prey (blue) and predators (red). Two predators (initially above and left of the center) chase the same agent allowing many others to escape. The predators are hunting very inefficiently. In this scenario, prey flocking has a very minor role.



4.1.3 Forked Attack

Figure 4.5: Four simulation frames from seed 3 with flocking prey (blue) and predators (red). Two predators force a large flock of agents to split while a two other predators performed a forked attack.



Chapter 5

Discussion

5.1 Flocking In Prey

When prey do not flock, the individual agents are scattered across the simulated area in a fairly distributed manner. Therefore, the distance between otherwise perceived flocks is rather small. The agents do however, not react to external threats by following the movements of other nearby prey. The flocking model could be extended with a factor of fear, which should result in increased survivability when flocking [Delgado-Mata et al., 2007].

The non-flocking prey behavior results in a uniform death count per simulation frame when predators do not flock. When matched against flocking predators, however, the visualized number of agents alive can be seen as a line. This indicates that a uniform distribution is good when there are few different hunters - or when they are close to each other.

When prey agents flock, however, they tend to die off in chunks (see the graphs in appendix B). The uniform distribution is gone, and the various agent formations are instead scattered across the simulated, meaning that the distance between flocks is greater than before.

Flocking prey has about the same time alive as non-flocking prey. Thus, the ununiform prey distribution seems to be neither advantageous nor disadvantageous when simulated using the *Boids flocking model* (see section 2.2.1).

5.2 Flocking In Predators

The results show that when the predators hunt in flock they do not kill nearly as many agents as they would if they hunted on their own. When an agent follows flocking behaviour it attempts to stay in close proximity to other agents. In the case of predators, chasing preys is only one part of the resulting vector. This may result in a predator only partially chasing a prey. - When predators are not flocking, the number of unique preys being chased approaches 4 while that number decreases significantly when flocking (figure 4.4).

The simulations when both predators and prey followed flocking behaviour revealed that when the predators did travel in a flock towards a flock of preys, they did (mostly) split up after the first impact to individually chase fleeing animals (figure 4.5). This proved to be somewhat efficient in bigger groups as seen in the first slope of seeds 9 and 10 in appendix B. But beyond that, the predators act too much like a single unit to efficiently hunt every prey down.

There does not seem to be a clear advantage to predators flocking. To efficiently utilize their numbers, predators would need a factor of teamwork or coordination. The simulation showed that flocking predators all attacked from the same side, giving the prey an easy escape route. This may have caused lower deaths when predators were flocking. There is a bigger chance that a predator might interfere with the escape route of a pray if they are not flocking, further decreasing the benefit of flocking in comparison.

What we have seen is that flocking for predators is a bad strategy for hunting. It should not be excluded that predators can make use of flocking in other situations - for example when they themselves are being hunted by predators further up the food chain.

5.3 Initial Conditions

All results for the same category are very similar. This means that the simulations are indeed deterministic and that the initial conditions do not impose much on the outcome.

The only difference between all the simulations in each category is the agent starting position. Starting positions are determined by a deterministic random number generator that is seeded upon creation. This means that the initial seed and position does not affect the simulated animal hunt.

Mitigating the importance of starting positions is intentional as the main focus of this study is the aspect of flocking - without any external factors. Thus, the 1000 first simulation steps assure that flocking agents are already grouped correctly when predators are released.

5.4 Flocking Is Defensive

Flocking could be ineffective for predators because it is a defensive tool and not an offensive strategy. Flocking in defensive purposes could collectively provide better vision of surrounding areas and it only puts the agents in the outer edges of the flock in immediate danger, as previously discussed. It could also reduce air drag resulting in less energy being spent on transportation - lowering heart rates [Cavagna et al., 2015].

The results seem to show that flocking is a method better used for preys or defensively acting agents. This becomes apparent because the results showed little difference in deaths depending on whether or not the preys were flocking. Furthermore, there are other advantages to flocking t for preys hat is not directly related to survival. Only putting a few agents in immediate danger means most of the flock can spend time resting, or consuming food etc.

5.5 Other Advantages To Flocking

The amount of preys killed while flocking compared to not flocking were essentially the same. That could mean flocking has no clear advantage. It does however come with other advantages as can be seen in wildlife. Flocking comes with advantages for most of the group because they spend less time in immediate danger [Caraco et al., 1980]. While the results of this research did not entirely match that of real-life scenarios (see section 5.7), it is still a good strategy for preys to flock because of the other advantages that comes with flocking.

