School of Computing

FACULTY OF ENGINEERING

UNIVERSITY OF LEEDS

The Simulation of Swarm Behaviour

Yang Ming

Submitted in accordance with the requirements for the degree of MSC Advanced Computer Science

<2017/2018>

The candidate confirms that the following have been submitted:

Items	**Format**	**Recipient(s) and Date**
Deliverables 1, 2, 3 ,4	*Report*	*SSO (04/09/18)*
Deliverable 5	*The URL of software code and raw data*	*Supervisor, assessor (04/09/18)*

Type of Project: Exploratory Software

The candidate confirms that the work submitted is their own and the appropriate credit has been given where reference has been made to the work of others.

I understand that failure to attribute material which is obtained from another source may be considered as plagiarism.

(Signature of student)_________________________

Summary

This project is about simulation of animals' swarm behaviour, and investigating the effect of varying parameters in a movement model on swarm behaviour in simple *boids* worlds. The effect of the rules or parameters tested on the movement of the animal intelligence swarm behaviour is examined by collecting and analysing data from many simulation runs. Chapter 1 discusses the deliverable and the planning of project. Chapter 2 introduces the background research of swarm behaviour and relevant mathematical model. Chapter 3 explains the design and implementation of the experiments, and the results are exhibited in chapter 4. Chapter 5 is evaluation of the whole project and discusses future work. The external material would be show in Appendices A. The ethical issue and raw data are exhibited in the Appendices B and C respectively. Finally the Appendices D shows some shot screens about boids movement.

Acknowledgements

At the beginning, I want to appreciate my supervisor Brandon Bennett, because he gave me a lot help when I conduct my project. He not only give me a hand on my programming skills, but also improving my logical writing skills and transform my way of thinking about problems. It is a kind of precious treasure in my life. When I got some confuse with my project, he always give me many suitable and useful suggestion. And he is a kind and knowledgeable person who usually intends to slow down his speed of speaking to care about my poor English listening.

Apart from this, I also intend to express my gratitude to my assessor Haiko Muller, who gave a deep understanding in my final project. After the meeting with him, I got clearly idea about how to conduct my project specifically.

At last, I am grateful to my parents and friends, who encourage me to try my best to finish my final project. I cannot spend my tough time without their support.

Table of Contents

Chapter 1
Introduction

1.1 Overview

Nowadays, computers have penetrated into various industry fields and have branched into many divisions of computer science. With the development of science and technology, the computing power of computers is getting stronger and stronger, making them able to take on more arduous work at the same time. Simulation computing is one of them. Scientists often use software platforms to simulate biological movements to explore the unknown mysteries of nature. Even when a simulation is only an approximation of actual behaviour, the ways in which simulated behaviour changes depending on certain parameters or environmental factors can give significant insight into actual behaviour.

1.2 Aim

The main aim of the project is to investigate factors that affect survival situation of social animals subject to predation by predator animals. This will be done through simulation of the movement of a group of animals using a software platform. The software platform is able to simulate the animal intelligent movement, like flocking and herding behaviour among groups. The codes are written using Python and Tcl/Tk modules and focus on the parameters that affect group life as well as how they affect individuals. The project has two entities: predator and organism (fish), their interactions, the factors affecting the survival rate of the group and individual are evaluated through observing and changing the parameter values.

Many factors could potentially influence the swarm behaviour, like food attraction, attraction between animals and some different movement (selfish movement). In all following sections, individuals in the group will be collectively referred to as boids. The words “Boid” is an abbreviation for the word “bird-oid object” [1], each boid would follow the basic rule of movement, this is the key to the successful simulation of swarm behaviour in the mathematical model.

1.3 Problem statement

The core theme of the project is to add additional functionality onto the existing platform software, combining information visualization techniques to find out potential factors that may impact swarm behaviour and analyse test results to draw conclusions. In addition to the horizontal comparison of the effects of potential factors on the group, there will also be vertical explorations of the effects that single factor may have on groups and individuals. For example, some factors may have a negative impact on the group, but the opposite is true for the individual.

1.4 Objectives

1. The attraction force between animals.

The attraction is caused by the Cohesion rule, whereby the principle is that animals could influenced by their neighbours and it could be change with the number of neighbours. This experiment would find how strength of cohesion affects survival when a group is subject to predation.

2. The repulsion between animals.

There always exists a force that avoids animal collision with each other in movement. The one main aim of project is figure out what influence the repulsion would bring to individual and group of boids.

3. The selfish herd theory.

The effect of selfish rule on boids herding behaviour would be test on group and individual respectively (including the change the selfish strength).

4. Leader.

How does a fish school make decisions? This project will simulate a leader of a school of fish who has another "leadership" that is different from the Cohesion rules, and find how strength of leadership will affect the herding behaviour.

1.5 Methodology

Using existing scientific methods to develop project is important step in saving energy and speed up the efficiency of research. In this project, Agile is chosen as the development methodology because it not only has the characteristics of fast feedback, which is very suitable for developers to meet with the supervisor every week; but also each sub-project (Objectives) contains several steps such as design, implementation, testing, data collection and drawing. This is in line with the idea of agile development that simply and continuously delivers valuable results.

1.6 Deliverables

1. The result of object 1-4.

2. The report includes but not limited to 1) Background research 2) Methodology 3) Evaluation.

1.7 Project Planning

The initial plan was given below in figure 1.1. This is the original plan that was submitted in Planning and Scoping documents.

Week (from 4 June 2018)

Task	start	end
Familiar with Boids model	1	2
Test the cohesion rule	2	3
Test the repulsion rule	4	5
Development the selfish rule	6	8
Test the selfish rule	8	9
Develpmenet the leader	9	10
Test the leadership	10	11
Evaluation of project	11	12
Project Writing	8	13

Figure 1.1 The original planning of project

A changed Gantt chart was made after the final project began due to the huge number of tests for object 1 and some wrong parameters in the test.

Task	start	end
Familiar with Boids model	1	2
Test the cohesion rule	2	5
Test the repulsion rule	4	5
Development the selfish rule	5	8
Test the selfish rule	8	10
Develpmenet the leader	10	11
Test the leadership	11	12
Evaluation of project	12	13
Project Writing	9	13

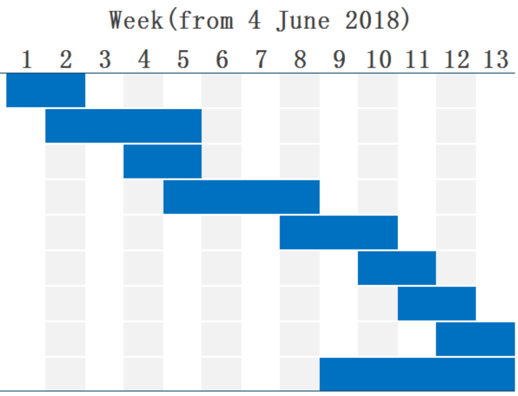


Figure 1.2 The planning of project after modify

Chapter 2
Background Research

2.1 Computer Simulation

Computer simulation is a dynamic and realistic imitation of the structure, function and behaviour of the system as well as the thought process and behaviour of the people involved in the system control. Since it has been used in many different subjects, like physics, climatology, chemistry and biology**.** Computer simulation is an important method used to gain understanding of the ever-changing nature because of advantages such as safety, repeatability, economy and freedom from climate.

The key to computer simulation is the building of the mathematical model. Mathematical model is a form that abstracts the essential part of the system to descriptive pattern.

2.2 Swarm behaviour

Swarm behaviour is an interesting phenomenon observed in nature. Huge groups of fish are usually seen swimming together in museums or television, they gather not only to find food and avoid predators, but also to save the energy for themselves. According to Wikipedia [25], swarm behaviour is a collective behaviour shown by animals, particularly social animals. Various swarming behaviours are displayed by different species of animals:

- Herding - This relates to the swarm behaviour of quadrupeds.
- Flocking - Flocking behaviour is a kind of behaviour exhibited when a group of birds.
- Shoaling and Schooling - The behaviour shown by a group fish as they gather together to move or do some activities.

Figure 2.1 Flock of auklets exhibit swarm behaviour [25]

2.2.1 Predator evasion

Why do animals exhibit the swarm behaviour? Some experts suggest that the swarm behaviour could aid animals evade predators and reduce the predation risk to some extent. For example, Milinski and Heller (1978) [2] proposed and demonstrated a potential method that might obstruct predators titled “predator confusion effect”. The principle of his theory is that predators tend to struggle when trying to pick out individual animals from huge groups because the large number of moving objects will create an overload of the predator’s visual ability. Another theory states that the anti-predator effect created by animals with swarm behaviour is known as “many eyes” [14], whereby the task of scanning the environment for predators will be undertaken by many individuals with the increase in group-size. Such large-scale cooperation not only provide a high level of vigilance, but also offer more time for individuals to feed [19].

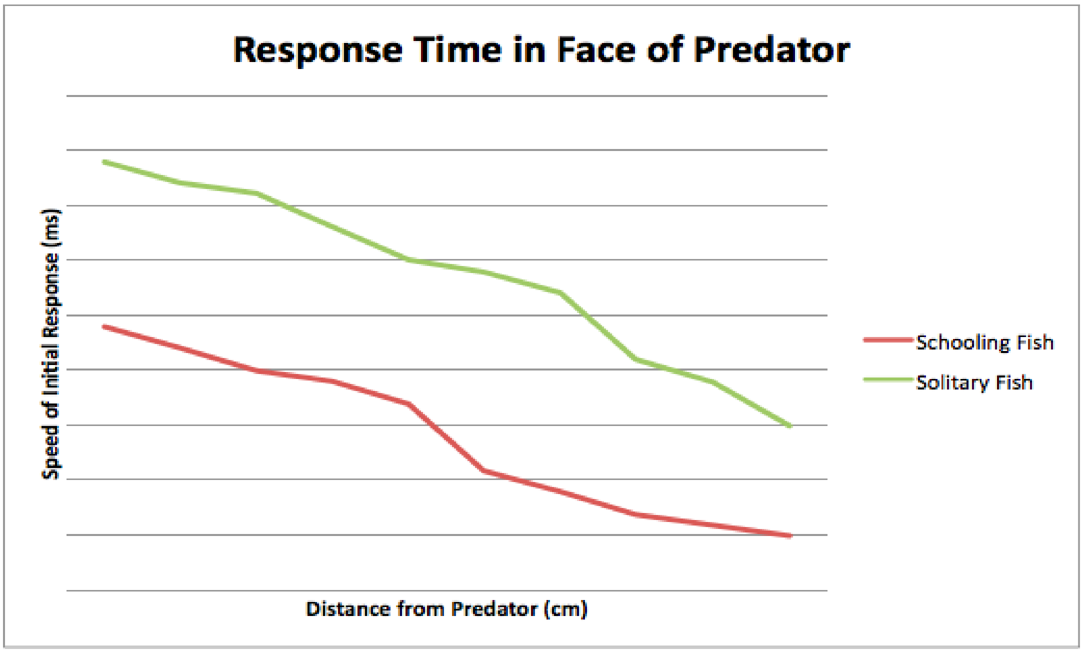


Figure 2.2 The response time of different fish in face of predator [20]

Furthermore, another interesting hypothesis that describes the anti-predatory effect of fish school is “encounter dilution”, which is related to safety in numbers and interacts with the “predator confusion effect” mentioned above. Hamilton [24] proposed the “selfish herd theory” to describe it: the act of fish gathering together is caused by the “selfish gene”. He supports the opinion that individuals would escape to the space between others and predators to reduce their predation risk thus grouping is a form of seeking cover. This forms an extremely important part of the experiment therefore will be the main focus of this section.

2.2.2 Social interaction

Fish has other social interactions with other groups like humans. For instance, the single herring captured from a school will become extremely annoyed [21]. Experiments have approved that some fish removed from schools will have a high respiratory rate caused by stress.

2.2.3 Foraging advantages

The experts also proposed that the swarm behaviour could enhance the success of foraging. Pitcher [22] along with others agree with this theory, they designed a comparative experiment which included different group-sizes of fish and tested the time in which they found the path to food sources. The conclusions drawn from this experiment was that fish schooling could decrease the amount of time taken for larger groups of fish to find food. The researcher Pitcher and Parish [22] mentioned that as many eyes are looking for food in schooling, the fish in the population are able to share their information by monitoring the behaviour of each other, which means that the food searching behaviour in some fish could be stimulated by the feeding behaviour in one.

2.2.4 Reproductive advantages and hydrodynamic efficiency

Another benefit of fish group is that it brings reproductive advantages. The possibility of successfully accessing potential mates might increase since finding mates in schooling does not consume much energy.

One theory proposed that fish could save their energy when swimming as a group, just as how bike racers save stamina during the race by being in the middle of the group. Although it seems reasonable to think that regular spacing and size can result in hydrodynamic efficiency, there is no clear laboratory outcome to prove that the hypothesis is correct.

2.2.5 The mathematical method

Currently, some existing mathematical models have been able to simulate the swarming behaviour: The most typical ones are Self-propelled particles (Vicsek *et al*. 1995) and Boids (Reynolds 1987).

To better understand the behaviour of clustering, transfer, and phase transitions in non-equilibrium systems, T.Vicsek [1] proposed the famous (Self-Propelled Particle, SPP) model (also known as For the Vicsek model). But this project will use another mathematical model “Boids” in this experiment and the detail of this model will be described below.

2.3 Swarm intelligence

2.3.1 Principle

The swarm intelligence (SI) originates from the study of the swarm behaviour of social animals such as ants and bees. Its control is distributed without any central control and the group is self-organising, which means that it is more adaptable to the working state in the current environment with strong robustness. In other words, the overall behaviour exhibited by the whole group when solving potential problems will not be affected by the failure of one or several individuals.

The SI system consists of a group of agent or individuals (boids), they only follow some basic rules and interact locally with the environment and each other. The interactions between each individual cause the global swarm behaviour even unknown to themselves. Every individual in the group is able to change the environment and is a pattern of indirect communication between individuals. This method is known as the “Stigmergy work”. It has better scalability since the increase of communication overhead is small as the number of individuals increases since group intelligence can transmit and cooperate information through indirect communication. The fish schooling, birds flocking, bacterial growth and animal herding are the real examples of the nature.

Five basic principle are found within the SI system:

- Proximity principle: the group has the ability to perform simple space and time calculations.
- Quality Principle: The group could respond to quality factors in the environment.
- Principle of Diverse Response: The scope of action of the group should not be too narrow.
- Stability Principle: The group should not change its behaviour every time the environment changes.
- Adaptability Principle: Where the group could change its behaviour at the appropriate time if the cost is not too high.

2.3.2 Application

The technology based on swarm intelligence has already been used in a huge number of applications. Since the Italian scholar Dorigo [5] proposed the theory of Ant Colony Optimization (ACO) in 1991, group intelligence has been formally proposed as a theory and has gradually attracted the attention of a large number of scholars. ACO is a population-based metaheuristic that was inspired by the foraging behaviour of ant colonies (Figure 2.3) and is able to find the optimal approximate solution for difficult problems. In ant colony optimization (ACO), the given challenge finding the minimum cost path on a weighted graph through the "artificial ants" to find the good solution [5]. ACO has been applied to many classical combinatorial optimization problems and discrete optimization problems that have stochastic and dynamic components as well, it is probably the most successful instance of artificial engineering SI system [5].

