Supplementary Material

Accompanying Rands, SA (2012) Using physical and computer simulations of collective behaviour as an introduction to modelling concepts for applied biologists. *Bioscience Education*, Volume 19, DOI: 10.11120/beej.2012.19000005

Example of a worked practical modelling session (Activity 5)

Following are example problem sheets and an answer/discussion sheet used to discuss the starling example described in the main text. A *NetLogo* Java environment run within a standard web browser was used to implement the modelling component. Copies of the files used (running within *NetLogo* 4.0.4) are available from the author (sean.rands@bristol.ac.uk), but the default 'Flocking' model (Wilensky, 1998) that comes bundled within *NetLogo* can easily be altered for use. The following changes need to be made to the code in order to fit the following practical sheets:

1. The following parameters (and the sliders on the interface) were changed to make meaning and discussion easier within the class: '*population*' to '*population-size*'; '*vision*' to '*how-far-I-can-see*'; '*minimum-separation*' to '*minimum-safe-distance*'; '*max-align-turn*' to '*maximum-turn-for-alignment-with-group*'; '*max-cohere-turn*' to '*maximum-turn-towards-centre-of-group*'; and '*max-separate-turn*' to '*maximum-turn-to-avoid-collision*'.

2. As a means of discussing how metrics of behaviour could be extracted from the system, plotting windows were added to the interface that tracked the change in the mean heading of the group, and the standard deviation of the mean. Reasons why these two measures are taken are discussed below: the mean heading is obviously uninformative in this example, but would inevitably be the first metric chosen by many novice modellers.

3. In order to extract single metrics for a given set of parameters, reporter windows are also added to the interface that give the numerical value of mean and standard deviation of the agents' headings at a given moment in time, as well as a counter that records the number of timesteps elapsed. These are the figures that are recorded by the students on the worksheet.

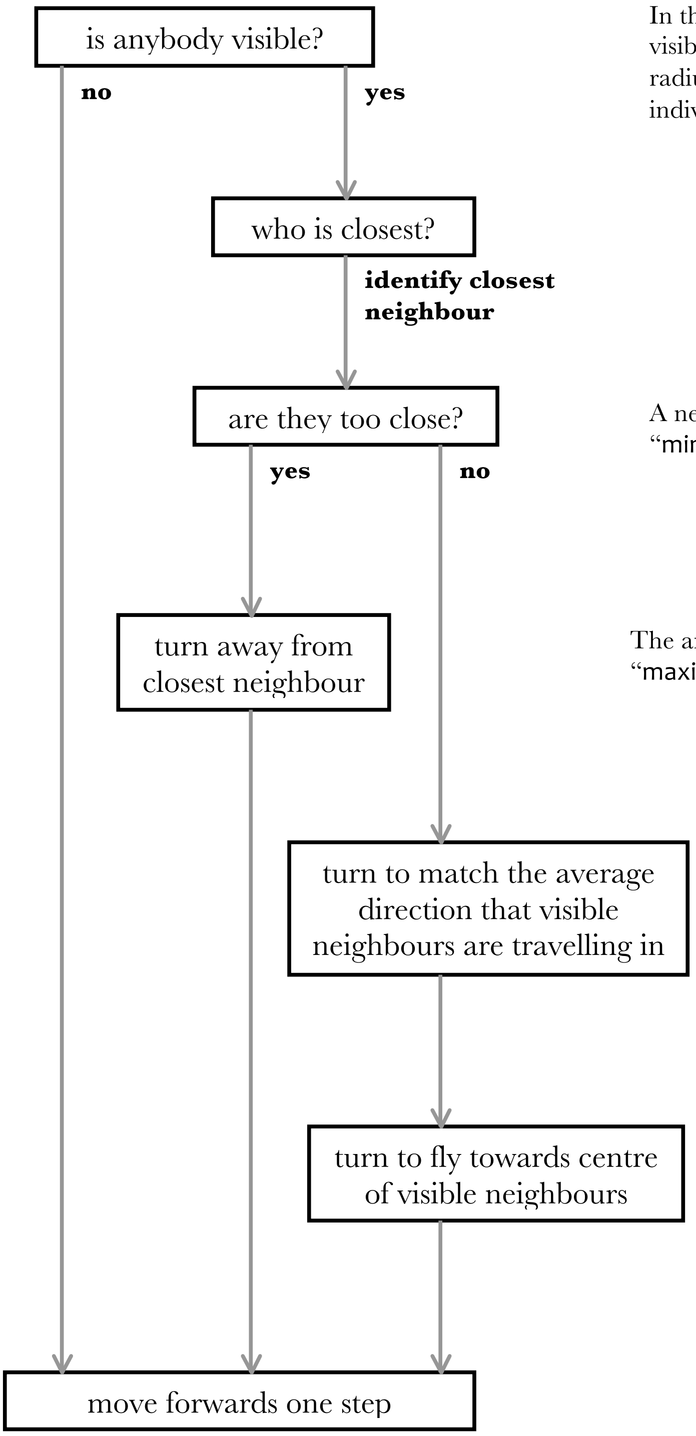
4. The environment used within the practical was a 61×61 torus.