5.6 Autonomous Drones

When considering flocking as a means of automating drones such as UAVs for military use, the strategic advantage of collaborating sensors and increased redundancy should by far exceed the performance of individualistic drones.

Boids flocking model should be viable as a means of flocking since drones would essentially move as one unit. Combining the flocking behavior with assigned leader following could be used when an operator must be able to control the flock.

The only real downside of using Boids flocking model as it stands. is that real world aerodynamics along with general military strategy would benefit from formation flight. Thus, drone programmers with these requirements would benefit from micromanaging ranges between drones in order to achieve the desired formations. This could be hard using Boids, meaning that a leader following approach is probably better.

Given the large availability of drones, the study of flocking in UAVs is very relevant as it could be as widely used in the field of of flight in a few years as it is in animation.

5.7 Sources Of Error

When running the simulations and analyzing the results, some potential sources of error were revealed.

5.7.1 Flocking Predators Act Like A Single Unit

The results show that flocking predators perform worse than if they hunt alone which would mean that hunting in group is a bad strategy. However, the simulations show that they act more like a single unit. This is because they try to stick in close proximity of each other. As a result, the predators cover less ground than if they were going in separate directions in the same amount of time, resulting in less prey killed.

An element of teamwork or strategy would probably be needed in order to properly give predators an advantage in those situations. This is not covered in the experiment.

5.7.2 Missing Individuality

In nature, all animals are created different, meaning that they are not equally fast or well-sighted. This means that some birds are inherently weaker than others, which in turn would affect the flocking behavior as some birds are dragged behind, potentially causing the grouping to slow down or change direction to circle around more.

Individuality could also affect predators as they could target weaker prey in hope of killing off a few more individuals. This could drastically alter the outcome as targeting could also be improved using tactics and cooperation to cut off animals instead of simply attacking head on whilst in tight formation.

The decision to drop individuality was taken at the very beginning of the study in order to shrink the scope. It would thus be a viable subject to study further in the future.

5.7.3 Unlimited Endurance

All agents can fly at full speed infinitely, which means that once a predator starts chasing an agent, it will be killed eventually. This may not model natural hunting properly as predators are faster in shorter sprints but not in the long run. This is partly due to the reduced wind resistance experienced by large flocks of prey whilst the smaller birds are lighter and thus require less energy.

Prey agents are also killed in one time step and predators do not stay with the prey to "finish the kill" or start eating. Once a prey is caught it is considered dead instantly. Actually killing the prey will normally take at the very least a few seconds (but probably longer), giving the surrounding prey a chance to run away.

5.8 Method Reasoning

The Boids model is decently accurate while it allows alternative and/or additional sources to affect the agent, such as pursuit and evasion. This model is thus accurate enough to simulate flocking while having the flexibility of adding external sources to affect each agent.

It was also decided that the tests should be deterministic in order to make the results easier to reproduce. Thus, ten seeds were randomly generated and nothing else was used. The same software with the same seeds will yield exactly the same result.

Creating the software was preferred to have greater control of the output, sequence of events, and input (randomized seeds). Furthermore, this allowed for exports of the internal state in order to generate visual representations of the individual simulation time steps.

We have mentioned that the agents could be modeled as birds, despite working in a two dimensional environment. The major rules that the animals follow - field of view, and speed - are more or less the same for animals moving in two or three dimensions (for example gazelles, lions, and eagles). We chose to model the agents as birds because it is intuitive when watching the simulations. Furthermore, the used vector math works the same in both two and three dimensions. The same holds true for the used flocking model.

Chapter 6

Conclusion

Starting positions have minimal impact on the simulation outcome when predators are released after the first 1000 simulation frames.

Flocking is neither advantageous nor disadvantageous in prey. When flocking, they are killed in chunks, where as they are killed proportionally to the number of alive agents when they are not flocking.

Flocking is a disadvantage for predators using a simple implementation of Boids flocking model. As a flock, they act too similar to a single unit and attack the prey from a single direction, giving the prey an easier way out. This means only the chased prey is eventually caught but the rest is not at that time.

Boids has proved to accurately model simulations for flocking. But modeling predator behaviour requires another factor of decision-making. This factor should be teamwork and/or coordination to adequately give predators their proper advantage.