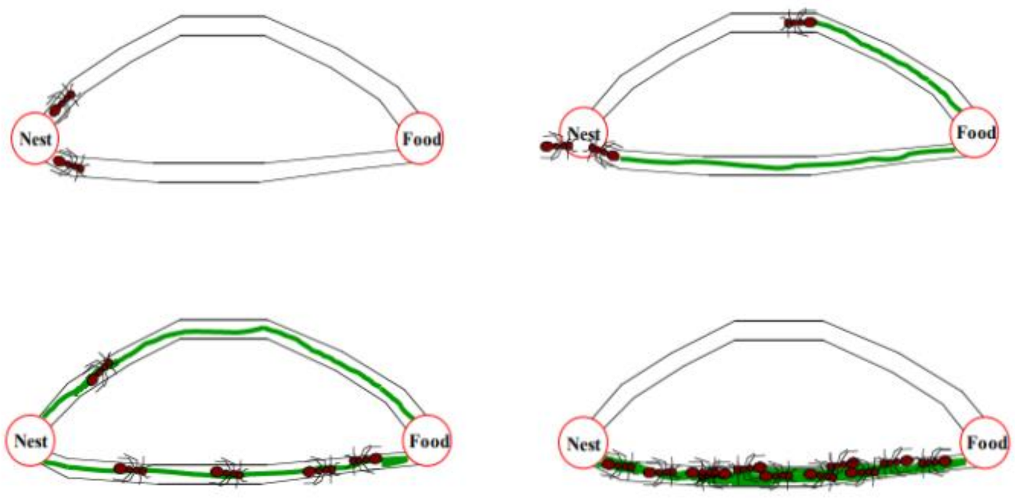


Figure 2.3 Cooperative search by pheromone trails

Furthermore, according to the survey, swarm intelligence will be part of a huge big breakthrough in controlling crowd technology of unmanned vehicles. In the medical industry, M. Anthony Lewis and George A. Bekey [13] proposed the possibility of using swarm intelligence to control the Nanorobot to kill cancer tumours in the human body.

2.4 Boids

The word “Boids” is an abbreviation for the word “bird-oid object” [1], which means the bird animal or bird-like object. However, it is more similar to fish in this experiment, so the term “schooling” will be used to describe the swarm behaviour in the rest of report.

The concept “Boid” was first proposed by Craig Reynolds [17] in 1986. It is a good example of emergent behaviour like most artificial life simulation, which means that the complexity of boids depends on each agent (individual) adhering to a set of movement rules. The basic movement rules that could compose a boids world are as follows:

- **Alignment rule**

The direction of movement of each boids should be as consistent as possible with the direction of movements of surrounding neighbours. If individuals deviate from the average direction of movement of its neighbours, they would carry out slight adjustments to match the new direction of movement.

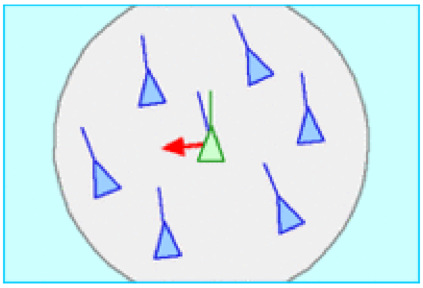


Figure 2.4 Alignment rule [17]

- **Separation rule:**

The purpose of this rule is to prevent boids from colliding and overlapping with other boids in the initial state.

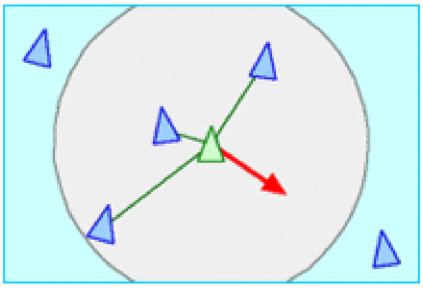


Figure 2.5 Separation rule [17]

- **Cohesion rule:**

The cohesion rule is also known as attraction. The purpose of this rule is to simulate the effect of boids grouping, which will shorten the distance between boids and update the position of each boids in real time.

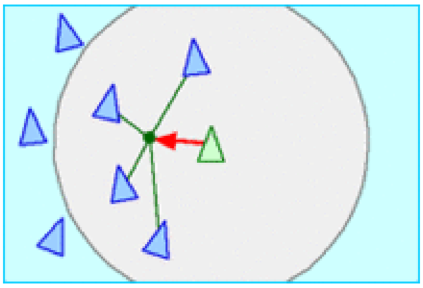


Figure 2.6 Cohesion rule [17]

Although Dr Moshi Charnell [3] successfully simulated the schooling behaviour without using the alignment rule in a master report published in 2008, the three rules will still be applied in the simulation of the schooling behaviour in this project.

It is impossible to get the most accurate and reliable data from only those three basic rules because there also so many noises and other potential factors in nature (like food). Other rules which affect movement have been listed below (chapter 3).

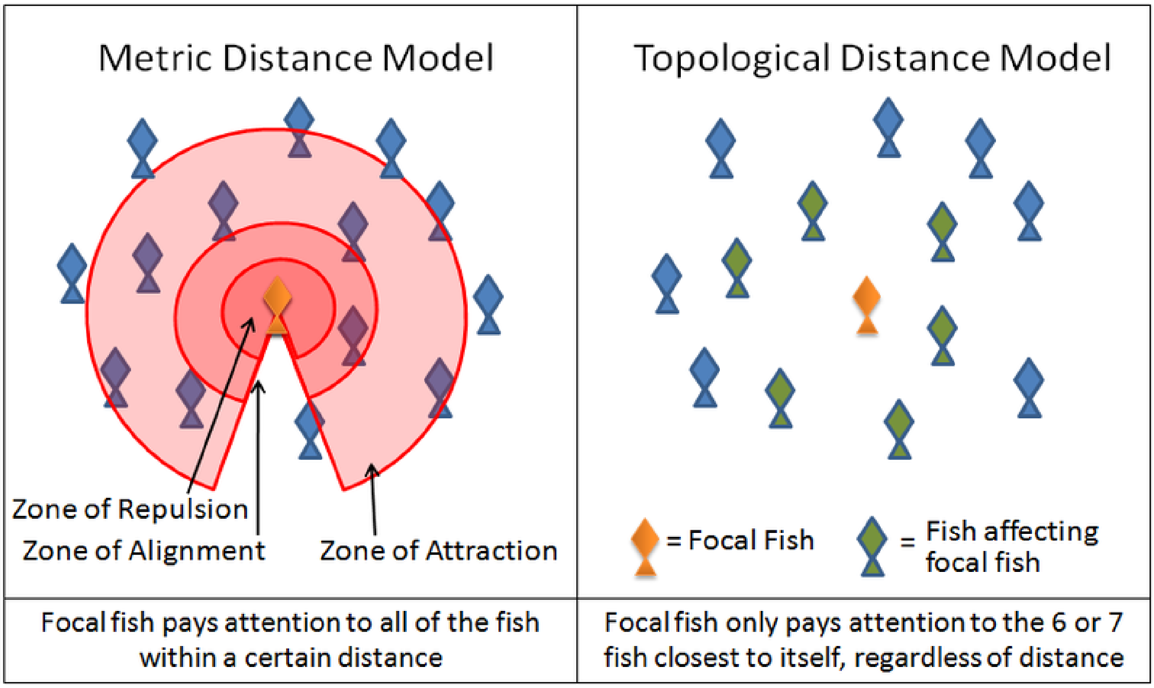


Figure 2.7 Different zone for different movement rules that apply on the fish in mathematical model [16].

The boids framework has been used in a number of fields. The famous first-person shooter game (FPS) Half-Life used the boids model to simulate a flying bird scene at the end of the game. In computer graphics, boids model be used to provide realistic simulations of birds and other biological groups, such as fish. In addition, the control and stabilization of the Micro Aerial Vehicles (MAV) [15] or Unmanned Ground Vehicles (UGV) [28] has also referred to the boids model. Lastly, it had played a key role in the simulation of a large group of flying bats in the famous move “Batman Returns”.

2.5 Selfish herd theory

There are many interesting and mysterious natural phenomenon in nature and the selfish theory is one of them. Selfishness is a natural characteristic of genes that are not only found in the humans but also in animals. If someone is altruist rather than selfish, it will give away the opportunity to live to others and be destroyed. Therefore, being a survivor in nature requires some elements of selfishness. The selfish herd theory was proposed by the English evolutionary biologist W .D. Hamilton [24] in 1971 to support some behaviour of animals.

2.5.1 Principle

The presence of the selfish herd theory is significant for biology. The core principle of it is that each individual would escape to the space that between conspecifics and predators to reduce the predation risk [24]. In this situation, a higher level of predation risk will exist at the edges of the population and it would gradually decrease toward the centre of the aggregations. This is because of the anti-predation from animals behaviour leads to group aggregation [7]. According to this research, social animals at higher predation risks in their natural habitats tend to form larger, more compact groups [16]. This could be caused by the fact that that most of the low-risk central locations are occupied by dominant animals, so the subordinate animals are compelled into the positions that with a high level of predation risk [6].

2.5.2 The domain of danger

Hamilton’s selfish theory [24] was clearly proposed in an article titled “Geometry for the Selfish Herd”. In this article, he conceptualised a circular pond where a group of frogs and a water snake was placed. The snake will prey on frogs at certain times of the day and it prefered to prey in the water. Because of this, all of the frogs were found to have distributed themselves randomly around the edges of the pond. It was assumed that the frogs have had opportunities to move on the rim of the pond and due to fear of the predator, none returned to the centre of the pond. However, the frogs were not satisfied with their position as they know that their natural enemies will appear soon. Individual frogs would get a much better chance of survival if they jumped to the narrow gap between two of its fellow frogs. The random part of the pond's perimeter where the snake is able to find the nearest frog is known as the unlucky frog's "domain of danger" [24]. The figure 2.8 shows how one smart frog reduce its domain of danger. The length of domain in this situation is half the gap between its nearest neighbours on both sides.

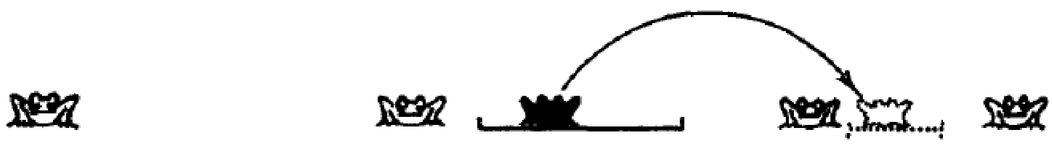


Figure 2.8 How a frog reduces its danger of domain [8]

However, under normal circumstances, all frog would move to reduce their domain of danger, which might result in a chaotic situation as it would be hard to find the ideal narrow space between their neighbours. Based on the location of all frogs in the image above, assuming the frogs in outside has larger gap than others, the new situation before them move might expected like Figure 2.9.

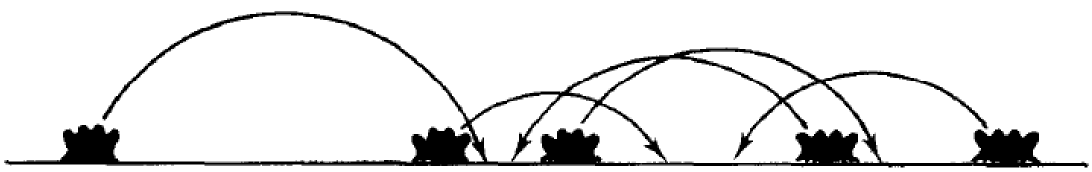


Figure 2.9 How a group of frog reduces its danger of domain [8]

It is clear from the image above that all frogs would attempt to move to the central position of group, which is also a hypothesis proposed by Hamilton [24]: individuals within the group will try to move to the central position to reduce the predation risk and domain of danger.

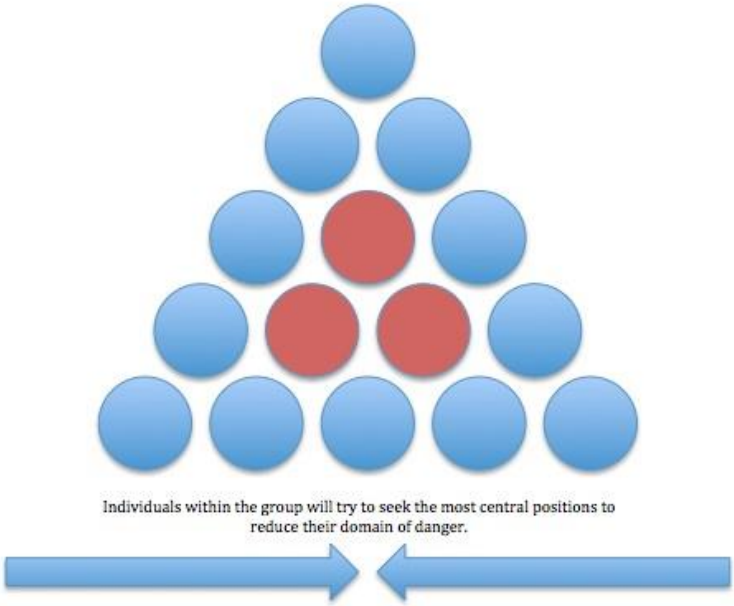


Figure. 2.10 The movement trend under the selfish herd theory [4]

2.5.3 Movement rules

The establishment of the movement rule of the selfish herd is difficult because it depends on a variety of complex movement rules. Movement rules which are easy to implement are often difficult to be used to form aggregations, but the rules that could easily create aggregation are usually considered too complicated to be biologically relevant. In 2002, Wethey, Miller and viscido [26] developed three standards which can be used to measure the quality of the selfish movement rules. The qualified movement rules of the selfish herd should (a) bring benefit to those who follow them, (b) be something that most animals we can imagine have the ability to follow and (c) generate concentrated aggregates. There are three determined realistic movement rules of selfish herds:

- **Nearest Neighbor Rule:** This rule states that each individual will move toward to the nearest neighbour. Hamilton [24] already mentioned this in his article but it might be negative in the small group because moving toward to nearest neighbors might cause some individuals to be closer to the predator.
- **Time Minimization Rule:** The rule stipulates that individuals in the group will move to the nearest neighbor in time (i.e. the neighbour that it can get to most quickly, given any constraints on movement due to the environment or nature of the animal) [8].

- **Local Crowded Horizon Rule:** This rule declares that members of the group will consider the other members within the group and adjust their movements accordingly [26].

2.5.4 Example and limitation

The selfish herd rule often appears in schooling and flocking behaviour. An example of a wide-ranging study is the fiddler crab. They will move in a way consistent with the selfish theory when they realize that a predator is approaching [27]. Adelie penguins will gather in a group to jump into the water in order to avoid predation by seals [18].

Although the selfish theory is now widely accepted, there are still some phenomena and behaviours that cannot be explained. For example, in three-dimensional space, flocks of birds and fish schooling may be subject to predatory attacks from above or below of space and selfish theories are unable to explain their grouping behaviour in this case [18].

2.6 The leadership and decision-making

The group needs to make decisions whenever they feel endangered in order to survive longer. For example, they need make the decision of which direction to swim when a predator is approaching, the direction that would make it easier to find food and point to a safe place to stop. How are those decision made and who are they made by?

2.6.1 Making decisions by consensus

There are two different theories with regards to the decision-making of flocking and schooling. One of them is making decisions by consensus. In the process of collective decision-making, once more than a threshold number of conspecifics have made this decision or behaviour, the probability that the entire group will perform the same behaviour will increase dramatically [29]. The threshold number of conspecifics is known as the “simple quorum rule”. According to a recent study, the group decision-making of fish is determined by this method such that the individual will watch other’s decision before they make their own choices. This decision-making pattern usually leads to the “correct” decision, but sometimes it might cause an “incorrect” decision.

2.6.2 Making decisions by leader

Another theory is that the group decision-making is determined by someone within the group, which means that others would follow the “leader” to swimming or stop somewhere. The leader is defined as someone who has more experience or own more information than others. In this theory, the leader would exert more influence than other group members. For example, in the observation of captive golden shiner (a kind of fish), experts found that the schooling formation is only led a small number of experienced members and they seem to know where and when food was available [23]. There will exist few individuals who are born leaders even when all of member own a similar level of knowledge of food availability and the behavioural tests show that they are more daring than others [12]. The smaller ones are often found in front of the group, which might be because they are hungrier than others. A survey of cockroaches showed that food-poor individuals tend to appear in front of the cluster to get more food, but the chances of being predated on are also increased [9] [11]. Individuals who are conservative about finding food behaviour will seek the central location of the group [10].