Also note that the discussion sheet included is written specifically for a cohort of second-year students interested specifically in animal behaviour. Consequently, many of the finer theoretical details of the model are glossed over here: refer to the main text for published studies that have rigorously explored these rules.

Animal Behaviour Practical

Individual decision-making and flocking behaviour

The model we use in this practical uses the following rules for each of the individual animals within an environment. At each time-step, an animal does the following:



In the simulations, a neighbour is visible if it falls within the circle with radius "how-far-can-I-see" around the individual

A neighbour is too close if it is less than "minimum-safe-distance" units away

The animal can turn away by a maximum of "maximum-turn-to-avoid-collision" degrees

The animal can turn by a maximum of "maximum-turn-for-alignment-with-group" degrees, once it has calculated the average direction that all its visible neighbours are heading in

The animal can turn by a maximum of "maximum-turn-towards-centre-of-group" degrees, towards the central point of all its visible neighbours

COMPUTING EXERCISE 1

Exploring the effects of the distance over which animals can see

Make sure the sliders show the following settings:

population-size: 40
minimum-safe-distance: 2 metres

maximum-turn-for-alignment-with-group: 8 degrees
maximum-turn-towards-centre-of-group: 5 degrees
maximum-turn-to-avoid-collision: 2 degrees

Run the simulations for about 1000 time-steps for different values of how-far-I-can-see, and record the values of the averaged standard deviation of the headings (given in the box marked deviation). Repeat this ten times for each value of how-far-I-can-see. At the same time, watch how the behaviour of the flock changes.

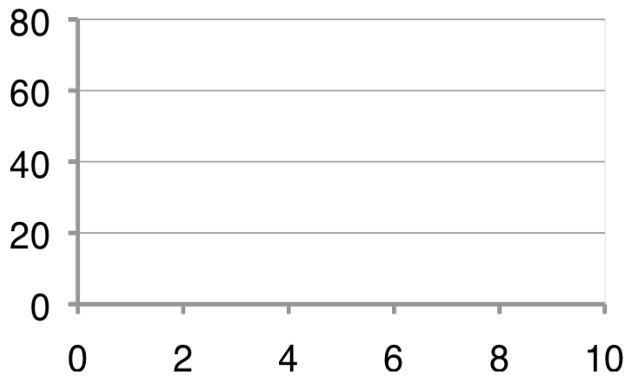
	value of how-far-I-can-see					
repetition	0	2	4	6	8	10
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
MEAN						

describe the flock behaviour for these values…

and for these values…

and for these values!

Use the graph below to sketch your results. (don't forget to label your axes)



What are the overall effects of changing the vision distance?

Could we have figured these out just by drawing the graph? Why?

COMPUTING EXERCISE 2

Exploring the effects of the safe distance between animals

Make sure the sliders show the following settings:

population-size: 40

how-far-can-I-see: 6 metres

maximum-turn-for-alignment-with-group: 8 degrees
maximum-turn-towards-centre-of-group: 5 degrees
maximum-turn-to-avoid-collision: 2 degrees

Run the simulations for about 1000 time-steps for different values of minimum-safe-distance, and record the values of the averaged standard deviation of the headings (given in the box marked deviation). Repeat this ten times for each value of minimum-safe-distance. At the same time, watch how the behaviour of the flock changes.