Flocking proved to be a defensive strategy and thus does not give an advantage to predators. This means that Boids flocking model does not adequately model the predator aspects.

6.1 Future Research

For future studies, we recommend looking into factors that this research concluded was necessary for a proper model which contains predator dynamics is most notably teamwork and/or coordination in group. Flocking using a rather simple Boids model is not a suitable way of modeling predator actions.

Furthermore, properly including a factor of fear would increase the realism of prey action. This could be modelled as a free expanding gas as suggested by Delgado-Mata et al. [2007].

Requiring a predator to spend some time to kill the prey could be a critical factor in the result of a research. This would mean that other preys could escape and increase the distance between to the predator before the predator can take off towards another prey.

Another thing to look at is finding a way of fixing the issue of lack of individualism can give agents different properties to make some agents weaker/stronger than others. This can increase the resemblance of real animals in flocks. The dynamic between weaker and stronger individuals could also prove to be interesting - do the sacrifice of weaker individuals increase the general survivability of the flock?

Chapter 7

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Appendix A

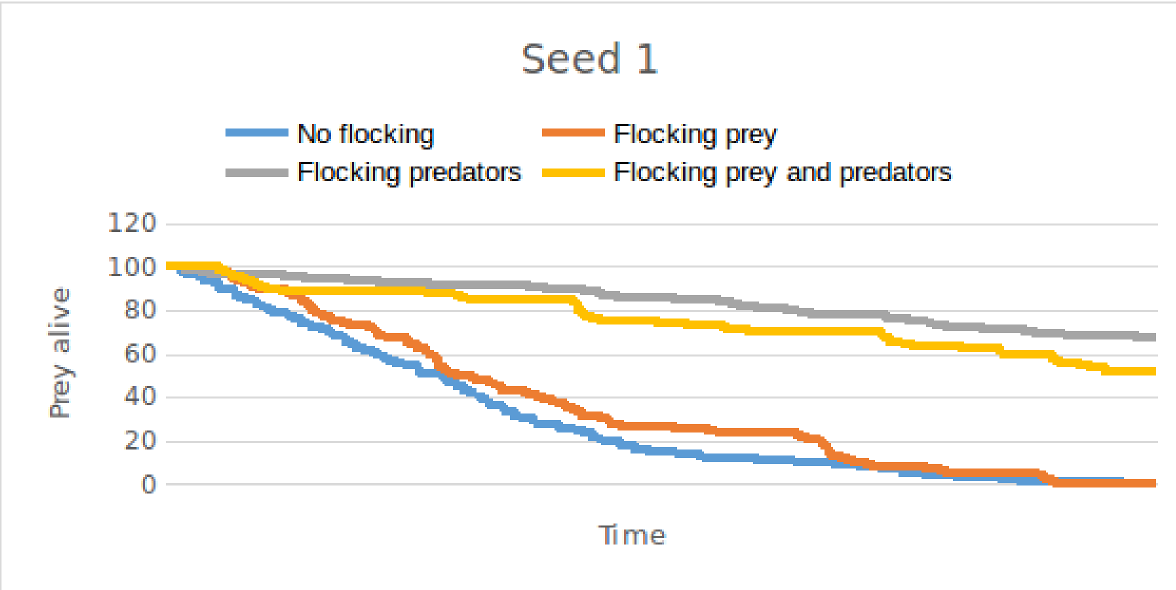
Random Number Seeds

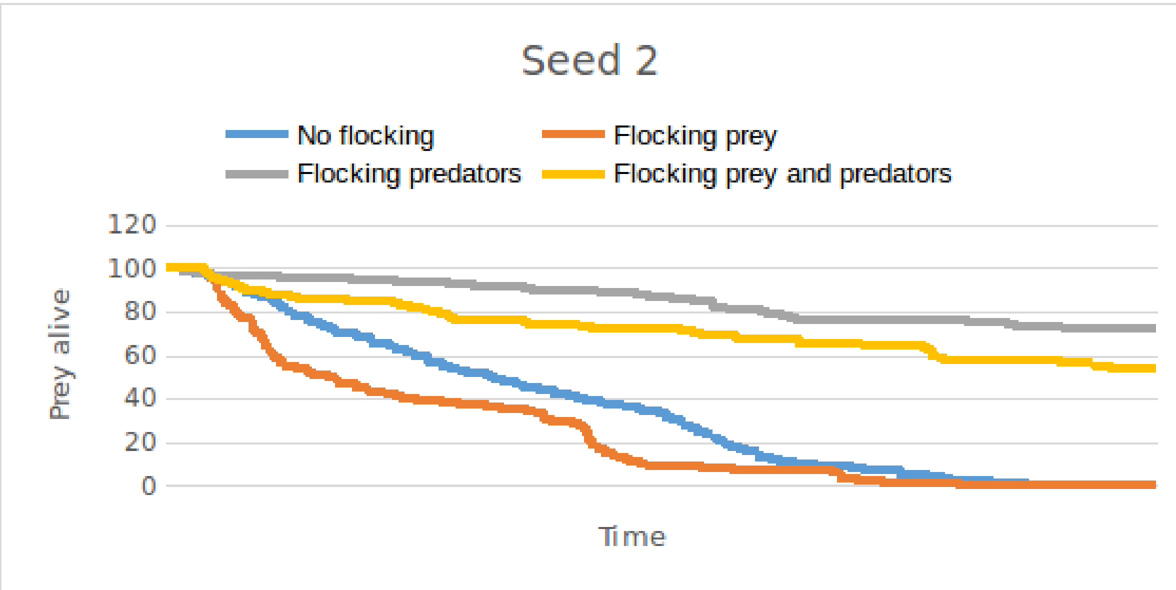
The following seeds were used for random number generation when selecting agent starting positions.

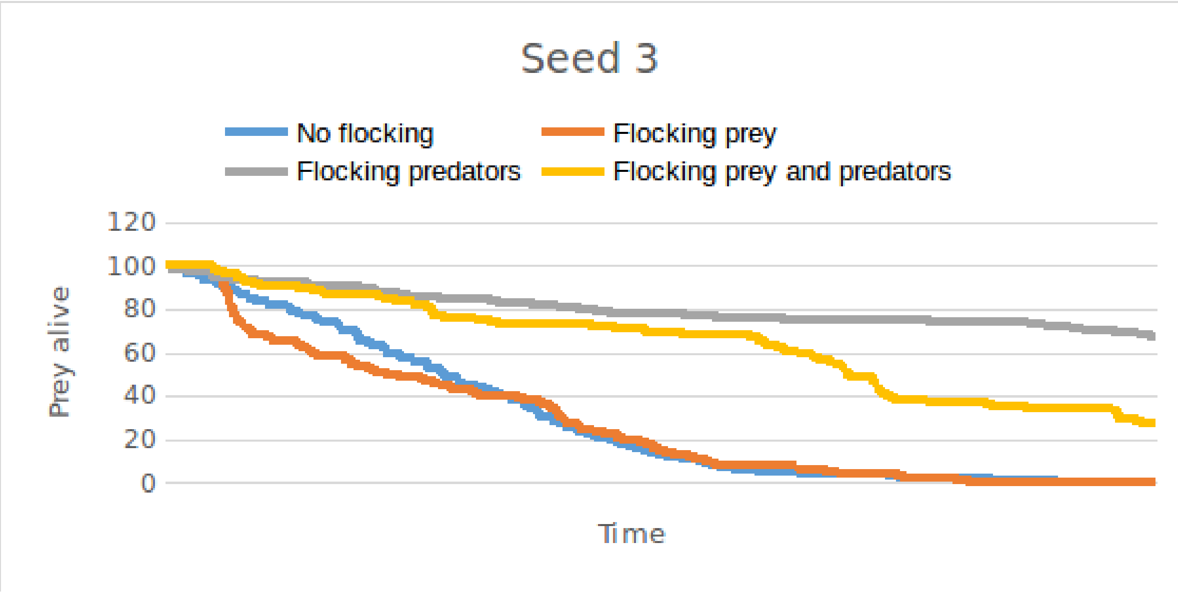
Simulation	Seed
1	-8795449841720950000
2	8682522807148010
3	-488963061
4	4915887297370740000
5	861178936920257000
6	766104113
7	965935330
8	187436842
9	696054169
10	-915743478