Chapter 3

Implementation and Design

3.1 The framework of software platform

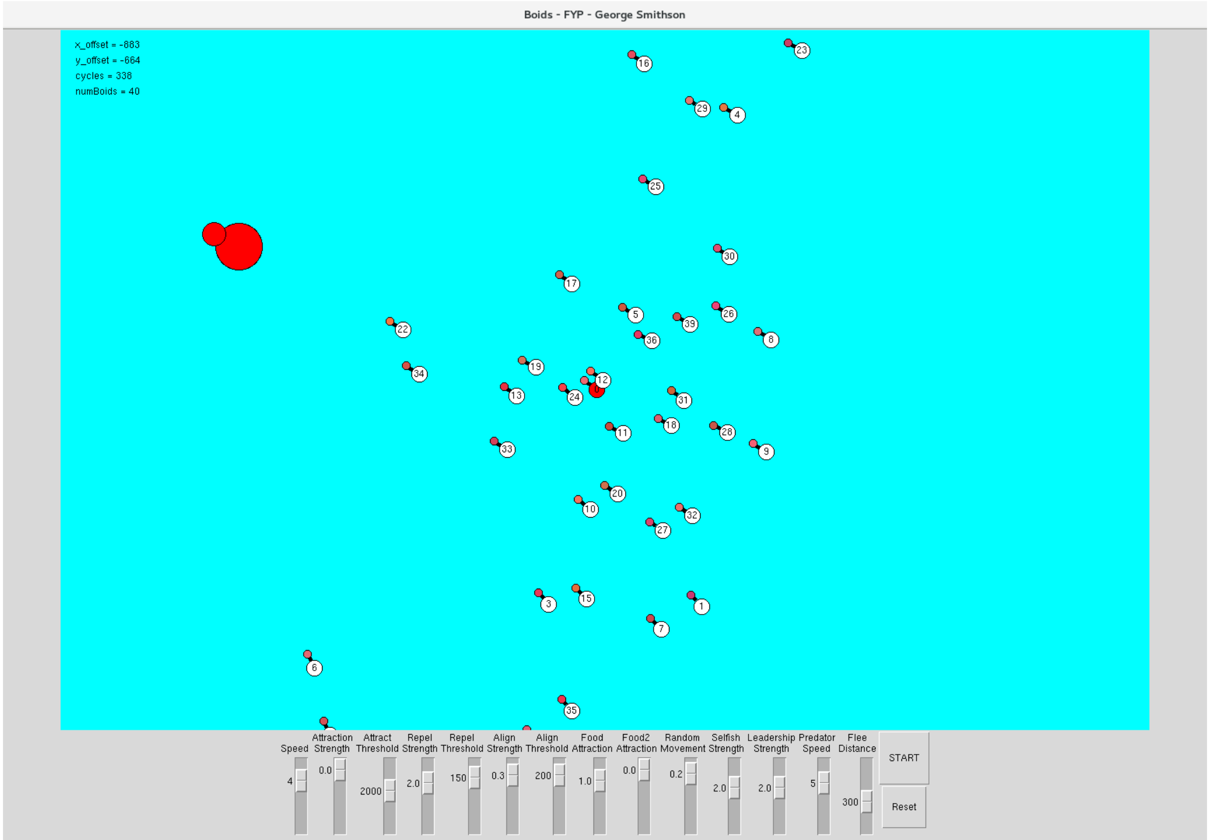


Figure 3.1 The interface of simple boids world with predator and leader (red one)

3.1.1 The basic function

Model hypothesis:

- The environment in which the group is located is not affected by weather and other factors
- There is no competition between individuals in the group.
- The perception of individual range is a circular area.
- The movable range of the group is unlimited

The symbol	The description
X_i	The X coordinate position of target i
Y_i	The Y coordinate position of target i
t	Time (cycles)
n	The number of initial boids.
m	The number of neighbours.
pos_i	The position of boids “i”.
pos	The position of target boids.
$X_{nearest\_nei}$ and $Y_{nearest\_nei}$	The coordinate position of the nearest neighbour of current boid
X_{pre} and Y_{pre}	The coordinate position of predator
X_{EP} and Y_{EP}	The coordinate position of escape point of current boid
∂	The speed of boids or parameter strength.
$\overrightarrow{direc1}$	The original direction of target boids.
$\overrightarrow{direc2}$	The cohesion direction of target boids.
$\overrightarrow{direc3}$	The separation direction of target boids.
$\overrightarrow{direc4}$	The alignment direction of target boids.
$\overrightarrow{direc5}$	The direction of food attraction of target boids
$\overrightarrow{direc6}$	The random direction of target boids

$\overrightarrow{direc7}$	The direction of predator repulsion of target boids

Table 3.1 Symbol Description

The position of boids “i” will be represented by the symbolpos_i, which consists of the two-dimensional coordinate system X_i and Y_i.

3.1.1.1 Basic Boids world

We already know the zone of different rules for boids from Figure 2.7. In this boids world, the movement of each boids is caused by different vector and vector is calculated by the formula. Detailed mathematical explanations for them are available and shows how each boids move in the program clearly.

- The cohesion rule

For each individual boid, neighbours must exist alongside it. The direction of movement of each boid is determined by the movement of its neighbours. Making the average of the locations of the neighbours as the neighbour centre, each individual should have the characteristics of moving closer to the neighbour centre. The range of the cohesion rule is the largest in those rules (2000), it would be the crucial point where boids gather together.

Formula 1: $\overrightarrow{direc2} = \frac{\sum_{i=1}^{m}(pos_i - pos)}{m}$

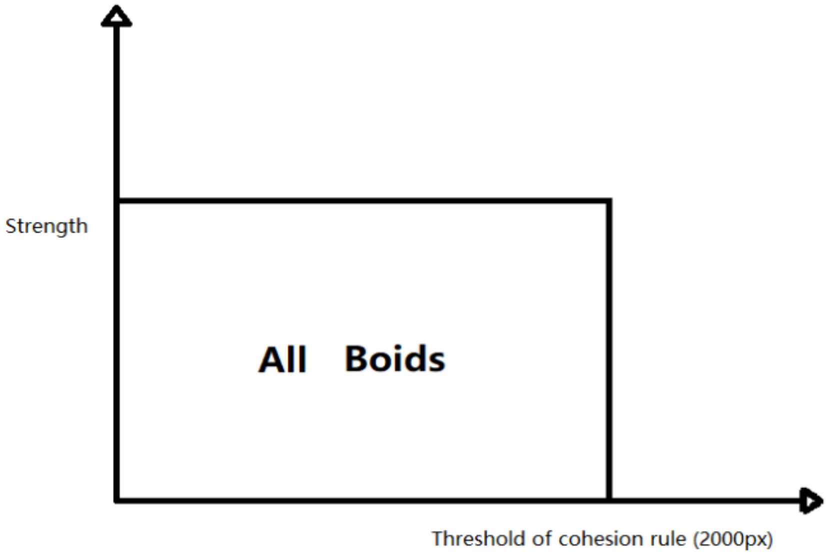


Figure 3.2 Scope of cohesion rule

The characteristic of the cohesion rule is that the scope of this rule is presented as a rectangle. This means that the boids who stay out of range of action are completely unaffected by the cohesion rules, but all boids within the threshold range will be subject to constant attraction, where "constant" does not mean that each individual has the same attraction, but that the attraction they receive will not change because of the distance between them.

- The separation rule

Collisions may occur when individuals are too close to their neighbours. In this case, each boid should own a zone which restricts the collision. In another words, both sides will be subject to a repulsive force. The scope of this rule is the smallest at only 150.

Formula 2: $\overrightarrow{direc3} = -\overrightarrow{direc2}$

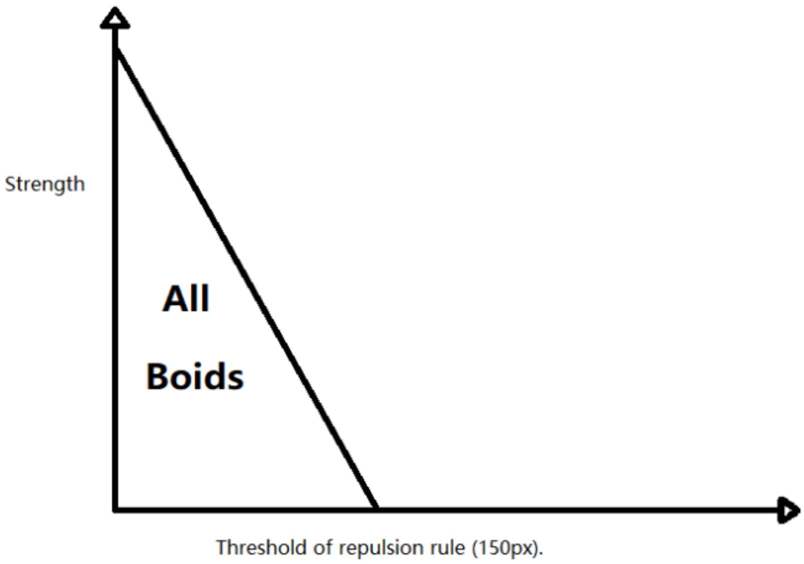


Figure 3.3 Area of repulsion rule

The operation mode of the repulsion rule is different from the cohesion rule. In this rule, the strength of repulsion between boids would decreased as distance increases, given that they were located in the threshold of repulsion rule. This means that the repulsion between two boids would be biggest when they are close to each other.

- The alignment rule

The individuals would carry out alignment operation and align with the average velocity of the flock, which provides the possibility that all individuals move in groups form and maintains velocity direction consistency.

Formula 3: $\overrightarrow{d\imath rec4} = \frac{\sum_{i=1}^{m} \overrightarrow{d\imath rect1_{\imath}}}{m}$

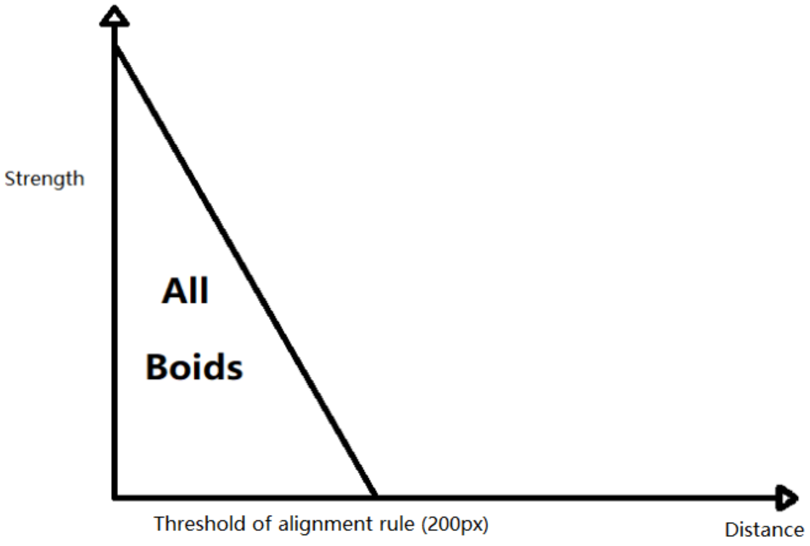


Figure 3.4 Scope of alignment rule

The alignment rule is similar to the repulsion rule except for the range of the scope. In the scope of this rule, the alignment force that each boids is subjected to is inversely proportional to its distance from the neighbours. In this case, boids will prioritize the speed direction of the nearest neighbour as a correction template and adjust its velocity direction accordingly.

3.1.1.2 Other rules

- The food attraction.

For each individual, there exist a food resource which could attract the boids. This will be able to provide a more realistic simulation of the environment and cluster all the boids into a group at an early stage, it is useful to get the results with less noise. However, the existence of food can make the group too compact and affect the results of the experiment, so it is necessary to set the intensity factor of the attraction of food to the individual appropriately.

Formula 4: $\overrightarrow{direc5} = pos_{food} - pos$

- The random movement.

For simulating the ideal boids world in the experiment, the suitable random value of movements is positive for simulation of the real environment.

Formula 5: $\overrightarrow{d\imath rec6}$ = Random Value (limited)

- Repulsion from predators.

There are two patterns of program running: with predator and without predator, which needs be set at the beginning of the main function. If with predator, repulsion will be applied to every individual when predators enter the perception range of boids, the direction of escape is exactly the opposite of the direction of the predator and the magnitude of repulsion is related to the velocity.

Formula 6: $\overrightarrow{d\imath rec7} = \overrightarrow{pos_{pre}} - \overrightarrow{pos}$

- The calculation formula of magnitude of vector.

All of the movement rules would be converted into vector form and then applied to each individual. The value and direction of velocity are relevant to the magnitude of the vector and its speed or parameter strength. The transform formula is:

Formula 7: $\overrightarrow{vector\ X} = \frac{\overrightarrow{directX} * \partial}{\left|\overrightarrow{d\imath rectX}\right|}$

Now suppose the global time is t, the sum of vector for each individual at time (t) is:

$$\overrightarrow{newvel}(t) = \overrightarrow{veloc\imath ty(t)} + \overrightarrow{d\imath rec1(t)} + \overrightarrow{d\imath rec2(t)} + \overrightarrow{d\imath rec3(t)} + \overrightarrow{d\imath rec4(t)} + \overrightarrow{d\imath rec5(t)} + \overrightarrow{d\imath rec6(t)} + \overrightarrow{d\imath rec7(t)}$$

The velocity of each boids in time (t) can be calculated:

$$\overrightarrow{velocity}(t) = \frac{\overrightarrow{newvel}(t) * \partial}{|\overrightarrow{newvel}(t)|}$$

The position of boids i in time (t+1):

$$pos_i\,(t+1) = pos_i(t) + \overrightarrow{velocity(t+1)}$$

In this experiment, the global time is presented by the “cycles”, which means the number of times the main loop function was run in the whole program. It ensures that all comparisons and outcomes for each parameter obtained are carried out with the same main loop function.

3.1.2 The improved function and added rules

3.1.2.1 Information visualization

It is necessary to combine program with information visualization techniques for the purpose of optimizing observer analysis. Due to the particularity of the experiment, many individuals (boids) moving on the canves can easily cause visual confusion and will not be easy to observe directly. To deal with this, the modified program has implemented the measure that the color of boids will change with changes in certain parameters through change in the RGB value. The attraction parameter, for example. The boids would increase its saturation of color.

Code:

```
XX = int (boid_boid_attraction_strength.get()*100)
x=255-XX
y=255-XX
z=255-XX
print(x)
   head_color = color_string_from_rbg_ranges( (x,x),(y,y), (z,z) )
```

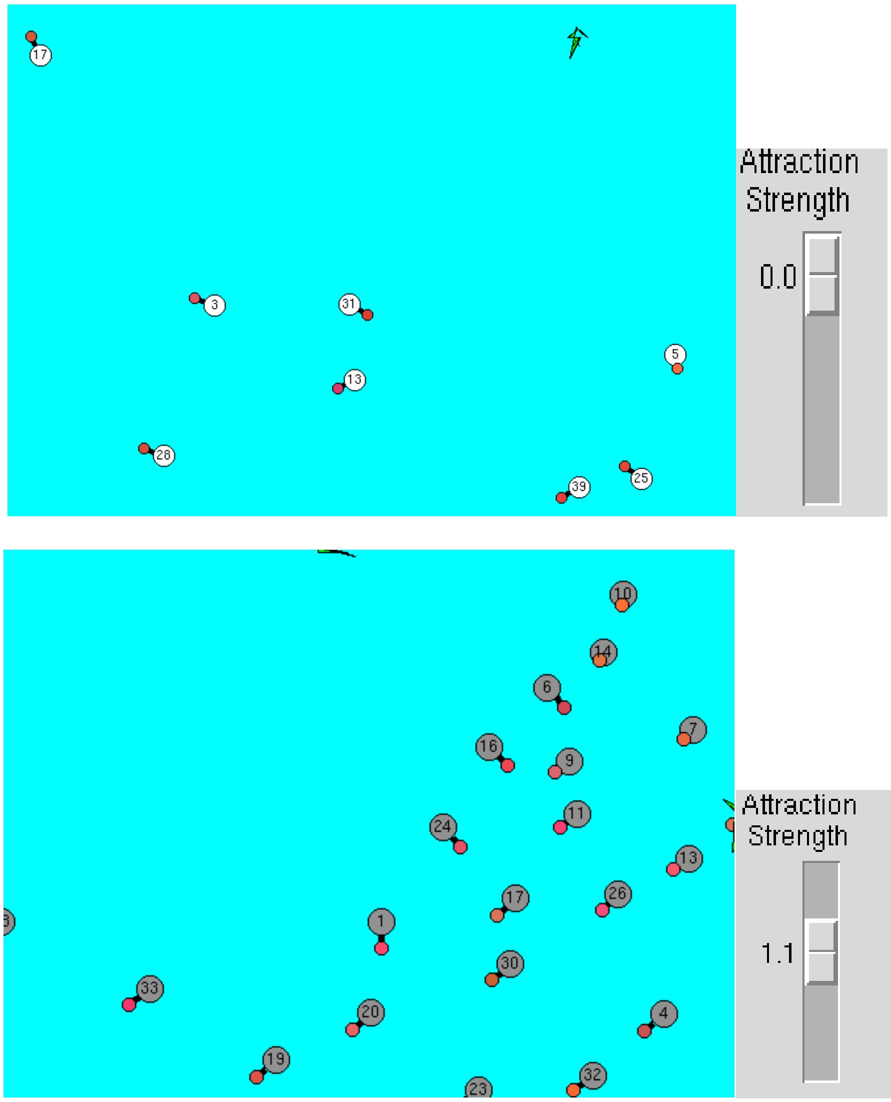


Figure 3.5 Information visualization be applied on Boids

3.1.2.2 Analysis from the view of individual

The end mode of the original program is setting the stop number, which means that the program would terminate when the number of dead boids reach a critical threshold. This method is suitable for testing the impact of the parameter on the overall group rather that exploring the significance of these factors on the individual. It is an imperative mission for the whole software on the account of some parameter bringing positive influence for whole group. Nevertheless, it might be destructive for individuals.