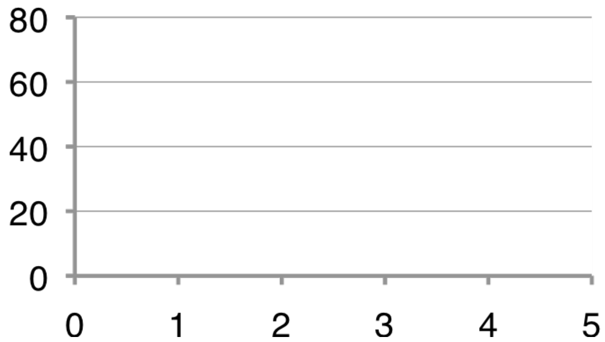
	value of minimum-safe-distance					
repetition	0	1	2	3	4	5
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
MEAN						

describe the flock behaviour for these values…

and for these values…

and for these values!

Use the graph below to sketch your results. (don't forget to label your axes)



What are the overall effects of changing the distance at which animals avoid each other?

Could we have figured these out just by drawing the graph? Why?

COMPUTING EXERCISE 3

Exploring the effects of turning distances

It's recommended that you start off with the sliders set at the following to begin with:

population-size: 40
minimum-safe-distance: 2 metres
how-far-can-I-see: 6 metres
maximum-turn-for-alignment-with-group: **5 degrees**
maximum-turn-towards-centre-of-group: 5 degrees
maximum-turn-to-avoid-collision: 2 degrees

a) Explore how the values of maximum-turn-for-alignment-with-group and maximum-turn-towards-centre-of-group affect the behaviour of the flock by playing with the sliders. How does the value of one parameter relative to the other change how the flock behaves?

b) The value of maximum-turn-to-avoid-collision also has an effect on the behaviour of the flock. What is this effect?

c) Does changing population-size have any effects on the behaviour of the flock?

d) Does taking the standard deviation of the flock's headings give us a good measurement of the behaviour of the flock? Is there anything else we should be measuring?

e) How could we make this model more realistic?