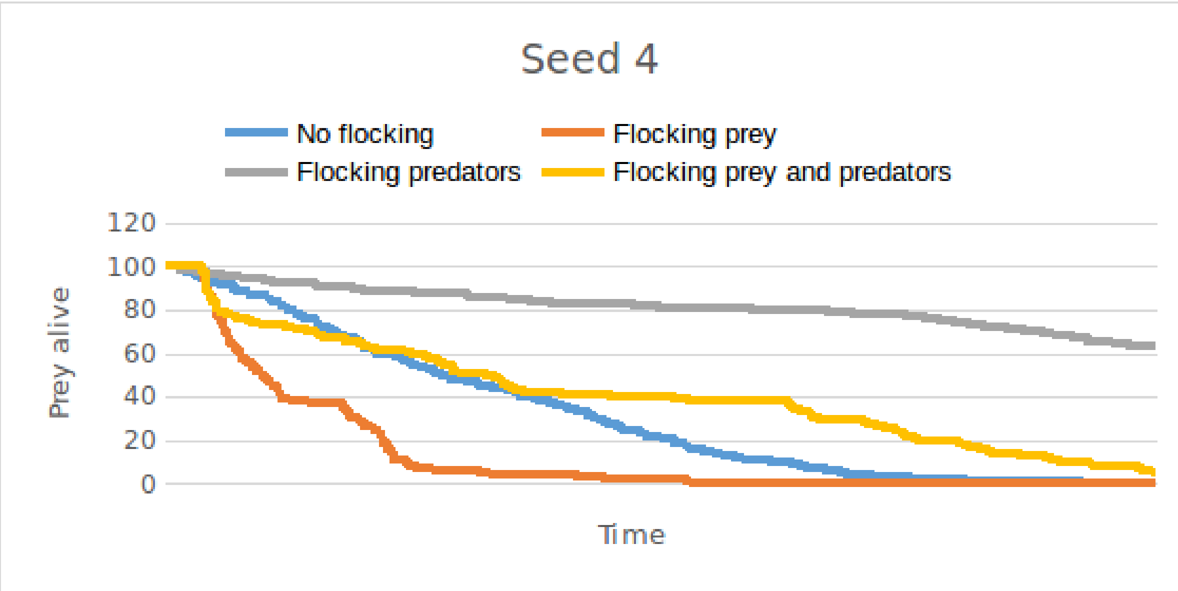
Appendix B

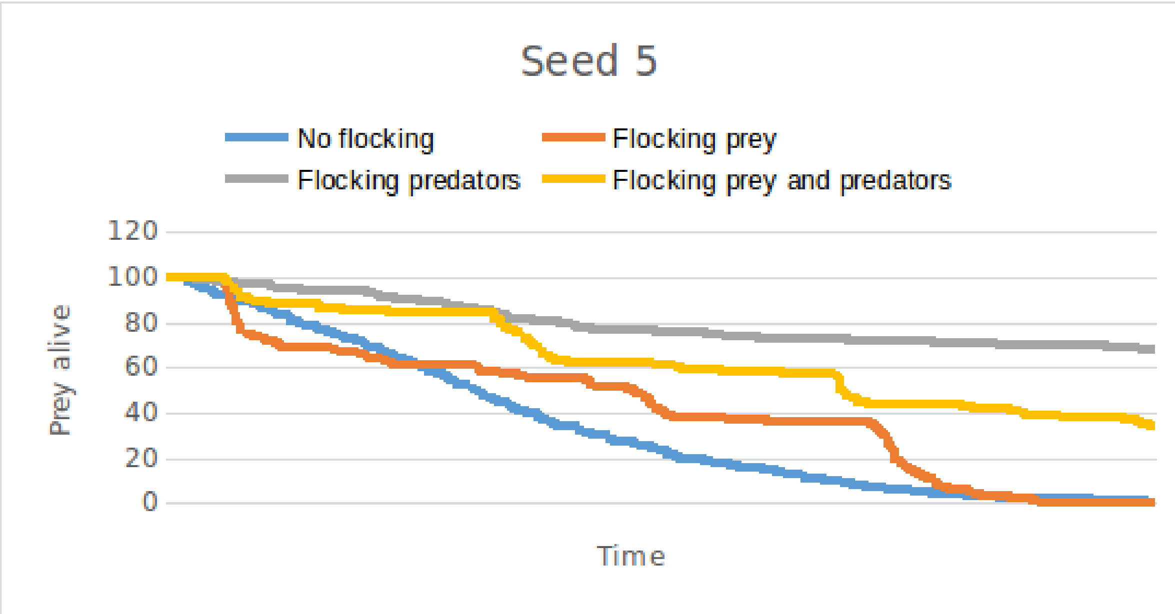
Results Per Seed



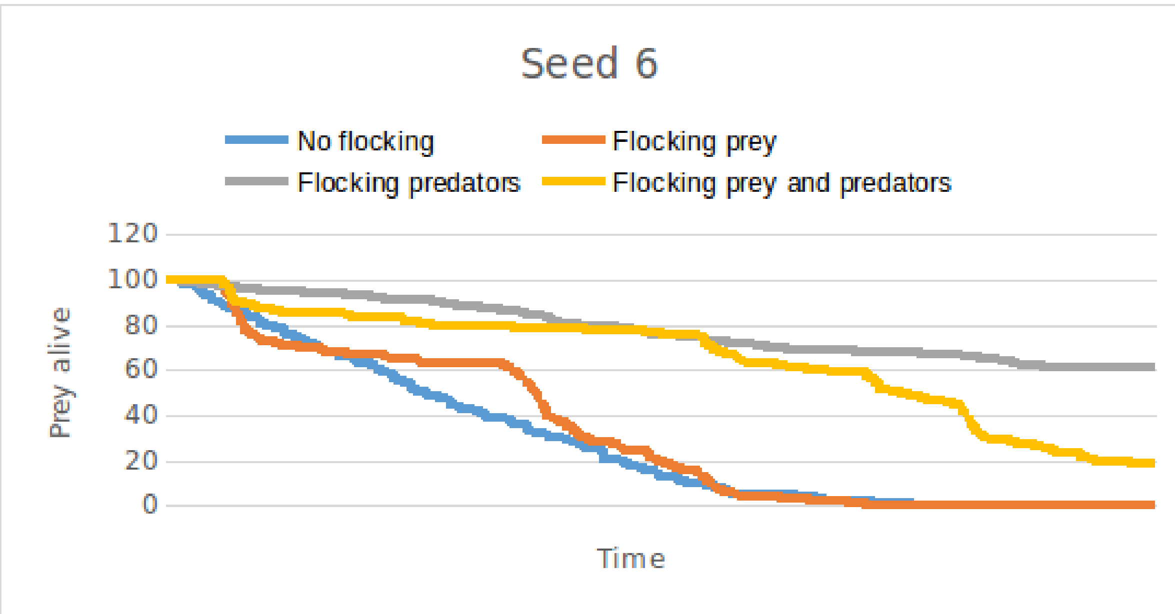



Seed 3
No flocking
Flocking prey
Flocking predators
Flocking prey and predators
120
100
80
60
40
20
0
Prey alive
Time