Code:

```
for b in dead_boids:
```

```
b.delete_graphic()
if b.id == 5:
    gauge_panel.update(cycles)
    canvas.update()
    return cycles
```

3.1.2.3 Analysis of the features of the cohesion rule and the repulsion rule

For the simple boids world, the cohesion strength and repulsion strength affect the formation of groups. The impact of the two rules were measured not only on groups but also from an individual perspective. Chapter 3.1.2.2 provides the main method in individual testing.

For group testing, the main objective of it is to test the parameters of the group, therefore, the test should be based on the whole group. For example, a group of 40 individuals can be set up, and the program should be reinitialised when 30 of them die (i.e. predated), the loop can then be continued. The main test parameters such as attraction or repulsion strength increase linearly. After hundreds of tests, the results are averaged to obtain reliable data for recording and analysis.

Another testing pattern in the mathematics module is from an individual perspective. A single boids could be picked from the group and marked, the cycle time of when it is dead will then be recorded. This is a useful method as some parameters are negative for groups but positive for individuals. In the case of a linear change in the key coefficients, it is also possible to compare the individual survival time when all individuals have the same parameters with the survival time of individuals with special parameters. This will determine whether the parameter is beneficial to individuals.

3.1.2.4 Selfish herd theory

The selfish movement rule is a completely new rule for this experiment. It was proposed by W. D. Hamilton [7] in 1971 to explain the gregarious behaviour of a variety of animals. This escape rule is similar to the movement of repulsion from predator, however, the principle and the effects are totally different. For instance, the vector of repulsion from predator is the exact opposite of the direction of predator. According to the selfish rule, each boids would escape to the back of its nearest neighbor to reduce the risk of predation once they realize that a predator is approaching. The distance between each boids was calculated and stored in a two-dimension list 2 (check below), so one nearest neighbor will always be present for each individual on canves. The distance between each boids and predator was also calculated and saved to list 1.

The distance between the boids themselves:

$$Dis_X = \sqrt{(X_i - X_p)^2 + (Y_i - Y_p)^2} \qquad Dis_y = \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2}$$

$$\text{List 1} = [Dis_{X1}\ , Dis_{X2}, \cdots, Dis_{Xn}]$$

$$\text{List 2} = \begin{bmatrix} Dis_{y11} & \cdots & Dis_{y1n} \\ \vdots & \ddots & \vdots \\ Dis_{yn1} & \cdots & Dis_{ynn} \end{bmatrix}$$

Here a method similar to bubble sort method was used to iterate through all the boids and successfully gain the id of the individual with the shortest distance.

Code:

```
 def calculate_boid_separations():
   global boid_separations
   for nb1 in range(numBoids):
       for nb2 in range( nb1 +1, numBoids ):
           sep = point_separation( boids[nb1].position(), boids[nb2].position() )
           boid_separations[nb1][nb2] = sep
           boid_separations[nb2][nb1] = sep

def calculate_predator_boid_separations():
   global predator_boid_separations
   for nb in range(numBoids):
       sep = point_separation( (predator.xpos, predator.ypos), boids[nb].position() )
       predator_boid_separations[nb] = sep
```

The experiment assumes that the detection range of Boids is a circular region with a radius of 400px. The target individual senses the predator nearby and triggers selfish regular movement, this then cause it to move behind the nearest neighbor Boids 1. In the case above, there will be a precise location known as the “escape point” for the Boids 1 to give target Boids a direction to escape. Since the location of the nearest neighbor to the target individual is constantly changing, the escape point will be updated accordingly.

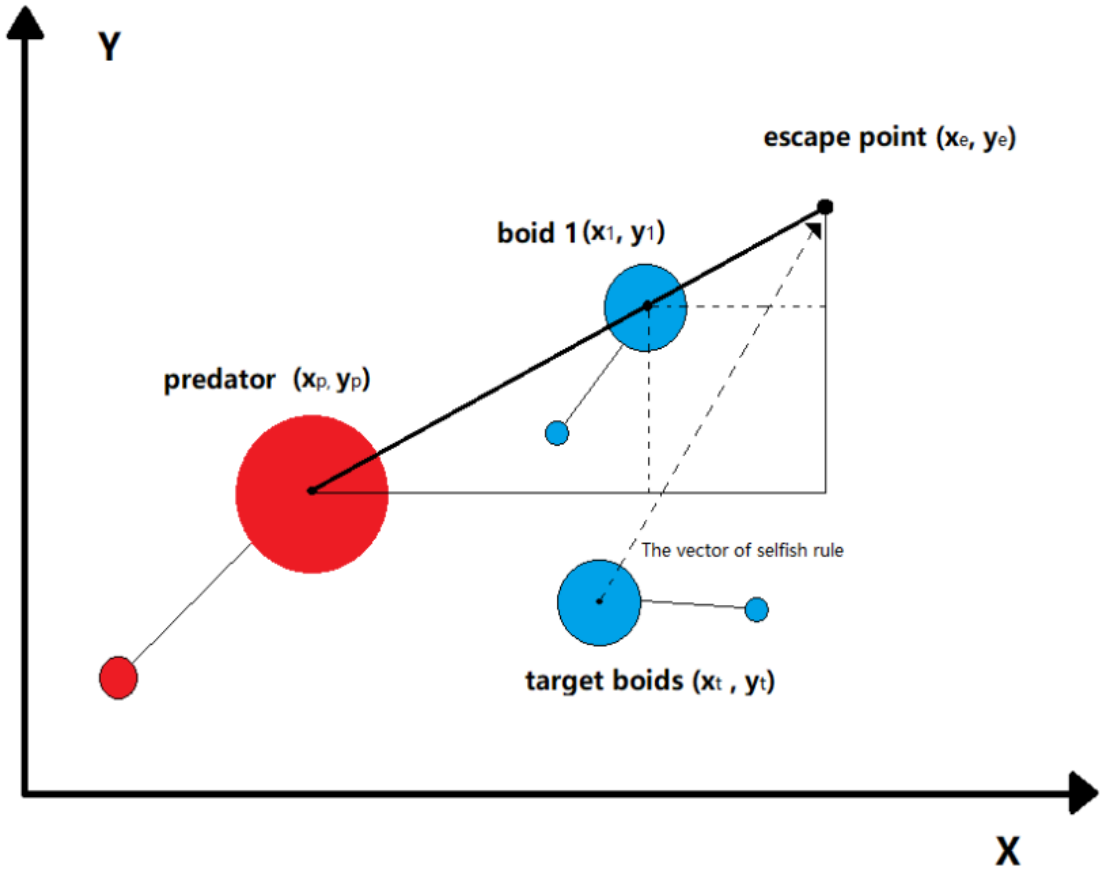


Figure 3.6 The implementation of selfish rule

First, build the function "the nearest boids", which calculates the nearest neighbors of all individuals. The return value is the nearest neighbor current boids.

Code:

```
def nearest_boid_to_boid( p ):
  x, y = p
  nearest_boids = boids[0]
  nearst_dist_boids = point_separation_squared( p, nearest_boids.position() )
  for b in boids[1:]:
     dist = point_separation_squared( p, b.position() )
     if dist < nearst_dist_boids and dist!=0 and point_separation_squared != 0:
```

```
        nearst_dist_boids = dist
        nearest_boids = b
    return nearest_boids
```

Then, build a "selfish" function to calculate the escape point (EP) and convert it to a vector. The function will need to determine whether the predator has entered the perceived range of the current boids. In this experiment, the perceptual range of boids within which predators can be detected is 400px. When it is detected that a predator has entered the range, the selfish rule will be triggered. First, calculate the EP point by using similar triangles (shown in Figure 3.5). By subtracting the position of the nearest neighbor and the position of the predator, a directional and sized vector can be obtained. Therefore, a similar triangle can be used to calculate the "behind" point of the nearest neighbor. The formula is as follows:

$$X_{EP} = \frac{Fix_{Dis} * (X_{nearest\_nei} - X_{pre})}{\sqrt{(X_{nearest\_nei} - X_{pre})^2 + (Y_{nearest\_nei} - Y_{pre})^2}} + X_{current\_boids}$$

$$Y_{EP} = \frac{Fix_{Dis} * (Y_{nearest\_nei} - Y_{pre})}{\sqrt{(X_{nearest\_nei} - X_{pre})^2 + (Y_{nearest\_nei} - Y_{pre})^2}} + Y_{current\_boids}$$

There could get the the new vector that the direction is from the target boid to the EP point and the velocity can be calculated using formula 7.

The code:

```
def boid_boid_selfish(self):
    pred_dist = point_separation((predator.xpos,predator.ypos),self.position())
    if pred_dist < selfish_dist.get():
        target = nearest_boid_to_boid((self.x, self.y))
        similar_line_x = target.x-predator.xpos
        similar_line_y = target.y-predator.ypos
        similar_hypotenuse = point_separation( (predator.xpos,predator.ypos),
target.position())
        fix_dis = 300
```

```
        x_po = (fix_dis*similar_line_x)/similar_hypotenuse + target.x
        y_po = (fix_dis*similar_line_y)/similar_hypotenuse + target.y
        sep_vect = (  x_po - self.x, y_po - self.y)
        selfish = boid_selfish_strength.get()
        return scale_vector_to_magnitude( sep_vect, selfish )
    return (0,0)
```

In the design stage of the selfish rules, the selfish strength coefficient is originally fixed. The experiment simply tests the influence of the selfish rules on the survival rate of boids. However, after a long period of consideration and a reminder from the supervisor, the selfish coefficient is now considered to be a parameter of great reference value and experimental value. It was eventually decided to set the selfish coefficient as one of the parameters that can be adjusted in real time on the Graphical User Interface.

Code:

```
make_gauge_widget( slider_panel,  "selfish\nStrength", boid_selfish_strength, 0, 6, 0.5)
```

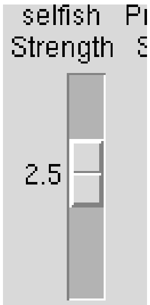


Figure 3.7 slide bar of selfish strength

3.1.2.5 The leader

There are two different theories surrounding the decision-making of the group (detail see the chapter 2.6) and the second theory has been chosen and implemented in this experiment. The leader is defined as someone who owns more information such as food position and location of safe habitats. Therefore, to successfully carry out the experiment, it is necessary to add or change some of the original conditions for the leader so that it has the ability to attract other individuals and leading individuals to find food. For example, the range of attractiveness of food in the original program was unlimited, which meant that all individuals have a same level of knowledge of food resource location. But in the test for leader boids, the range of attraction of food was set within 1500px and only boids who stayed in the scope of the food will be attracted.

Code:

```
def boid_food_attraction(self): ## Attraction to food
        if self.id == 0:
            dx = food.xpos - self.x
            dy = food.ypos - self.y
            food_attraction = scale_vector_to_magnitude( (dx,dy),
                                          boid_food_attraction_strength.get() )
        else:
            food_dis = point_separation((food.xpos, food.ypos),self.position())
            if food_dis<1500:
                dx = food.xpos - self.x
                dy = food.ypos - self.y
                food_attraction = scale_vector_to_magnitude( (dx,dy),
                                          boid_food_attraction_strength.get() )
            else:
                return (0,0)
        return food_attraction
```

The leader is set to be an individual with more information which means that leaders are attracted to food at any locations and are not limited by distance. In order to simulate the most realistic situation, the food is embodied as a slow-moving, irregular polygon with a constantly changing shape.

Furthermore, the leader is not affected by the velocity alignment rules but still follows the cohesion and repulsion rules, which means that the decision (speed direction) made by the leader has a certain randomness to it. Leaders have the potential to make decisions that are beneficial to the group, but at the same time, they may lead the team to the path of “destruction”.

Code:

```
def boid_boid_leader(self):
        cx = 0
        cy = 0
        for  boid in boids:
            if ((boid.id == 0) and (not boid is self) and (self.separation(boid) < 1500)):
                cx = boid.x
                cy = boid.y
        dx = cx - self.x
        dy = cy - self.y
        leader_strength = = boid_leadership_strength.get()
```

```
return scale_vector_to_magnitude( (dx,dy),
                                  leader_strength
```

In this experiment, a pre-discovery function was added to the leader whereby the leader will detect the presence of the predator 100px earlier than the others.

3.1.3 The Program flow and explanation

Figure 3.8 is a general flow chart of the program. The first step was to create a desktop, also known as the program interaction interface. Its function was to embody the boids and predators on the canvas so that the user can visually observe how the schooling works. Initialization is the first step carried out at the beginning of each loop. It includes clearing the old canvas and creating a new one, initializing the position and number of boids and predators, to prepare for restarting the program. After initialization, it would be necessary to detect if there is a predator present to determine whether to run the predator action function (if the distance between predator and boids falls below a certain figure, boids die and are removed from the canvas). The termination condition is then determined. The predator and boids continue to move if the termination condition is not reached. When the termination condition is reached, the result (number of runs) is returned and the program is stopped.

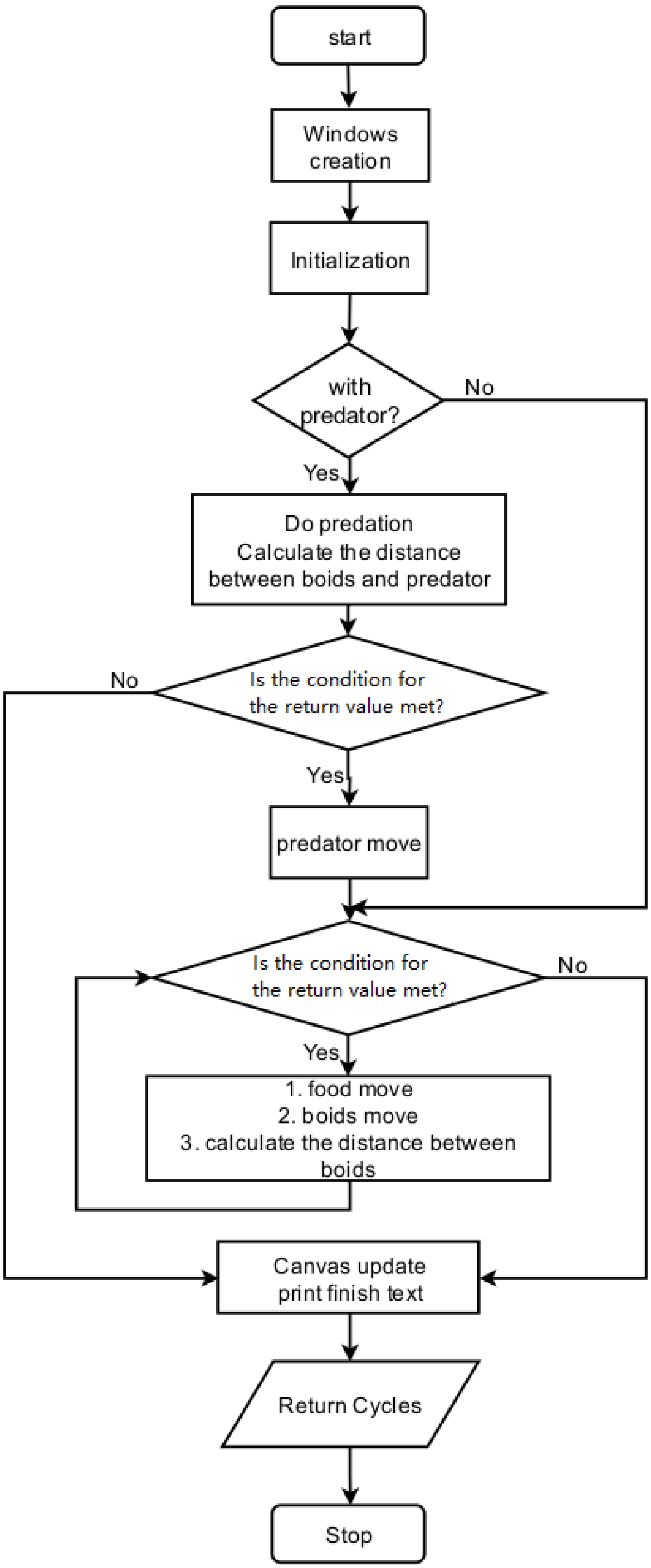


Figure 3.8 whole process program

3.2 The design of experiments

3.2.1 Cohesion and repulsion rules

In this project, the two different test methods mentioned above have used the cohesion rule and repulsion rule respectively to test the influence of coefficient strength on groups and individuals. In the results displayed, the data is drawn as an image and displayed in a two-dimensional coordinate system. The X axis represents the test parameter of the linear increase, and the Y axis represents the average of the return value of the program after multiple runs.