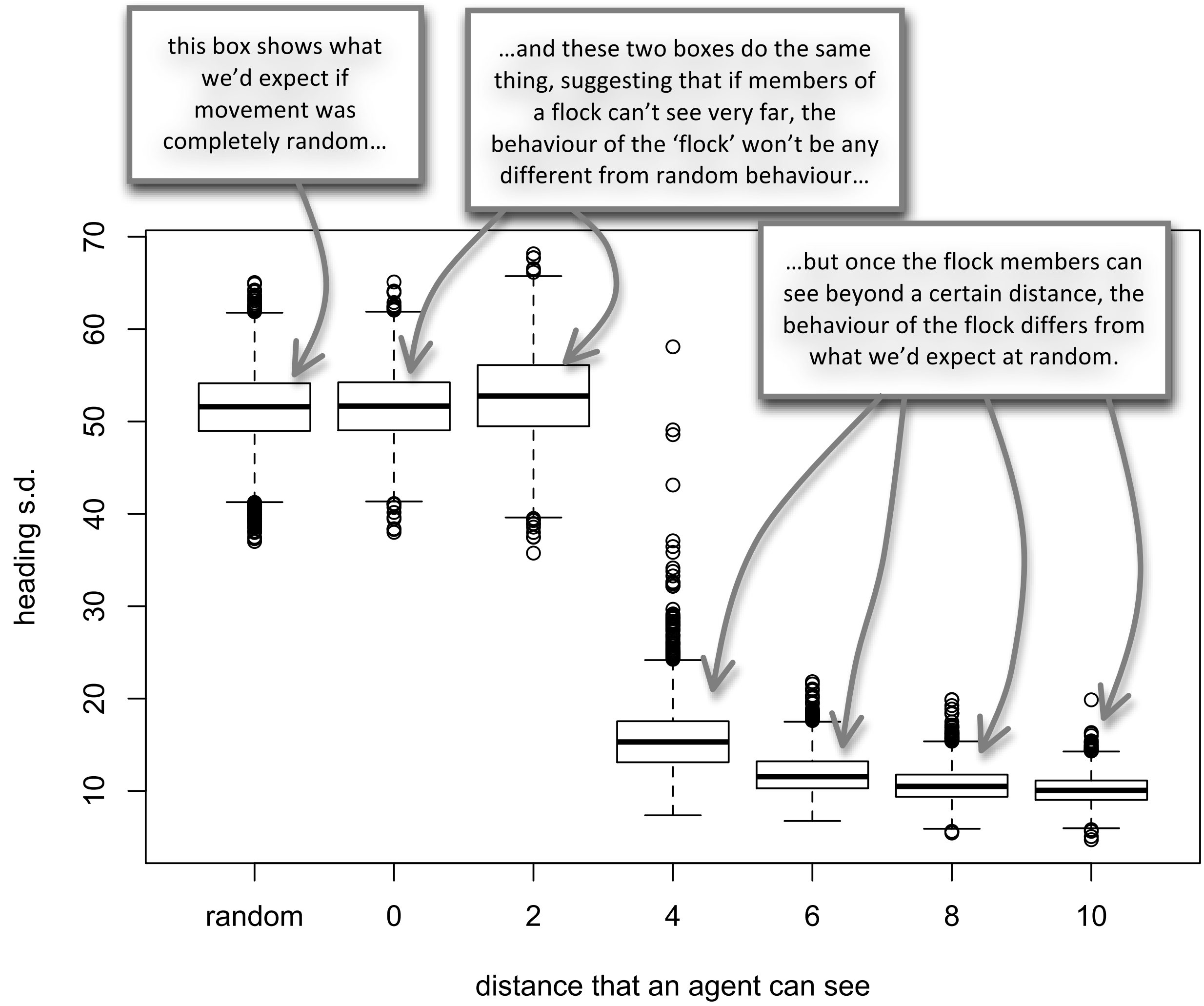
Animal Behaviour Practical

Individual decision-making and flocking behaviour

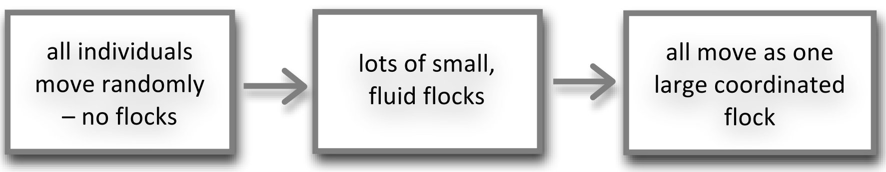
DISCUSSION SHEET FOR THE COMPUTING EXERCISES

Exercise 1
Exploring the effects of the distance over which animals can see

This Boxplot shows the standard deviation of the headings of a flock of agents, for differing values of the distance over which the agents can see (denoted '*how-far-can-I-see*' in the program). The left-most box gives the headings of a randomly distributed flock that has not been allowed to move or conduct any orientation behaviour. All boxes show the results of 2,500 simulations measured 1,000 time-steps into the simulation, except for the 'random' box which displays the results of 15,000 randomised distributions of agents. All parameters other than '*how-far-can-I-see*' were as given in the practical handout.