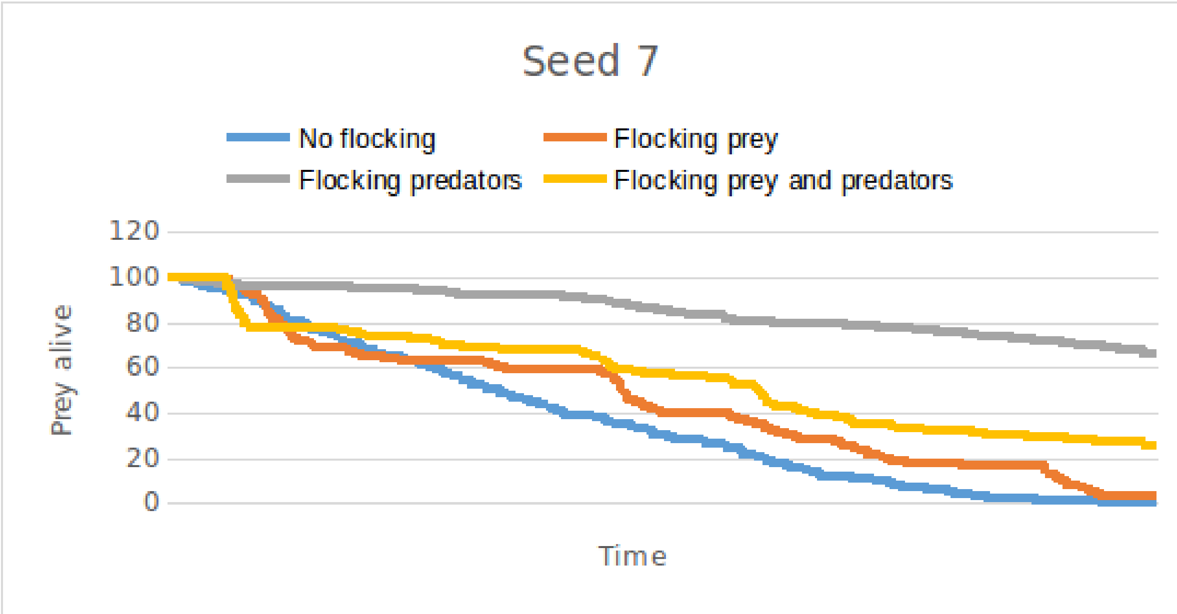

Seed 4
No flocking
Flocking prey
Flocking predators
Flocking prey and predators
120
100
80
60
40
20
0
Prey alive
Time