Testing of cohesion rules, the cohesion parameter would be linearly changed and the other parameter would be constant. Repulsion strength is 2, alignment strength and random movement value are 0.3 and 0.2 respectively, and they would not be changed in all of the experiments below. The food attraction is 0.2 and its function is lead boids form an aggregate during initialization, which has benefit to collect the clear data. We could test in the group and individual two difference aspect.

For Testing of repulsion rules, the cohesion strength is 0.6 and repulsion parameter would linearly be changed. Others parameter and method of the experiment are same with experiment above.

3.2.2 The Selfish rule

3.2.2.1 The effect of the existence of selfish rule on herding behaviour

First is testing the influence of selfish movements on the boids, both on groups and on individuals. The way to measure the influence of selfish rules is to plot area charts. For instance, the X-axis represents the number of test groups and each group can be represented by the average of the results of a hundred tests. The Y-axis corresponds to the number of main loop runs returned by each group of programs. The area chart is one of the most powerful expressions as it allows for operators to intuitively notice that the size of the area is different due to the differences in return values (average cycles). This will in turn help with determining how outstanding or bad the existence of selfish rules is for groups or individuals.

The return condition of the main loop function can be set autonomously, such as initializing 40 individuals, returning when 20 of them die (be preyed), or marking any one of 40 individuals at the time of initialization "smart fish." The main function returns the current cycle time when the smart fish is eaten by the predator. In this environment, the cohesion and repulsion strengths are 0.6 and 2 respectively, the random value is 0.2 and the alignment strength is constant as well (0.3). The selfish strength is 2.5. In testing of the selfish rule, we do not need the food attraction to gather boids together.

3.2.2.2 The effect of the of selfish strength on herding behaviour

A plane Cartesian coordinate system can also be used to show the impact of the selfish strength on boids. In the test for groups, the X-axis of the coordinate system represents a self-increasing parameter that grows linearly where the rate and magnitude of growth should be adjusted as appropriate. The Y axis of the coordinate system is the number of runs that the program main loop function returns when the qualification is met. In the group test, the result return condition is generally death of 50% to 70% of total boids.

With regards to the effects of the selfish strength on boids individuals, most of the features are similar to those described above except two crucial points. Initially, a special boids will need to be marked. When a special individual is caught and eaten, the function returns and the number of times the main loop function has been run will be recorded. On the other hand, excluding the special marked individuals, the selfish parameter strengths of all other individuals are the same, while the selfish intensity of special individuals varies linearly, and the degree of change should be consistent with the group test mentioned above for comparison purposes. The selfish parameter is a key point for herding behaviour. In this environment, all of the parameter is same with 3.2.2.1 except linearly changed selfish strength.

3.2.3 The leadership

In design part of leader, there need pay attention to the group rather than individual, because it is about group decision-making. The environment has three basic rule: cohesion, repulsion and alignment rule with 0.6, 2 and 0.3 strength respectively. The random movement value is 0.2 as well as the food attraction. Leader is black individual and has linearly changed leadership strength. The outcomes is the survival time of 75% boids with different leadership.

Chapter 4
Results and analysis

4.1 The cohesion rule

4.1.1 The cohesion rule for group

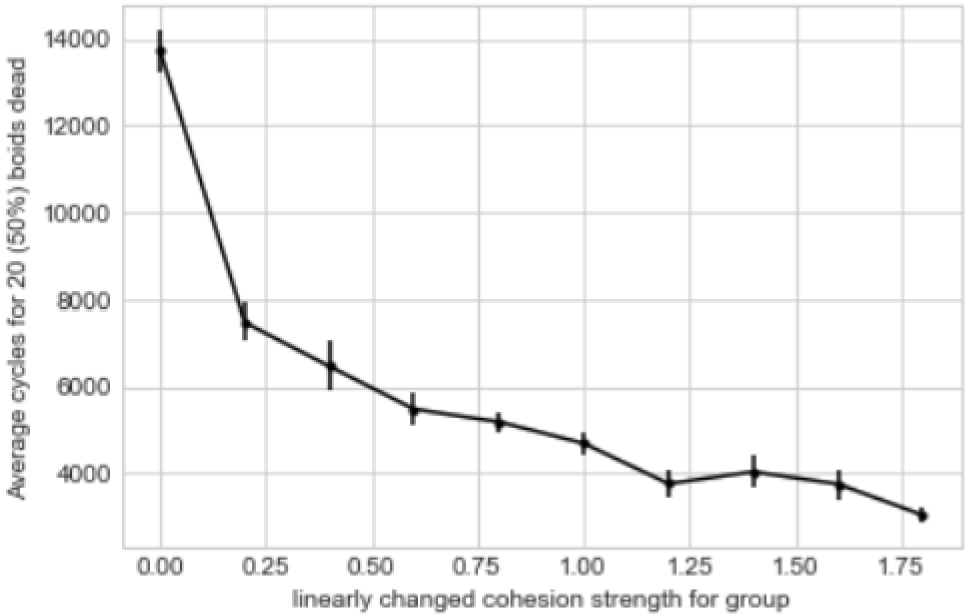


Figure 4.1 Effect of different cohesion strength on group

The X axis contains a total of 10 different coefficients from 0 to 1.8, which represents the linear increase in attraction strength with a growth of 0.2. While the Y-axis represents the number of cycles of the main cycle function when 20 boids are captured by the predator. The chart adds the error bar in the figure 4.1. The error bar is a useful method in data statistics that represent the fluctuation range of data and the length of error bar could directly reflect the accuracy of the data. In this experience, this error bar show the standard error in figure.

It can be clearly seen from Figure 4.1 that the overall survival rate of the boids population decreases with the linear growth of intensity However, the survival rate of the boids group has a slight increase in coefficient strengths equal 1.4, which may be due to too few experiments being carried out or the existence of noise.

The reason for this may be that as the intensity of the attraction coefficient increases, the degree of intensity of the population then becomes larger and the group becomes more compact, resulting in a predator that can obtain a higher predation efficiency with less moving distance.

4.1.2 The cohesion for individual

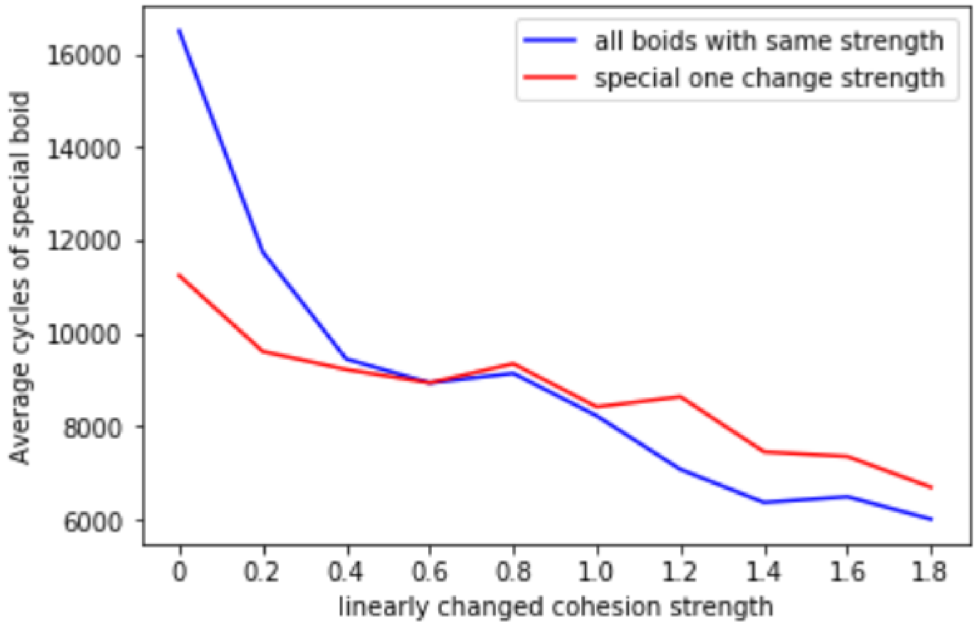


Figure 4.2 Effect of different cohesion strength on individual

Figure 4.2 shows a comparison of the effects of different strengths of attraction on individuals. As mentioned above, when carrying out individual testing, it is necessary to mark a particular individual (special one). The Figures in Y-axis is the number of cycles returned by the program when a particular individual dies. On the other hand, the X-axis represents the attraction strength of a particular individual. The difference between the two lines is that in the blue line, the strength of the attraction of all individuals is the same as that of the particular individual, while in the experiment represented by the red line, the coefficients of all other individuals were constant except for the special one, the attraction was set to 0.6 in this experiment. Since the attraction strength was set to 0.6 by default in the experiment represented by the red line, the two experiments were the theoretical equivalent of each other at X = 0.6.

It is worth noting that in Figure 4.2, the point corresponding to the coefficient strength of 0.6 appears to be a turning point. This is because before this point, all values of the red line are smaller than those of the blue line test. However, all values on the red line became larger than values on the blue line when the intensity is greater than 0.6. For example, an individual with an intensity of 1.5 has a longer survival time in an environment with an intensity of 0.6 than in an environment with an intensity of 1.5. Although the results obtained in both experiments showed a downward trend, the relative increase in the attraction strength prolonged the survival rate of individuals. Therefore, it can be can concluded that the intensity has a negative impact on the survival rate of the boids population, but has a positive effect on-individuals.

By observation, the possible reason for this is that an individual with a high intensity parameter in the group will move toward the centre of the group under the action of the cohesion rule, which will increase the survival rate of the individual.

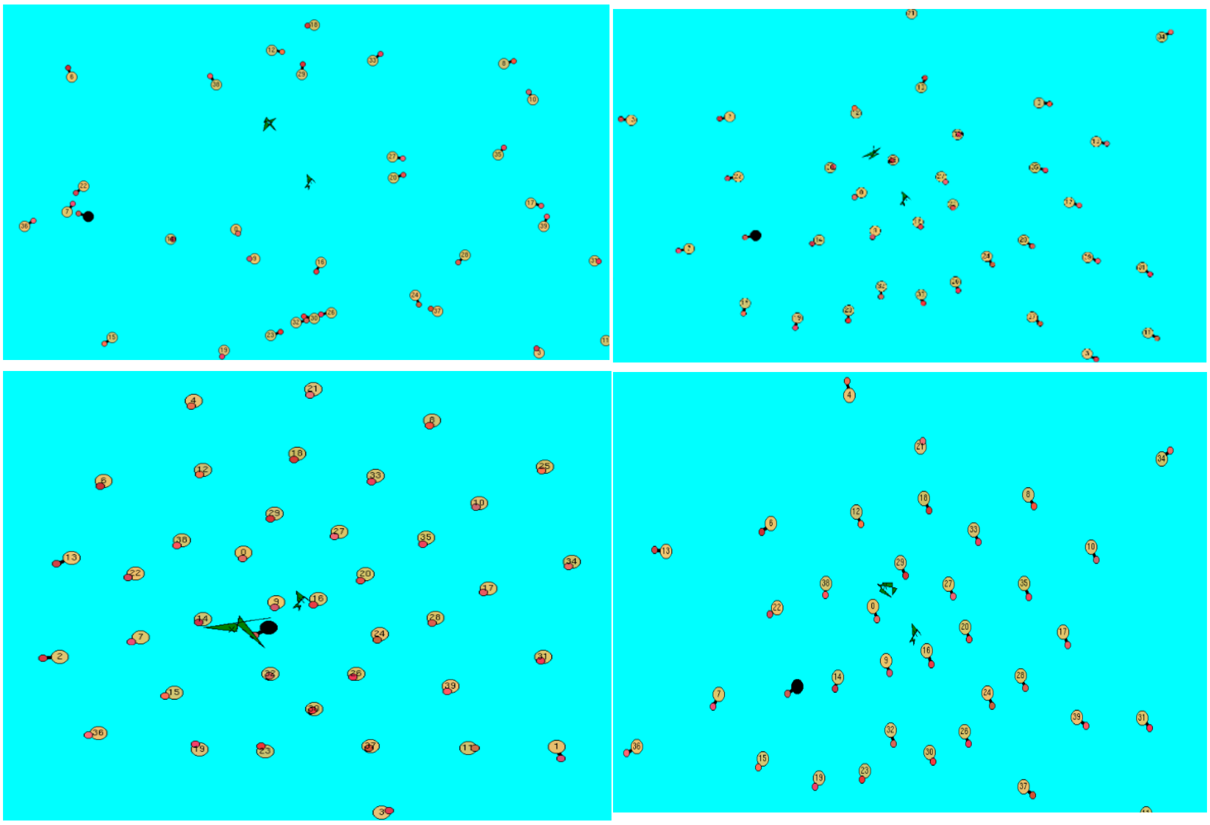


Figure 4.3 Special one (black) go to the central position

4.2 Repulsion rule

4.2.1 Repulsion strength for group

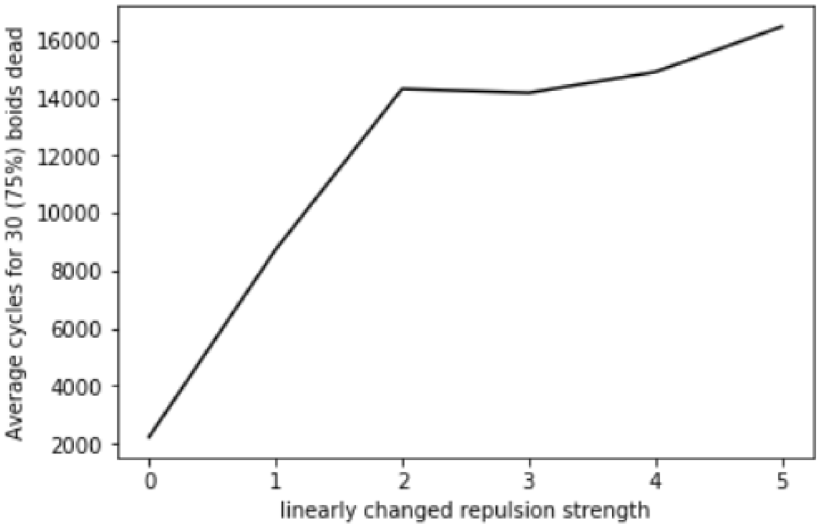


Figure 4.4 Effect of different repulsion strength on group

Figure 4.4 shows the effect of the repulsion rule on the boids group. The Figure on the Y-axis is the cycle time when the predator preys on 75% of the total number of boids. It can be clearly seen that the average of cycles showed an upward trend with the increase of the strength of repulsion. In particular, the survival rate of the boids group increased sharply between 0 and 2 (from 2234 to 14319).