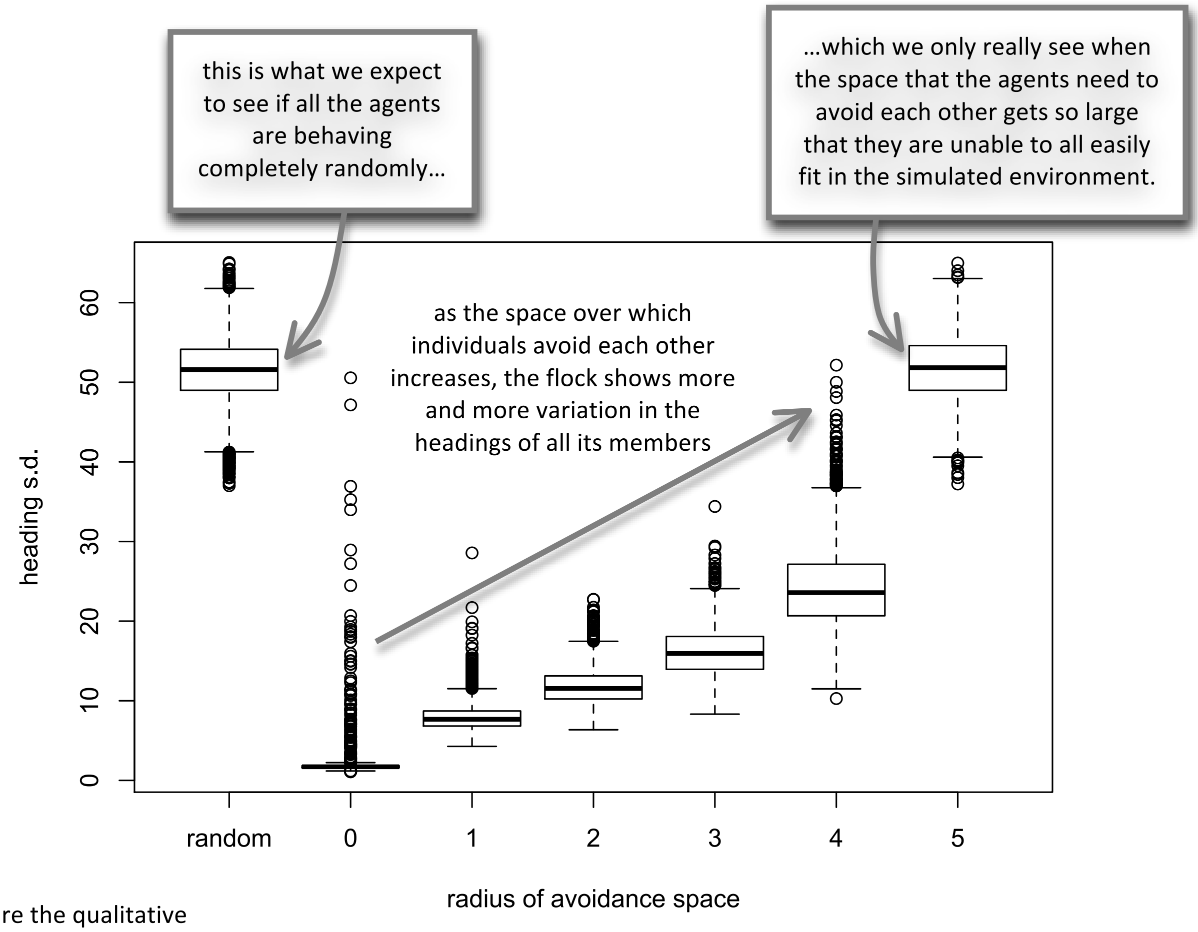
These are the qualitative changes in the behaviour of the group. These can only be seen when the simulations are observed – they can't be ascertained from just looking at the mean standard deviation of the headings:



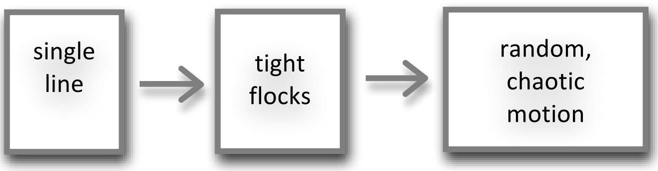
Exercise 2

Exploring the effects of the safe distance between animals

This Boxplot shows the standard deviation of the headings of a flock of agents, for differing values of the distance at which the agents start to avoid each other (denoted '*minimum-safe-distance*' in the program). The left-most box gives the headings of a randomly distributed flock that has not been allowed to conduct any orientation behaviour. Parameters are the same as for figure 1, except that '*how-far-can-I-see*' = 6.



These are the qualitative changes in the behaviour of the group. Again, these can only be seen when the simulations are observed – they can't be ascertained from just looking at the mean standard deviation of the headings:



Exercise 3

Exploring the effects of turning distances

a) Explore how the values of *maximum-turn-for-alignment-with-group* and *maximum-turn-towards-centre-of-group* affect the behaviour of the flock by playing with the sliders. How does the value of one parameter relative to the other change how the flock behaves?

If the group alignment value is set at zero, this means that all the members of the flock, when they aren't in danger of collision, will be trying to move towards the middle of groups of other flock members, which in turn means that no flocking behaviour is seen, and that the variation in heading directions is unlikely to be different from what we'd expect at random. If the group alignment value is increased, the behaviour of the individuals in the simulation changes from being random to showing a slight degree of alignment (it looks a bit like the movement of the bubbles in fiercely boiling water), through to small co-ordinated flocks when the alignment parameter is at about the same value as the 'move towards the centre' parameter. As the alignment parameter gets still bigger, all the individuals behave as one large, co-ordinated flock.