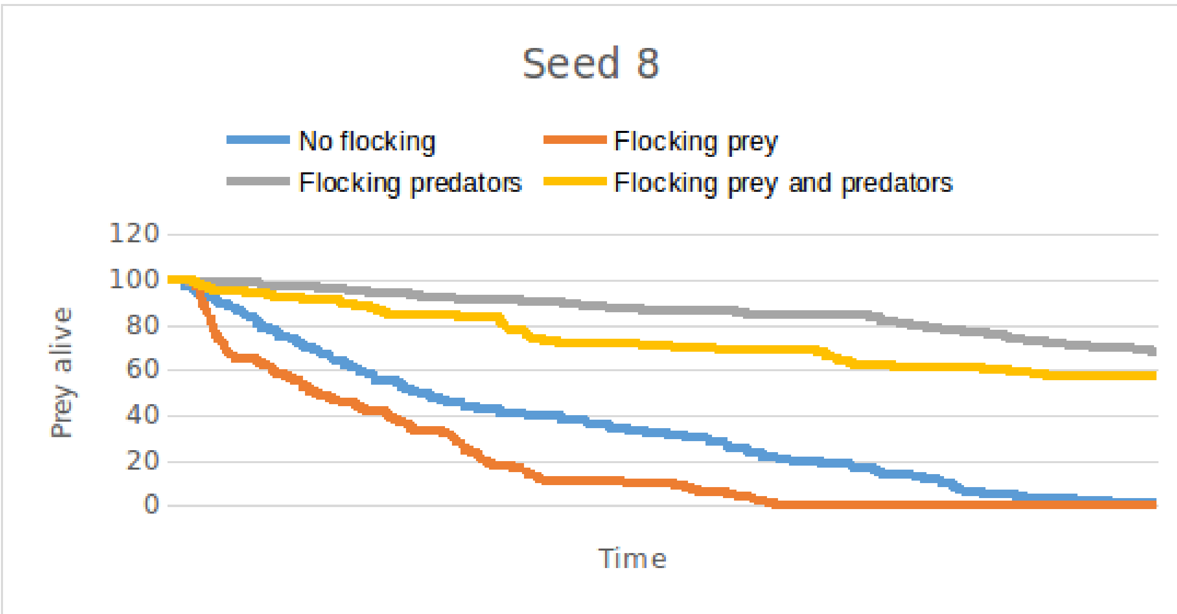


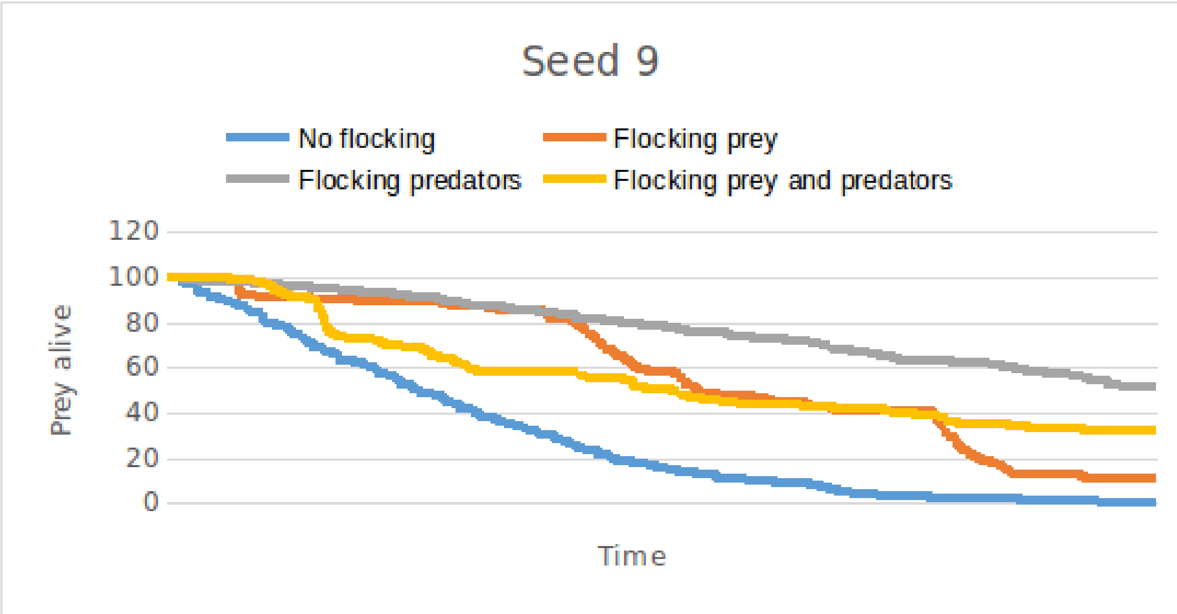
Seed 5
No flocking
Flocking prey
Flocking predators
Flocking prey and predators
120
100
80
60
40
20
0
Prey alive
Time

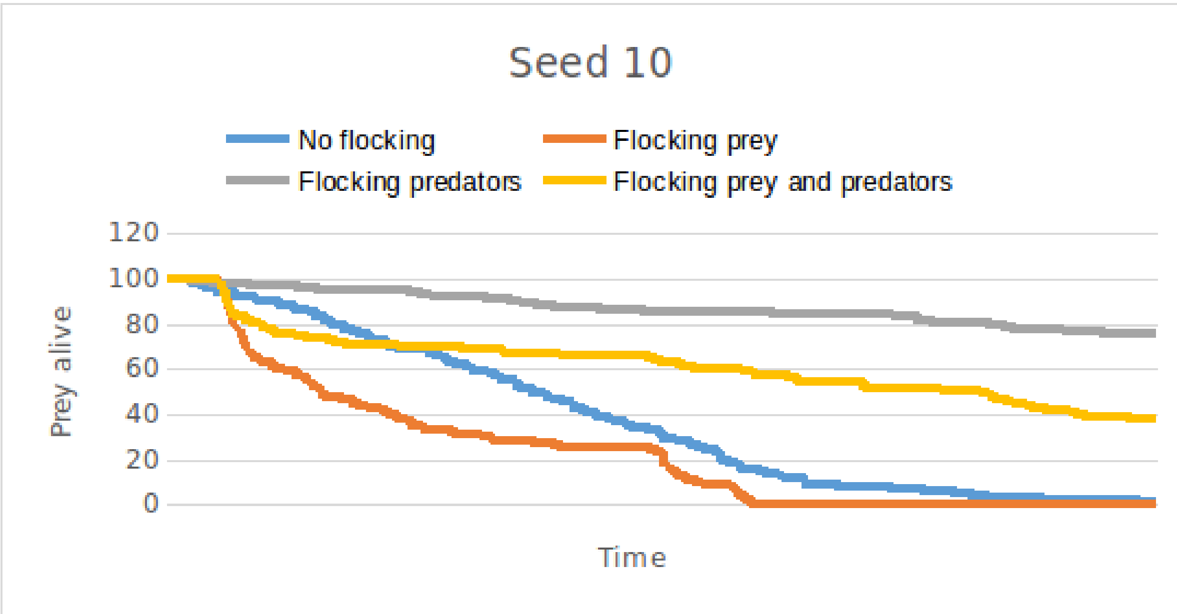


Seed 6
No flocking
Flocking prey
Flocking predators
Flocking prey and predators
120
100
80
60
40
20
0
Prey alive
Time


Seed 7
No flocking
Flocking prey
Flocking predators
Flocking prey and predators
120
100
80
60
40
20
0
Prey alive
Time


Seed 8
No flocking
Flocking prey
Flocking predators
Flocking prey and predators
120
100
80
60
40
20
0
Prey alive
Time


Seed 9
No flocking
Flocking prey
Flocking predators
Flocking prey and predators
120
100
80
60
40
20
0
Prey alive
Time


Seed 10
No flocking
Flocking prey
Flocking predators
Flocking prey and predators
120
100
80
60
40
20
0
Prey alive
Time