The reason for this might be that the gap between each individuals would increases with the linear-change of repulsion strength, which directly reduces the intensive degree of the whole group and makes the schooling very fluffy. When the predator approaches the boids group, the boids who are located at the edge of the group would flee to the opposite direction of the predator due to repulsive force from the predator, most other boids would move to similar direction as well because of the high repulsion strength between them: the predator broke the steady state of the original group, so the biods had to restore the balance by moving.

4.2.2 Repulsion strength for individual

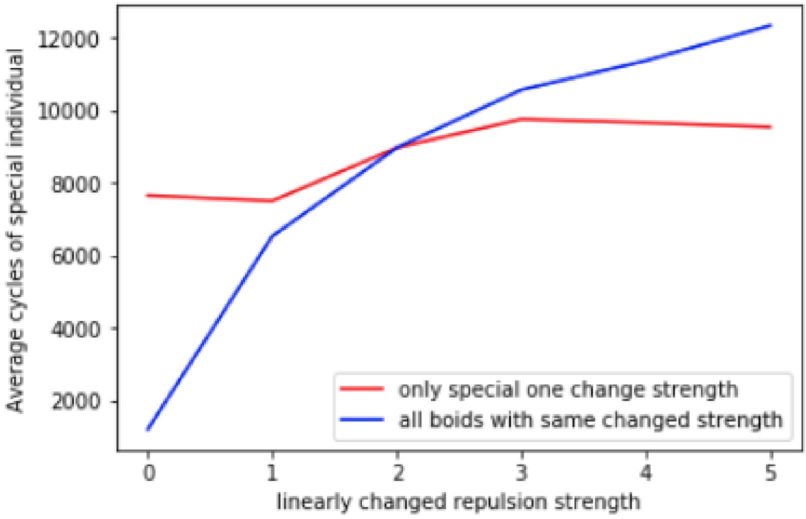


Figure 4.5 Effect of different repulsion strength on individual

Figure 4.5 represents a comparison of the effects of different cohesion strengths on individuals. Similar to the graph shown in Figure 4.2, the blue line represents the experiment on all boids including the special one with the same repulsion parameter strength. The repulsion is increased by 1 each time. The experiment in red line is different because that the all boids except special one own the same and constant repulsion strength equal 2 and only the repulsion strength of a particular individual is linear changed. Therefore, the two experimental values at X = 2 are theoretically the same.

Not only that, through observing Figure 4.5, it can be discovered that the point X=2 is also the intersection of the two lines and there follow some special rules: the number of cycles of the red line at X=0 and 1 is greater than the value in blue line. In contrast, the specific individual survival rate of the red line experiment at all points after X=2 was lower than the experiment represented by the blue line. In other words, individuals with relatively high repulsion coefficient strength for boids will on average, have a shorter survival time than individuals with relatively lower strength. This shows that the increase of repulsion might be positive for the survival for whole group, but it may bring negative influence for individuals.

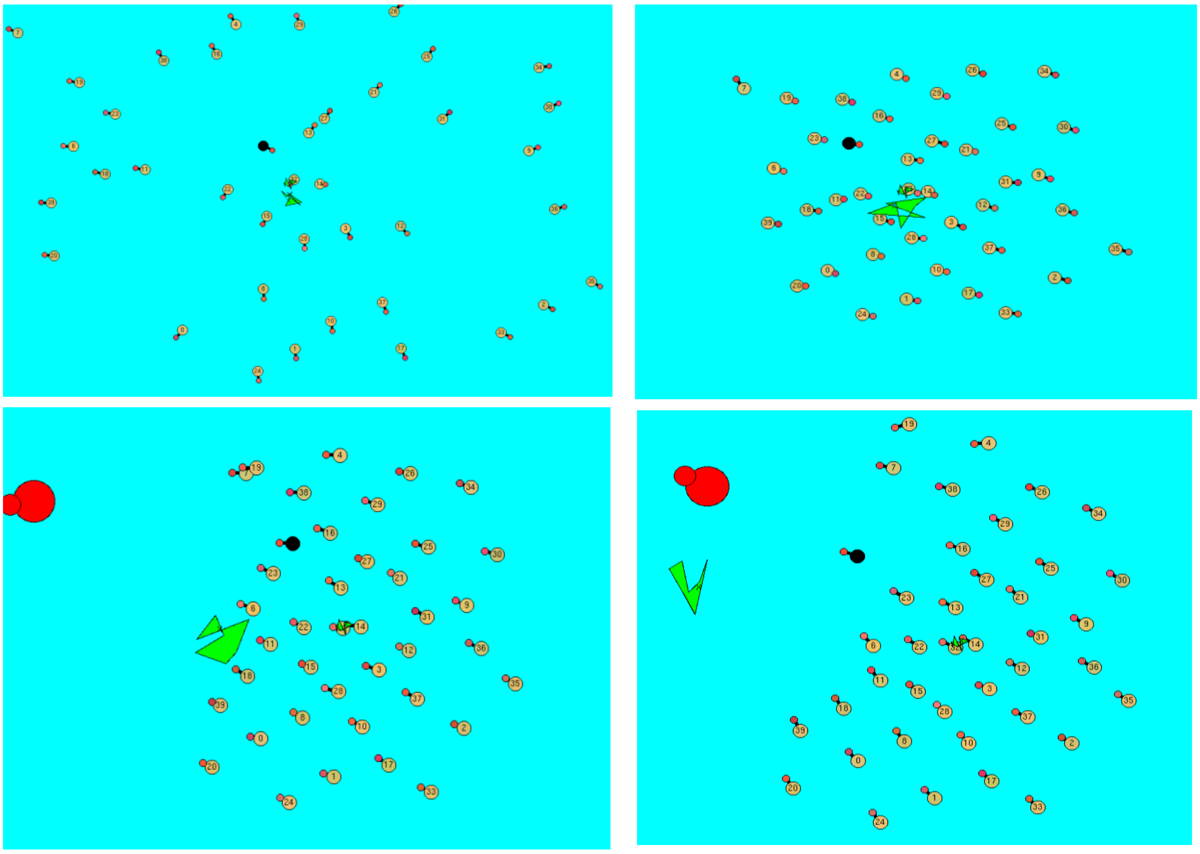


Figure 4.6 Special one (black) Come to the edge

This phenomenon may be caused by the characteristics of the repulsion rule. As can be seen in Figure 4.6, as the intensity of the repulsion increases, the interval between the particular individual and the other individuals will be larger than usual. After the initialization is over, the special one could be easily "extruded" by other conspecifics to the edge of the group. This will directly increase its predation risk

4.3 The influence of Selfish rule on herding behaviour

4.3.1 The existence of selfish rule for individual

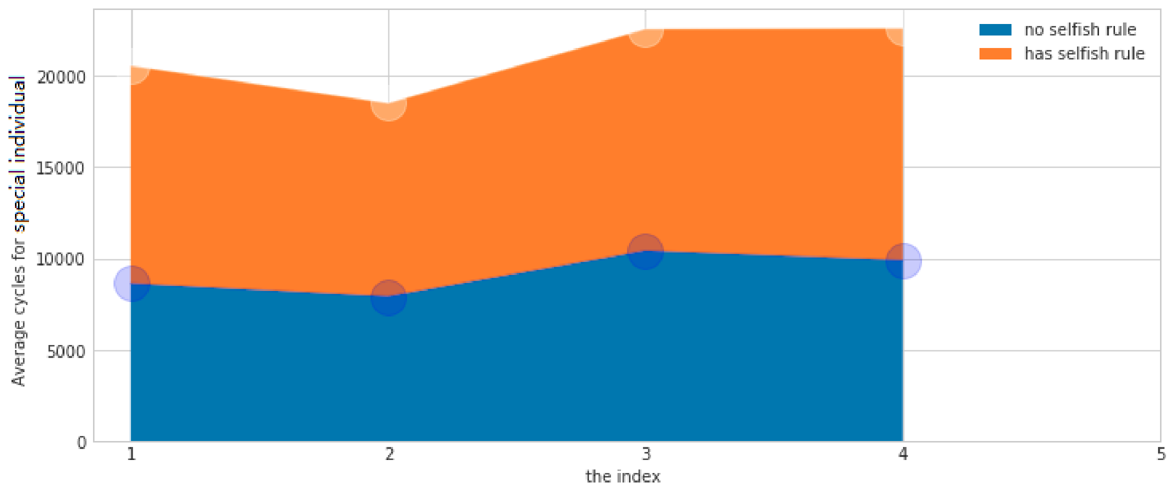


Figure 4.7 Effect of existence of selfish rule for individual

Figure 4.7 shows the effect of the existence of selfish rules on a single individual, so this is a set of comparative experiment and specific individuals are marked in two experiments. X represents the number of trials and the Y-axis is the cycle time of death of a particular individual. In the experiment represented by the yellow line, only special individuals have been set to follow the selfish rules and other parameters are the same as other boids. In the experiment represented by the blue line, the special individual has been set to have the same proprieties as all other boids and do not follow the selfish rules. This is so that a clear contrast can be obtained. The boids of both experiments were in the same environment (please check 3.2.2.1 for detail).

From the Figure above, it can be observed that the area of the yellow line is constant larger than the area covered by the blue line. This means that the survival rate of the special individual under the yellow line experiment is greater than the survival rate of the special individual in the blue line experiment. This experiment shows that a particular individual with the “selfish gene” has the ability to escape from the predator and reduce its predation risk. The principle of selfish rules is that individuals move to predators and other similarities to reduce the risk of predation [24], so the experimental results are consistent with the selfish herd theory.

4.3.2 The existence of selfish rule for group

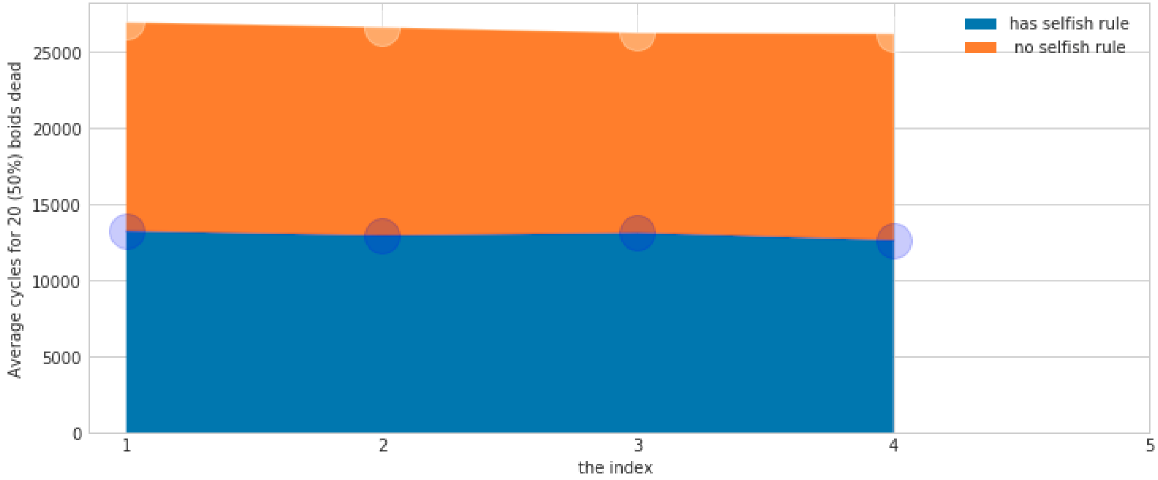


Figure 4.8 The effect of existence of selfish rule for group

This experiment demonstrates the impact of the selfish rules on the entire boids herding behaviour. Its principle is similar to the experimental principle represented by Figure 4.7. The X-axis is the number of experiments and the number of tests per experiment is approximately 300. The Y-axis represents the number of main function loops returned when 50 percent of the individuals in the boids population die. All individuals move in the experiment represented by the yellow line exercise under normal environment, while the blue line experiment adds extra selfish rules and all boids are set to follow the selfish rules.

The size of the area in the Figure represents the survival time of the group. It could be clearly observed that the blue area is small than the yellow area, which indicates that the whole boids group has a “worse” rate of survival when they are made to follow the selfish rules. Conversely, groups that do not follow selfish rules will survive for a relatively long time.

A reason to explain this phenomenon is that the aggregation of the boids group is indirectly created by selfish rules. In selfish rules, each boids move to the space that is between predator and others [24], which then causes the formation of aggregation in the boids world and the predator's predation interval is drastically shortened.

Since this experiment uses a single parameter of selfish strength (2.5), the results are somewhat random and unreliable, so it was decided to make the planning more detailed and repeat the experiments to gain more insights on the impact of selfish rules on the entire boids group (please check 4.3.3).

4.3.3 Selfish strength for group

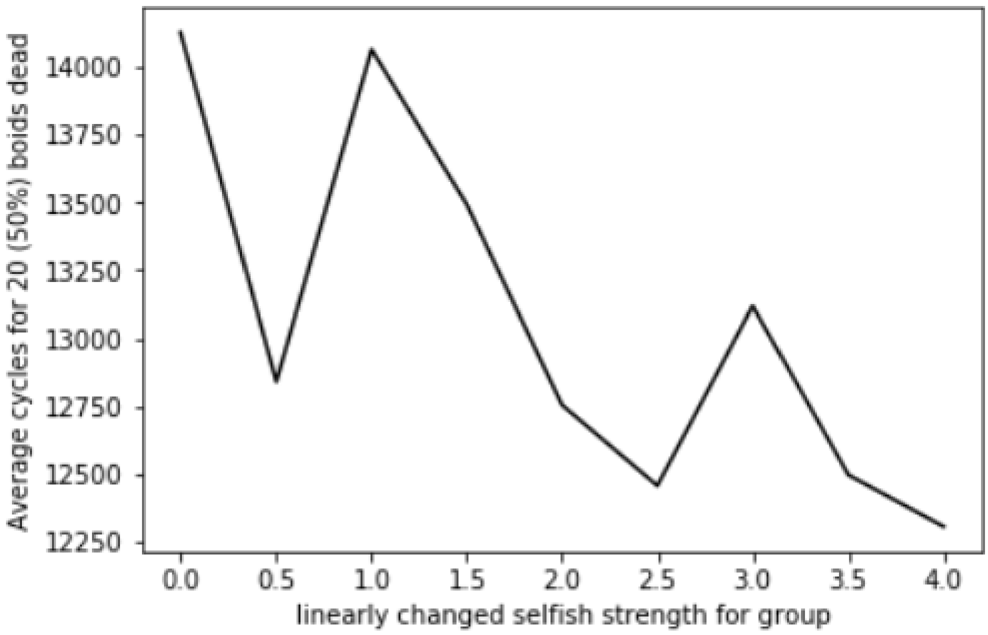


Figure 4.9 Effect of changed selfish strength for group

A repeated experiment was carried out on the boids population in another test mode due to the unreliability of the previous experiment. The X-axis in this test represent the selfish strength which has a linear increase, the environment and other parameters are the same as the ones used in the experiment presented in 4.3.2.

Figure 4.9 shows the results of this experiment. It can be observed that the overall survival time of 50% of boids (initializing 40 boids) showed a downward trend, which is consistent with the hypothesis proposed in the previous experiment. But the point X=1 and X= 3 are abnormal points. The survival time of the group decreased sharply and increased at X=1 and X=3 respectively. It also decreased steadily between X=1 and X=2.5 and after point X=3.