Now we should consider the parameter that defines the amount that an individual can turn to face towards the centre of a nearby group. Setting this parameter to zero means that the flock will behave as a co-ordinated single group, where all the individuals take the same heading. Increasing the value of this parameter to and beyond the value of the alignment parameter sees this degree of co-ordination break down – the group is still behaving as a single or several co-ordinated flocks, but all the individuals within those flocks are constantly changing direction, meaning that the overall direction of the flock becomes much more chaotic.

b) The value of *maximum-turn-to-avoid-collision* also has an effect on the behaviour of the flock. What is this effect?

This parameter has a large effect on the spacing behaviour of the individuals within a flock. When this value is large, the flock spreads out to fill the space in the simulated environment, and eventually the space needed to spread out and remain in a cohesive flock becomes much greater than the space available within the simulated space. At this point, the co-ordination of the flock breaks down.

c) Does changing *population-size* have any effects on the behaviour of the flock?

The size of the population has an effect upon the space available to all the individuals within the simulation. Increasing population size will ultimately mean that there isn't enough space for successful co-ordination, and the cohesion of the flock will break down.

d) Does taking the standard deviation of the flock's headings give us a good measurement of the behaviour of the flock? Is there anything else we should be measuring?

The reason we chose to measure the standard deviation of the flock's headings here was because we wanted a simple, easy measurement of what was happening in the flock that could be summarised with a single number. Simply considering the mean heading of the flock wasn't sufficient, for two reasons: firstly, from a practical perspective, it's limited between 0˚ and 359˚, and can easily flip between these two extreme values as the flock turns full circle; secondly, from an analytical perspective, the heading doesn't tell us much about the behaviour of the flock within the environment that we are using here, which is featureless and doesn't impede or otherwise affect any individual's behaviour at any point. Calculating the standard deviation instead means that we are able to assess the variation in the movement of the flock. If everybody is heading in the same direction, this value will be small. If everybody is heading in different directions, this value will be large (as is shown in the calculations given for the left-hand boxes in the two boxplots presented earlier).

However, we have also seen from observing the behaviour of the flock that just taking the standard deviation doesn't tell us much about what the flock looks like when it moves. Consider a hypothetical example where every individual in the flock was travelling in the same direction, and repeatedly conducted simultaneously turns through 90˚ to the left and then to the right. This would be obvious zig-zagging behaviour if we were to observe it, but if we were to look at the standard deviation of the headings, there wouldn't be any visible change because all the agents are doing the same thing at the same time.

Therefore, we would have to consider some other measure of the flock's behaviour to be able to characterise the actual movement of the flock. Statistics that gave some measure of the size of a group (how do we define a group?), the cohesion of individuals inside the group, and the moment-to-moment changes in the headings of group members may give us a way of characterising the collective behaviour, but we would probably still need to observe the behaviour in real time to be able to understand what exactly is going on!

e) How could we make this model more realistic? Why should we?

Adding realism into the model is useful if we are using the model to explore how flocks behave in the wild. Exactly what we add into the model depends on the exact questions we are trying to address: in practice, any good model is a fine balance between being too simple and too complicated, and so adding realism in for the sake of making things more complex alone isn't a good idea – the simpler the model, usually the easier it is to analyse what is occurring. You can probably come up with a host of different ways of making the model more realistic, but some ideas include:

- Changing the space that the agents move in – we could make it much larger (you will have noticed from your experimenting that space is a big constraint on the behaviour of the flock), or constrain it so that there are 'walls' that individuals 'bounce' off (like in the physical simulation we conducted), or objects in space that need to be avoided.
- Different individuals may have different abilities to change direction or move (*e.g.* in several species of bird, it has been shown that carrying a lot of weight means that you are less manœuvrable when you're flying), and so having individual differences in parameters might affect flock behaviour, as well as which individuals flock together.
- What happens if there is a leader, or at least an individual or set of individuals who are biased towards heading in a particular direction? Having biased individuals may have knock-on effects for the overall behaviour of the flock.
- What about predators? Can we introduce a rule that allows individuals to respond to a predator that is included in the simulation?
- Are the rules used a realistic description of what flocking animals actually do? Are there other rules that will produce similar collective behaviours? How simple are they?