In order to prevent the contingency and randomness of the experimental results, it was decided to use the same program for parallel testing on different computers at different times. The error bars were also used to mark the pictures to show the range of fluctuations of each data point. The test results are as follows:

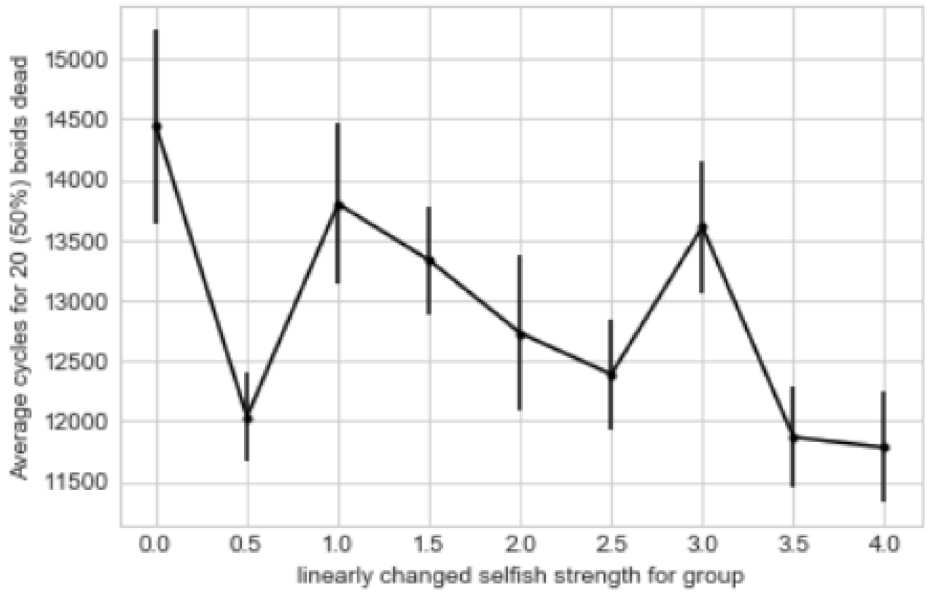


Figure 4.10 Parallel experiment with selfish rules

The result in Figure 4.10 is similar with the last one and the error bar is already applied in this result. In Figure 4.10, the average of cycle is still declining and there are no major changes in data, so we could infer that the selfish rule brings negative influence for the whole group.

4.3.4 Selfish strength for individuals

The influence of the selfish rule affect for the population has been tested and analysed, the focus of the research will now move towards testing for the individuals.

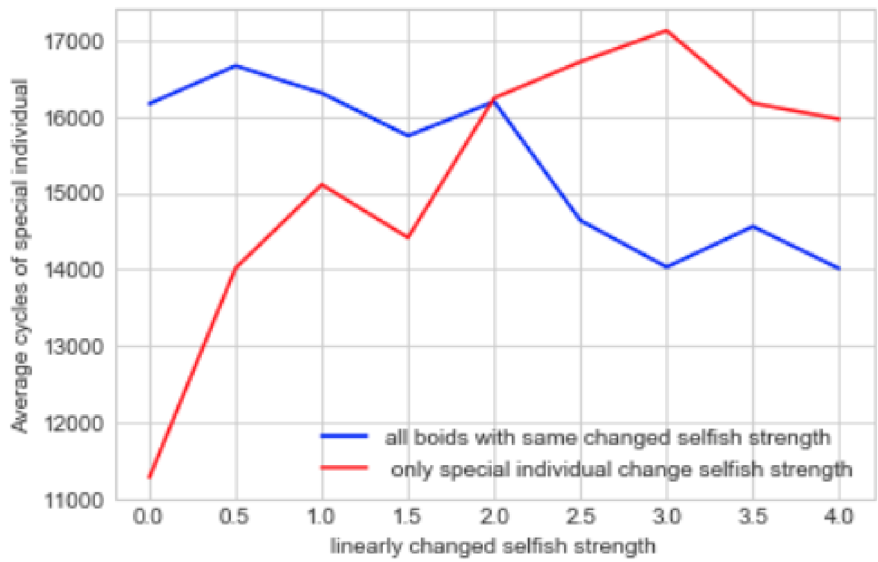


Figure 4.11 The effect of selfish strength for individuals

The Figure 4.11 shows the result of the changed selfish rule strength on individual boids. So, in this experiment, the special one needs to be marked out and the program would return the figure when it is dead. The X-axis is the strength of the selfish rule increasing linearly and the Y-axis represents the cycles times of the main loop function of when the special one is eaten. The selfish rule was applied to both experiments, but minor differences exist. The blue line is the experiment where all special individual and other boids have the same parameters and environment, the strength of the selfish rule is same. In the experiment indicated by red line, only the selfish rule applied on the marked individual follow the liner-change as shown on the X-axis whereas the strength of the selfish rule on all other boids are kept constant at 2. Other parameter such as cohesion rule and repulsion rule strength are the same in both experiments. The point X=2 is special in this test as it is the only cross point of the two lines in this Figure. It is worth noting that all points on the blue line are larger than those on the red line one before x = 2. However, the situation is reversed before point X=2 and all points on the blue line are smaller than the corresponding point on the red line.

It could be imagined that after point x=2, the special individual’s selfish strength on the red line is always greater than the special individual’s selfish strength at the corresponding point on the blue line. In other words, the individual with a higher level of the selfish gene relative to other conspecifics will live longer than them. So, it could be inferred that the selfish rule might be positive for individual but is not very “friendly” to the whole group as it causes aggregation within the group.

4.4 The effect of leadership for boids herding behaviour

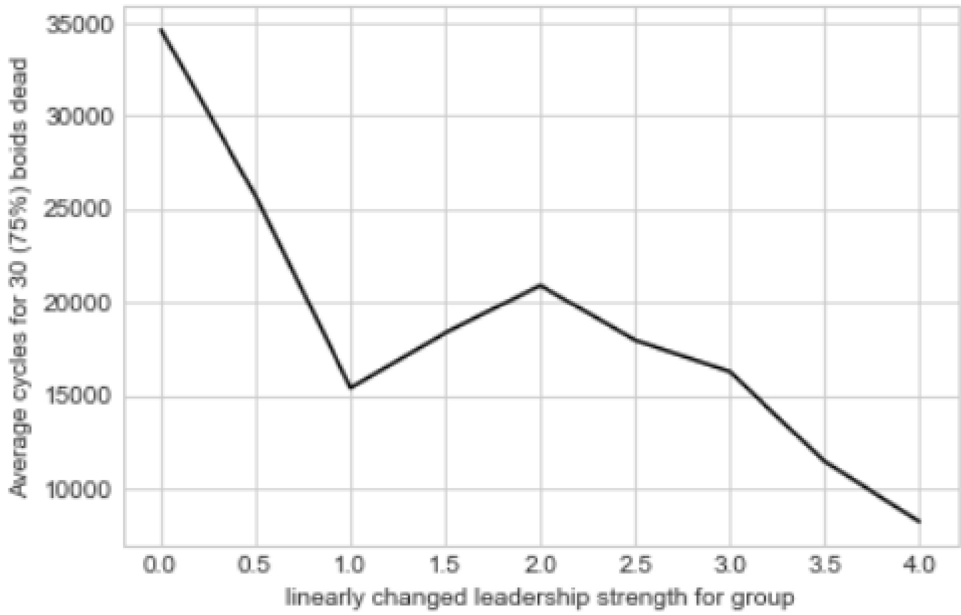


Figure 4.12 The effect of leadership for group herding behaviour

The final experiment is focused on the effect that leadership has on the boids. There will not be a separate test for individuals because the leader is the special one and it exhibits some “leadership” to lead the group.

As the mentioned in chapters 3, the leader is the boid who owns more information than others. In this experiment, the leader be defined as the boid who knows the location of the food. The X-axis show the strength of leadership changing linearly whereby others will be more attracted to the leader with the increase in strength. The Y-axis represent the cycle time when 75% boids be eaten by predator (talk about the function of leader food area).

The total value of survival time for 75% of the boids shows a downward trend in figure 4.12. It goes down at the first two points X = 0.5 and X = 1 and then rises back to 22113 cycles at the point X = 2, then continues to decrease in the rest of the 4 points.

The first decreasing trend might be due to that the existence of leader indirectly cause the aggregation in the boids worlds, which might increase predation risk of the whole group. However, as the leader is able to detect the approaching predator much earlier than others, this may be why the total survival time has increased between the points x = 1.0 and 2. Although this appears to be beneficial for the boids, excessive leadership strength still causes aggregation in the group leading to a lower overall survival rate (from 2.0 to 4.0). In other words, most individuals sacrifice part of their survival time to get to the food resources. It can be concluded that a strength of 0.2 strikes a perfect balance between obtaining food and avoiding predators.

Chapter 5
Evaluation

5.1 Achievements

1. The project has successfully tested the effects of the parameters of the cohesion rule on the boids schooling behaviour.
2. The project has successfully tested the effects of the parameters of the repulsion rule on the boids schooling behaviour.
3. The project has successfully implemented the selfish herd theory and tested the impact of selfish intensity on the boids schooling behaviour.
4. The project has successfully implemented leadership and tested the impact of the leadership strength on the boids group of schooling behaviour

5.2 Lessons learnt

5.2.1 Methodology

Agile development is great for this project because every small delivery goal is tested in a different environment. If there is a food resource in the environment when testing the selfish rule, it could potentially generate noise and interfere with the movement of the boids. The idea of agile development, meeting with the supervisor every week, getting feedback for this week and discussing the next step of the experiment was very beneficial for the implementation of the entire project.

5.2.2 Project Management

Most of the implementation steps are performed as originally planned. There is a slight delay in a small number of implementation phases. Looking back now, the knowledge background survey that was originally scheduled to be completed in a week actually took two weeks and resulted in more delays for subsequent tests.

5.2.3 Data testing

Error bars and parallel experiments can directly test the reliability of data that has not been learned before. Because some data is deceptive under test, thus, removing anomalous data tend to significantly improve accuracy.

5.3 Limitations

5.3.1 The abnormal data detection

In this project, due to the limitation of time, there was not enough time to use data strips to measure the reliability of data. Therefore, only error bars and parallel experiments were used. Other methods of detecting data reliability, such as a normal distribution, are also referred to as "Gaussian distribution." The mean μ can be calculated and variance σ of n points of a set of data. The mean and variance are defined as:

$$\mu = \sum_{i=1}^{n} x_i/n$$

$$\sigma^2 = \sum_{i=1}^{n} (x_i - \mu)^2/n$$

Under the assumption of a normal distribution, the region (μ±3σ) contains 99.7% of the data. If the mean μ of a value distance distribution exceeds 3σ, then this value can be simply marked as an outlier.

5.3.2 The design of selfish rule

There is a limitation in the principle of selfish rules: as shown in the figure, if both boid x and boids y are within the predator's predation range, then boids y will move towards the back of boid x: point EP, which is significantly shortened the distance between predator and itself. Although this situation is difficult under the predator repulsion rule, it still requires further improvements.

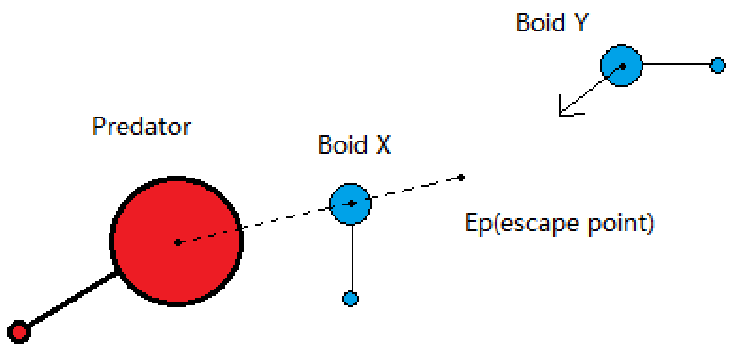


Figure 5.1 Special situation of selfish herd in program

The possible solution is to change the escape target of the boids. The escape target could be the nearest neighbours who are not in the predator's predation range.

5.3.3 Other limitations

As mentioned above, this program can only simulate the animal's herding behaviour in a two-dimensional space and cannot simulate animal movement in three dimensions. For example, fish in the sea may be subject to predation attacks from above or below. Another limitation is that the most of the experiments are based on initializing 40 individuals. If time is sufficient, there will choose more or fewer boids to explore the unknown possibilities of animal herding behaviour.

5.4 Future works

5.4.1 The view of the boids

The perceived range of boids is a circle in this experiment, which was not practical. In reality, fish and birds have their own field of vision. Suppose the angle of perceived range for each boids is θ, the scope of three basic rule is show as figure 5.2, R1, R2 and R3 represent the radius of action of the repulsion rule, the alignment rule and the cohesion rule respectively.

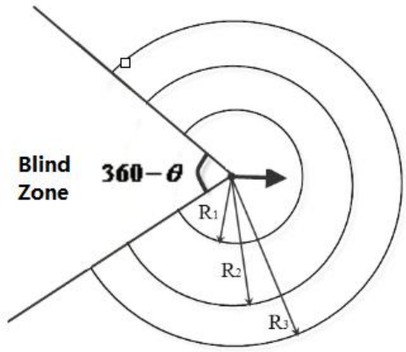


Figure 5.2 the blind zone for boids

5.4.2 The boundaries of boids word

In this series of experiments, there are no boundaries in boids world to limit them: they can move infinitely in the program, and some actual situations are bounded, so appropriate boundaries can be added to the program to get more accurate and reliable data. For example, a classic wall boundary that the boids will be forced to change direction when they run in the wall (like a rebounding ball).

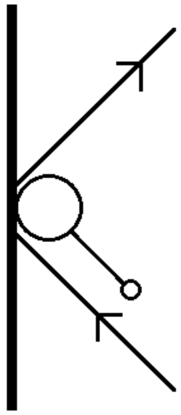


Figure 5.3 Boids will rebound when it hits the wall

5.4.3 The principle of cohesion rule

In Chapter 3, the principles and scope of the cohesion rule and the repulsion rule were introduced. With regards to the scope of cohesion, the cohesion rule could be re-designed into a new rule whereby the attraction strength would change with the distance from the surrounding neighbours.

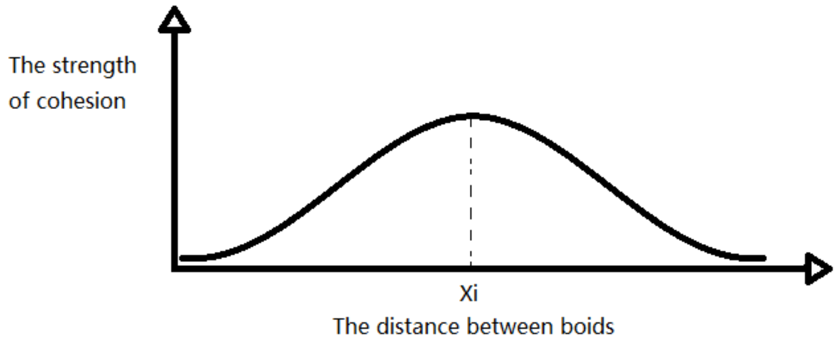


Figure 5.4 The new principle of cohesion rule

In figure 5.3, the value of Xi is the peak strength of cohesion rule. The advantage of this is that the individual does not change its direction of movement greatly due to the sudden attraction, which makes the overall change in movement is smoother and more holistic.

5.5 Reflection

Looking back, there are a lot of new things and learning methods that people could only learn through practical work. From the project plan step to the written of reflection now, I have benefitted a great deal from the final project.

This project was an excellent opportunity for readers and developers to get close to the field of bio-inspired computing. In this project, all boids belong to the same class of a real species of fish. In addition to studying the biological swarm behaviour, this project can also be used to study the migration of marine animals. Different classes can be constructed to represent marine animals of different races, each with different parametric variables, which simulate how they migrate under predation and predict real-world routes of migration.

The project was challenging and there were some difficulties to resolve. In the development phase, all the experiments experienced errors with completely random and irregular data. The supervisor reminded that it is necessary to make the boids a loose aggregation rather than a random dispersion at initialization in order to get clearer data than before.

As an overview, although it was challenging to develop initially, it was also an enjoyable process. The experience of writing long-form papers is also very helpful for future work.

List of References

[1]"Boids", En.wikipedia.org, 2018. [Online]. Available: https://en.wikipedia.org/wiki/Boids. [Accessed: 01- Sep- 2018].

[2]"Boids (Flocks, Herds, and Schools: a Distributed Behavioural Model)", Red3d.com, 2018. [Online]. Available: https://www.red3d.com/cwr/boids/. [Accessed: 01- Sep- 2018].

[3]]M. Charnell, "Individual-based modelling of ecological systems and social aggregations", Master of science, Univervsity of Victoria, 2018.

[4]"Domain of Danger Graphic.jpg", En.wikipedia.org, 2013. [Online]. Available: https://en.wikipedia.org/wiki/File:Domain_of_Danger_Graphic.jpg. [Accessed: 01- Sep- 2018].

[5]M. Dorigo and M. Birattari, "Swarm intelligence", 2007. .

[6]I. Eshel, E. Sansone and A. Shaked, "On the evolution of group-escape strategies of selfish prey", Theoretical Population Biology, vol. 80, no. 2, pp. 150-157, 2011.

[7]W. Hamilton, "Geometry for the selfish herd", Journal of Theoretical Biology, vol. 31, no. 2, pp. 295-311, 1971.

[8]R. James, P. Bennett and J. Krause, "Geometry for mutualistic and selfish herds: the limited domain of danger", Journal of Theoretical Biology, vol. 228, no. 1, pp. 107-113, 2004.

[9]J. Krause, "The relationship between foraging and shoal position in a mixed shoal of roach (Rutilus rutilus) and chub (Leuciscus cephalus): a field study", Oecologia, vol. 93, no. 3, pp. 356-359, 1993.

[10]J. Krause, "The effect of 'Schreckstoff' on the shoaling behaviour of the minnow: a test of Hamilton's selfish herd theory", Animal Behaviour, vol. 45, no. 5, pp. 1019-1024, 1993.

[11]J. Krause, D. Bumann and D. Todt, "Relationship between the position preference and nutritional state of individuals in schools of juvenile roach (Rutilus rutilus)", Behavioural Ecology and Sociobiology, vol. 30, no. 3-4, pp. 177-180, 1992.

[12]C. Leblond and S. Reebs, "Individual leadership and boldness in shoals of golden shiners (Notemigonus crysoleucas)", Behaviour, vol. 143, no. 10, pp. 1263-1280, 2006.

[13] Lewis, M. Anthony, and George A. Bekey. "The Behavioural Self-organization Of Nanorobots Using Local Rules." IROS. 1992.

[14]S. Lima, "Back to the basics of anti-predatory vigilance: the group-size effect", Animal Behaviour, vol. 49, no. 1, pp. 11-20, 1995.

[15]S. Martin, J. Vakula and L. Preucil, "warms of micro aerial vehicles stabilized under a visual relative localization", in IEEE International Conference on Robotics and Automation (ICRA), 2014.

[16]"Metric vs topological distance for animal aggregations.png", En.wikipedia.org, 2018. [Online]. Available:
https://en.wikipedia.org/wiki/File:Metric_vs_topological_distance_for_animal_aggregations.png. [Accessed: 01- Sep- 2018].

[17]M. MILINSKI and R. HELLER, "Influence of a predator on the optimal foraging behaviour of sticklebacks (Gasterosteus aculeatus L.)", Nature, vol. 275, no. 5681, pp. 642-644, 1978.

[18]L. Morrell, G. Ruxton and R. James, "Spatial positioning in the selfish herd", Behavioural Ecology, vol. 22, no. 1, pp. 16-22, 2010.

[19]D. Morse, "Feeding Behaviour and Predator Avoidance in Heterospecific Groups", BioScience, vol. 27, no. 5, pp. 332-339, 1977.

[20]"OpenStax CNX", Cnx.org, 2010. [Online]. Available:
https://cnx.org/contents/Cp8sC4k_@5.1:ETfm5re9@3/Schooling-in-Fish. [Accessed: 01- Sep- 2018].

[21]B. Partridge, T. Pitcher, J. Cullen and J. Wilson, "The three-dimensional structure of fish schools", Behavioural Ecology and Sociobiology, vol. 6, no. 4, pp. 277-288, 1980.

[22]T. Pitcher, A. Magurran and I. Winfield, "Fish in larger shoals find food faster", Behavioural Ecology and Sociobiology, vol. 10, no. 2, pp. 149-151, 1982.

[23]S. Reebs, "Can a minority of informed leaders determine the foraging movements of a fish shoal?", Animal Behaviour, vol. 59, no. 2, pp. 403-409, 2000.

[24]"Selfish herd theory", En.wikipedia.org, 2018. [Online]. Available:
https://en.wikipedia.org/wiki/Selfish_herd_theory#Evolution. [Accessed: 01- Sep- 2018].

[25]"Swarm behaviour", En.wikipedia.org, 2018. [Online]. Available:
https://en.wikipedia.org/wiki/Swarm_behaviour. [Accessed: 01- Sep- 2018].

[26]S. VISCIDO, M. MILLER and D. WETHEY, "The Dilemma of the Selfish Herd: The Search for a Realistic Movement Rule", Journal of Theoretical Biology, vol. 217, no. 2, pp. 183-194, 2002.

[27]S. VISCIDO, M. MILLER and D. WETHEY, "The Response of a Selfish Herd to an Attack from Outside the Group Perimeter", Journal of Theoretical Biology, vol. 208, no. 3, pp. 315-328, 2001.

[28]Z. Wang and H. Min, "Design and Analysis of Group Escape Behaviour for Distributed Autonomous Mobile Robots", in IEEE International Conference, Shanghai, 2011.

[29]A. Ward, J. Krause and D. Sumpter, "Quorum Decision-Making in Foraging Fish Shoals", PLoS ONE, vol. 7, no. 3, p. e32411, 2012.

Appendix A
External Materials

The original software platform develop by Dr Brandon Bennett: please check the link below (name: original schooling): https://github.com/yangm657/the-Code-part.git

Appendix B

Ethical Issues Addressed

This exploratory software is void of any ethical issue.

Appendix C

The modified code and raw data

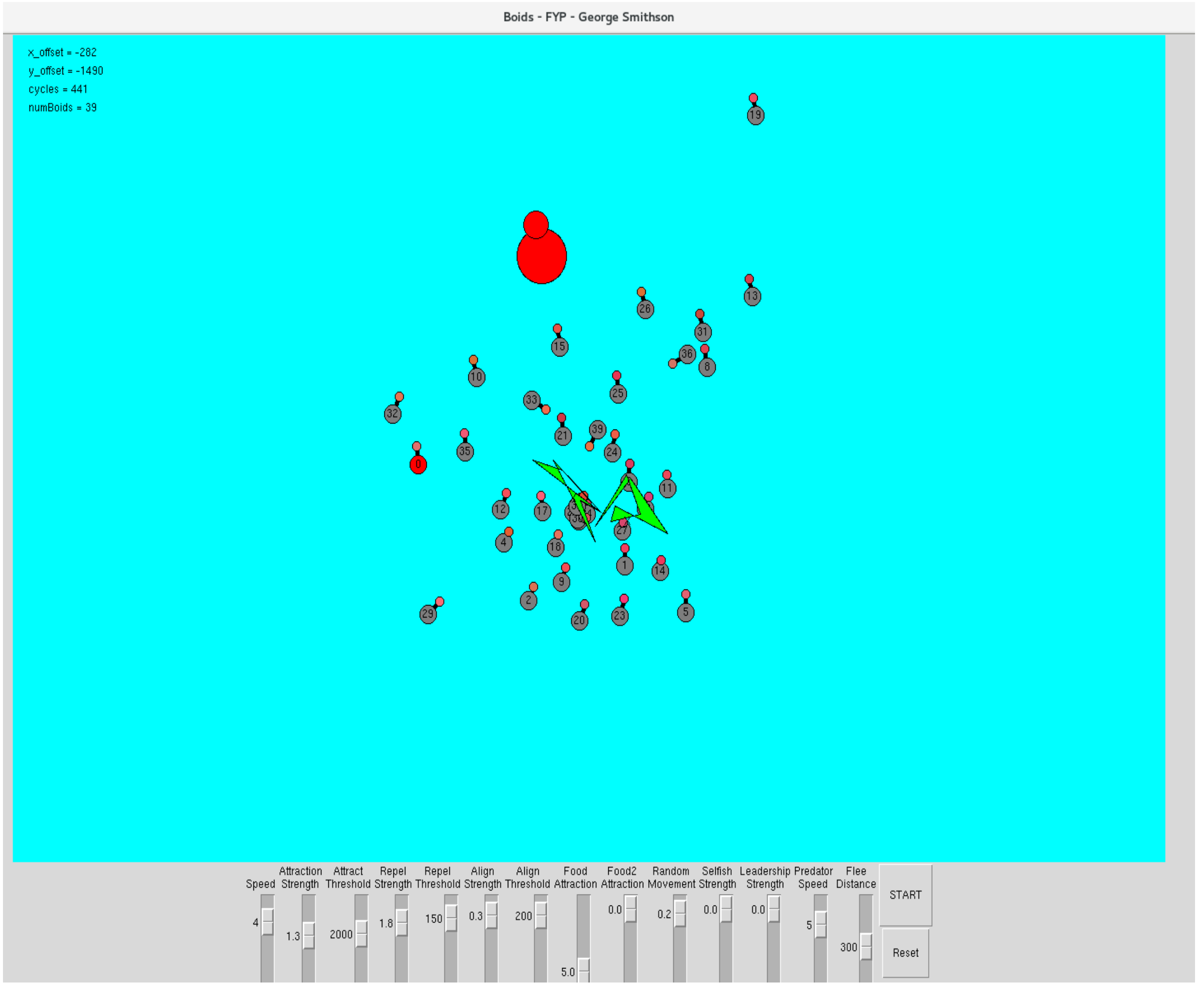
The link include:

1. The modified code: https://github.com/yangm657/the-Code-part.git
2. The raw data: https://github.com/yangm657/the-data.git#

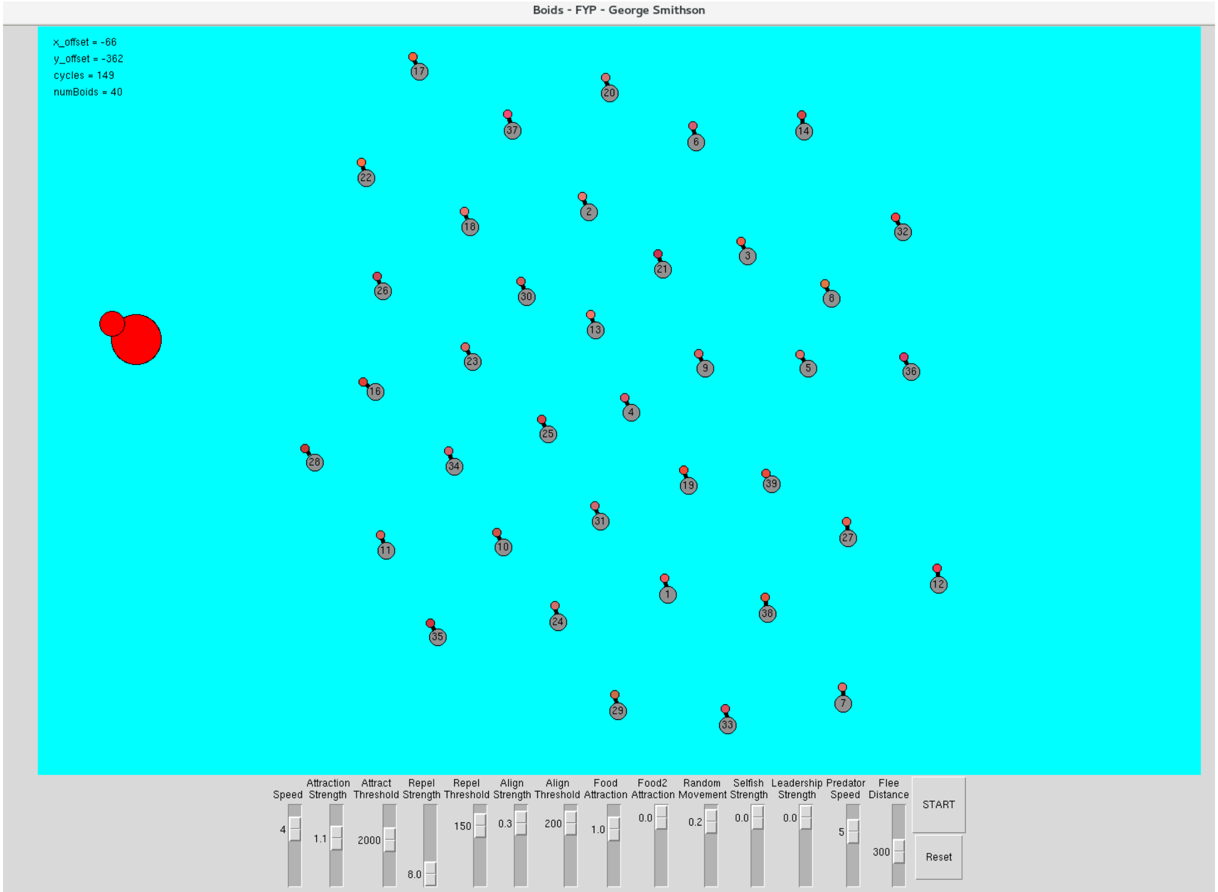
Appendix D

The screenshots of boids movement

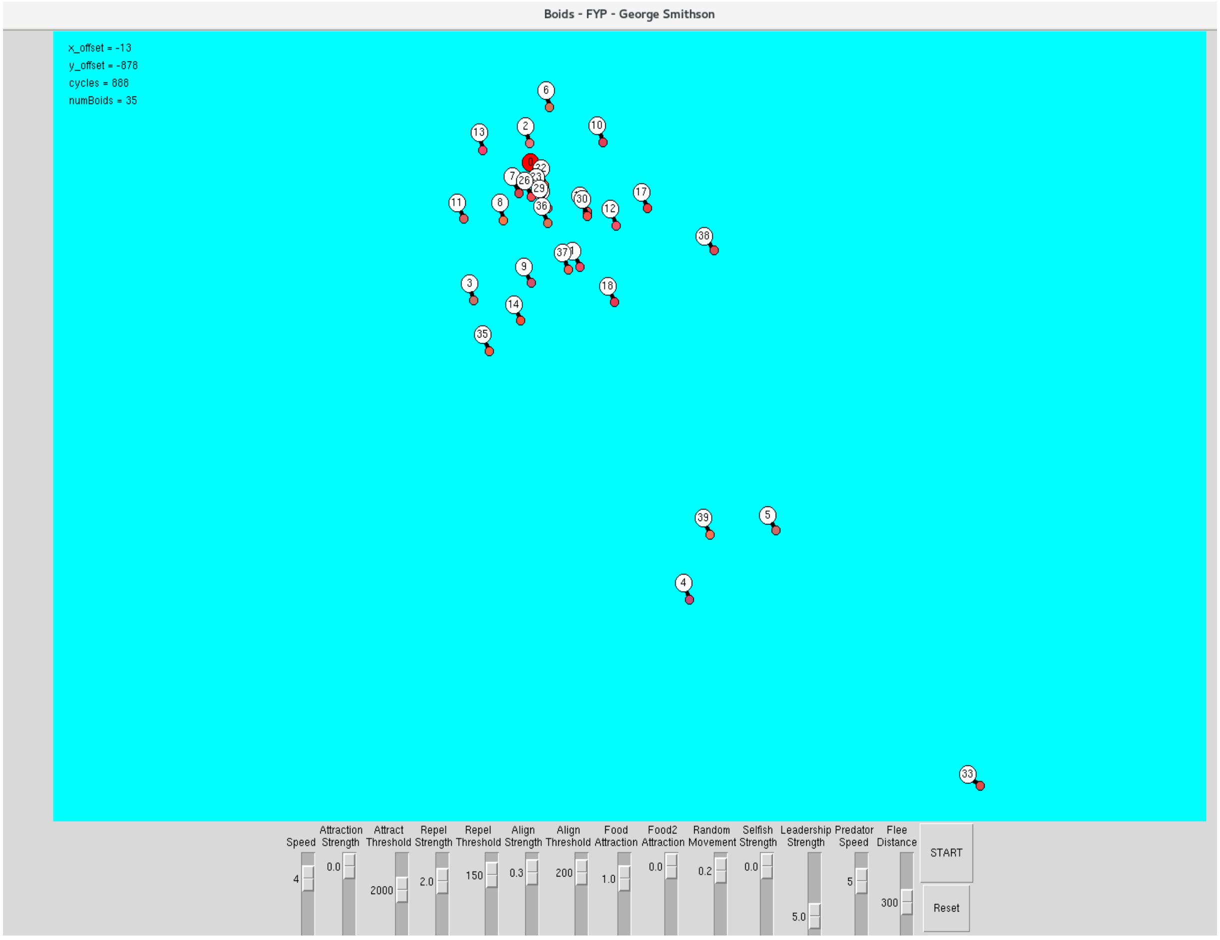
High level food attraction:



With high level repulsion strength:



With high level leadership strength (the red one is leader):



The boids escape from predatior under the high level selfish strength: