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Hierarchical Relationships and Spatial Emergence Amongst Multi-Species Animats

K. A. Hawick and C. J. Scogings

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Prof Ken Hawick, Computer Science, Massey University, Albany, North Shore 102-904, Auckland, New Zealand.

Technical Report CSTN-045

Hierarchical Relationships and Spatial Emergence Amongst Multi-Species Animats

K.A. Hawick and C.J. Scogings
Computer Science, Institute of Information and Mathematical Sciences,
Massey University, North Shore 102-904, Auckland, New Zealand
{k.a.hawick,c.scogings}@massey.ac.nz, Tel: +64 9 414 0800 Fax: +64 9 441 8181

Abstract

Predator-Prey animats in a spatial model have been found to form battlefronts and other geometrical arrangements that allow the two species to coexist in a dynamic equilibrium. We explore the consequences of adding a third super-predatorial species and the hierarchical relationships and spatial patterns that emerge. We compare our microscopic model with the predictions of a hierarchical species realisation of the predator-prey partial differential equation model based on the Lotka-Volterra equations.

Keywords: multi-species; predator-prey; animat; spatial emergence; Lotka-Volterra.

1 Introduction

The tradition of using "animat" simulations to model emergent behaviour is now well known – see for example [1–4]. Our predator-prey model has been introduced and discussed in several previous publications, for example [5] and [6]. The model consists of two species of "animats" that interact to produce fascinating emergent formations. Figure 1 shows a typical situation after 3000 steps where the animats have formed into clusters and various patterns have emerged. The most interesting of these are the spiral formations discussed in [7]. Some spirals are clearly visible in Figure 1.

In this paper we depart from the traditional two-species animat model to explore the introduction of a new third species to the model. This is in keeping with our previous work in which we prefer to introduce small incremental changes and then study the effects that these changes have on the model. Although a third species could behave in a number of different ways, we have decided to simply build up the "food chain". Thus the newly introduced Species C will be a predator that eats Species B (the original predators) and Species B will continue to eat Species A (the original prey).

In order to keep things simple and be able to manage change in the system, we will stipulate that Species C and Species A ignore each other. Future work may well tackle the further interesting questions that immediately arise, such as "What happens if Species C eats both Species B and A?"

We discover that the introduction of a third species is not as simple as may initially be thought. The model tends to become rather fragile and numerous experiments are conducted in which animat populations crash and a sustainable simulation can not be achieved. Species control parameters have to be adjusted and, in particular, a suitable starting configuration must be found.

In this paper we present an overview of our original predator-prey model in section 2; a discussion of the importance of the starting configuration in the model in section 3; the introduction of the new third-species into the model in section 4; a comparison of the model behaviour with a bulk prediction of the 3-species Lotka-Volterra equations in section 5; and finally we offer some concluding ideas in 6.

2 The Original 2-species Model

The original model contains two species of animat – the prey (Species A) and the predators (Species B). Species B needs to eat Species A to survive and Species A needs to eat "grass" to survive. The early versions of the model did not require prey animats to eat anything and the concept of "grass" has been recently introduced in [8]. Grass also carries a specific "grass value" and when a prey animat eats the grass, its current health is increased by the grass value. This means that animats will do well on grass with a higher value and will struggle to survive on grass with a lower grass value – these results are discussed in [8]. Grass also has a useful side effect in that animats can not exist without it and so the population is limited to the grassy area and can not increase to the point where it becomes unmanageably large.

The simulations discussed here all take place on a large, square"grassed area" with a uniform grass value of 60. A value of 60 is above average and thus ensures that a short-

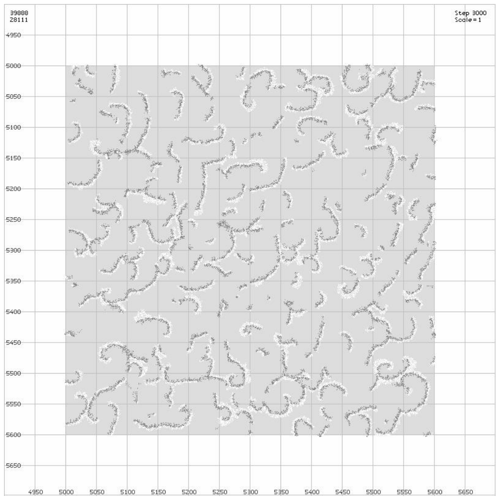

Figure 1: The situation at step 3000 for two species after starting from the random scattering shown in Figure 2 and passing through the decline shown in Figure 3. Species A (prey) are white and Species B (predators) are grey. The animats are situated on a square grassy area with a grass value of 60. Populations have now recovered and the usual emergent clustering is visible.

age of food will not affect the population changes recorded in these experiments. The grassed area (and the fact that the animats stay within the area) is clearly visible in the figures – see for example Figure 1.

Each species is allocated a set of control parameters as follows:
Species A:
max age = 20; max health = 100; birth rate = 40%
Species B:
max age = 50; max health = 200; birth rate = 15%

Each animat maintains a set of variables including current health, current age, location of neighbours and so on. In each time step, the current health is decreased and the current age is increased. If the health reaches zero the animat "starves" and if the age reaches the maximum age for that species the animat dies of old age. The current health can be increased by eating. Whenever an "eating" rule is successfully executed, the current health is increased but may never exceed the maximum health for that species. The birth rate is used whenever an animat attempts to execute the "breed" rule and provides the chance that a successful birth will occur. For example, if a Species A animat executes the "breed" rule there is a 40% chance that a new Species A animat will be produced. The birth rate is a convenient abstract way of simulating a host of factors such as birth complications, diseases, adequate shelter for young etc. In general, Species A animats (prey) breed more, do not live as long and are more prone to starvation than Species B animats (predators).

Every animat is also provided with a set of rules and in each time-step, each animat executes one of its rules. Every animat of a particular species has the same set of rules. In time, it will be possible to allow a genetic algorithm approach and allow the rules to mutate but the current model simply makes any new animat an exact clone of its parents.

The rule set for Species A animats (prey) is:

1. breed if health >30% and mate is adjacent
2. eat grass if health is <70%
3. move towards a Species A animat if health >30%
4. move away from a Species A animat if health <30%
5. move away from an adjacent Species B (predator)
6. move randomly to an adjacent position

Rule 3 is included in order to assist animats to find potential mates (of the same species) and Rule 4 is included to reduce overcrowding. If animats are too densely packed they are not able to eat and need to move apart before being able to feed again.

The rule set for Species B animats (predators) is:

1. breed if health >50% and mate is adjacent
2. eat Species A animat if health is <50%
3. move towards a Species B animat if health >50%
4. move towards a Species A animat if health <50%
5. move randomly to an adjacent position

The order of each rule set is very important. Every time step, each animat attempts to execute Rule 1. However, most rules have conditions such as "if health >50%", so it is quite possible that Rule 1 can not be executed. If this is the case, the animat attempts to execute Rule 2 and so on. Thus each animat works through the rule set and stops as soon as one rule has been executed. The rule set is therefore a priority list. We have experimented with changing the priority of the rules within the rule set and have determined that the rule sets listed above are the most effective [9].

3 The 2-species Starting Configuration

The size of the animat population depends greatly upon the starting configuration. This is because it is very easy to select a starting configuration that bears no resemblance to the way the animats normally behave during a simulation. If the animats are placed in a completely false situation, there is a very real possibility that the population will not be able to survive. Thus a badly selected starting configuration can lead to a rapid population decline and the end of any useful simulation. For example, in a standard simulation with two species, a random starting configuration was used as illustrated in Figure 2.

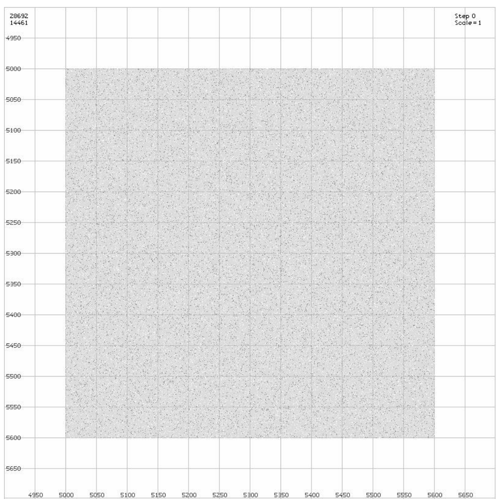

Figure 2: A starting configuration for two species using random scattering. Species A (prey) are white and Species B (predators) are grey. This starting configuration is not ideal and causes a substantial drop in population early on in the simulation.

Random scattering does not provide a suitable starting configuration and, after an initial spike, the populations of both species rapidly decline and narrowly avoid complete extinction. However, a few isolated groups of animats manage to reform themselves into the spiral formations that have been observed in [7]. This situation is shown in Figure 3.

The emergence of the first few spiral formations enables the populations to stabilize and then expand as shown in Figure 1. The population changes during this simulation are shown in Figure 4. Once a stable population is achieved, this configuration could be used as the starting configuration for future simulations. This means that future simulations would begin with a stable population that can form the basis for experiments in changing various control variables or, in this case, the introduction of a new third species.

4 The New 3-species Model

We introduced a third species (Species C) into the model, thereby creating a “food chain” in which Species C needs to

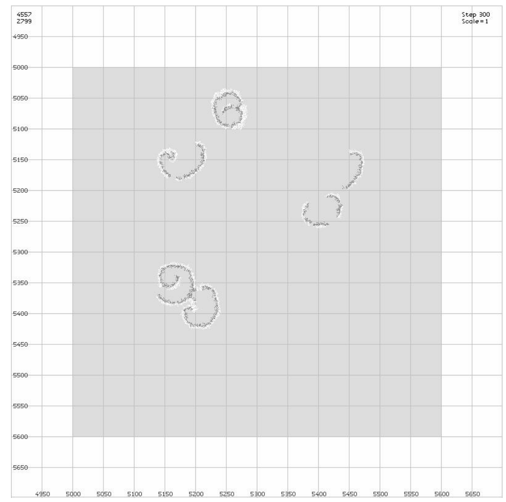

Figure 3: The situation for two species at step 300 after starting from the random scattering in Figure 2. Species A (prey) are white and Species B (predators) are grey. Both populations have declined dramatically but a few of the typical spiral formations are starting to emerge.

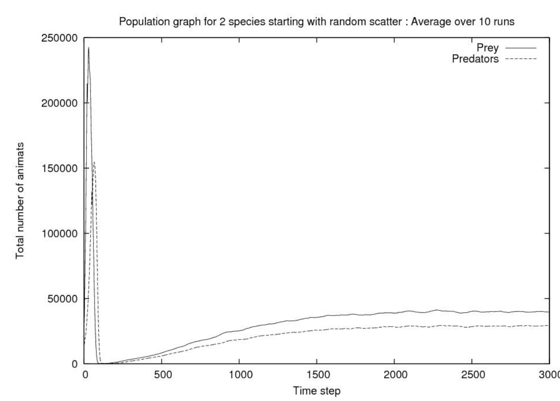

Figure 4: This population graph for two species shows the effect of a starting configuration based on random scattering. Populations dropped very quickly to extremely low levels before becoming stable.

eat Species B to survive, Species B needs to eat Species A to survive and Species A eats "grass". Note that Species C and Species A simply ignore each other.

The biggest problem posed by the introduction of a third species was the starting configuration. As shown by the two-species example discussed above, the starting configuration is crucial to the successful outcome of a simulation. The results from the two-species experiments showed that the best starting configuration is one which includes typical animat formations that emerge during a simulation. In the case of three species, these formations were initially unknown. Thus any selected starting configuration would run the risk of causing population decline and an unsustainable model.

A large number of starting configurations were selected and each caused a catastrophic decline in populations leading to the extinction of one or more of the three species very early on in the simulation. After much trial and error, the simulation was able to produce stable populations of three species. This starting configuration used a typical frame from a previous two-species simulation and then distributed the animats of the third species across a central square area – see Figure 5. This configuration was not entirely suitable and caused the usual population decline but extinction was avoided and the populations were able to stabilize.

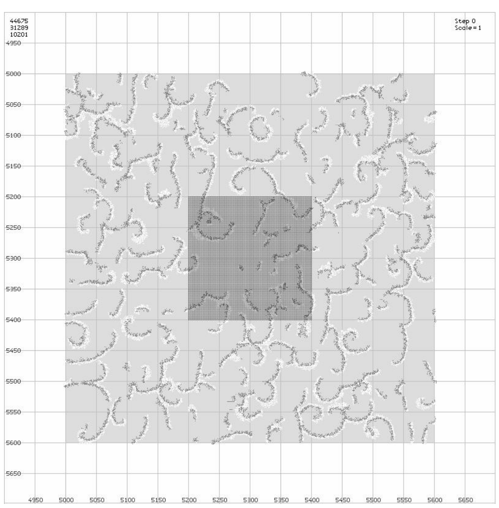

Figure 5: This figure shows the initial situation for three species. A frame from a previous run has been used as the starting position for Species A (white) and B (grey). Typical behaviour for the new Species C is unknown at this stage so animats of Species C (black) are distributed evenly across a central area.

The control parameters for Species C (such as maximum health, maximum age, etc) were initially copied from Species B. However, experimentation showed that the parameters for all three species needed to be adjusted as follows: (previous settings are shown in parentheses)

Species A:
max age = 20; max health = 100; birth rate = 30% (40%)
Species B:
max age = 50; max health = 200; birth rate = 30% (15%)
Species C:
max age = 60 (50); max health = 200; birth rate = 10% (15%)

The birth rate for Species B was increased from 15% to 30%. This is because Species B is now under pressure from Species C (previously it had no predators) and can not survive without an increased birth rate. Since Species A is now under less pressure from Species B, the birth rate for Species A was reduced from 40% to 30%. Finally, the parameters for Species C had to be adjusted to prevent the destruction of Species B and this was achieved by changing the maximum age for Species C from 50 to 60 and reducing the birth rate from 15% to 10%. Thus we retain the general rule that animats that are higher up the "food chain" live longer and breed less.

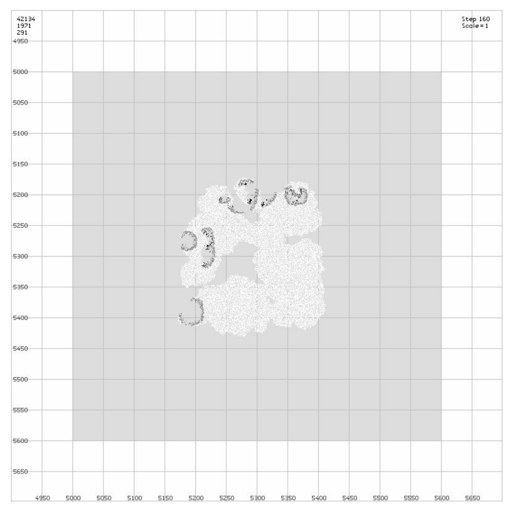

Figure 6: This figure shows the situation for three species at step 160. Species A is white, Species B is grey and the new Species C is black. There has been a rapid population decline in both Species B and C but this has now ended and the populations are starting to recover. Typical animat formations are emerging in areas in which only the original two species (A and B) are present. However, in areas in which the new species C is present, completely new macro-behaviours are emerging.

The rule set for the new Species C animats mimicked that for the original Species B predators as follows:

1. breed if health >50% and mate is adjacent
2. eat Species B animat if health is <50%
3. move towards a Species C animat if health >50%
4. move towards a Species B animat if health <50%

5. move randomly to an adjacent position

The following extra rule was inserted into the rule set for Species B animats:

5. move away from an adjacent Species C (predator)

Because the starting configuration did not accurately reflect the final positions of the three species, the simulation started with a population decline. Fortunately this decline was arrested when a few groups of each species managed to create animat clusters. The situation at step 160 is shown in Figure 6.

Once stable populations had been achieved for all three species, it was noted that the emergent animat formations were quite different from those of the two-species model. A typical situation at step 3000 is shown in Figure 7.

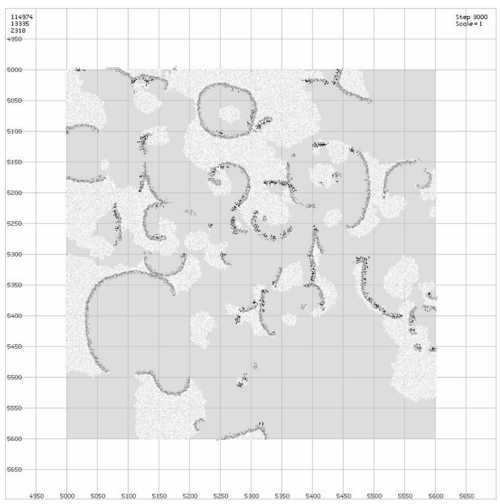

Figure 7: This figure shows the situation for three species at step 3000. Species A is white, Species B is grey and the new Species C is black. The three populations are now stable but the emergent animat formations are quite different from those of the two-species model shown in Figure 1.

The graphs representing the three populations during the simulation are shown in Figure 8. After the initial population decline, the populations for all three species stabilize. The experiment was conducted ten times, each time with a different random number seed. The populations shown in Figure 8 are averages over the ten runs.

5 3-Species Lotka-Volterra Equations

Our microscopic model can usefully be compared with the Lotka-Volterra predator-prey model [10, 11]. Let $R(t)$ be the

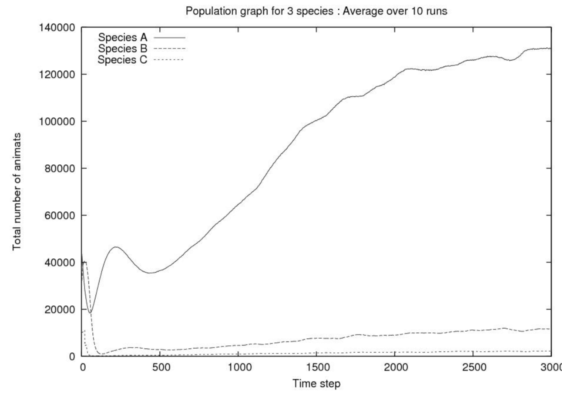

Figure 8: Graph showing the populations of the three species during the simulation. Due to an inaccurate starting configuration, there is an early dramatic decline in the populations of Species B and C but then the populations recover and stabilize.

number of prey ("rabbits") at time t and $F(t)$ the number of predators ("foxes"). The uncoupled equations for predators and prey in a non-interacting world are then:

$$\frac{dR}{dt} = |a|R \tag{1}$$

$$\frac{dF}{dt} = -|g|F \tag{2}$$

so that unmolested by predators, the prey grow exponentially in number, and the predators starve through lack of prey and die off exponentially. The two controlling rate constants are positive numbers shown by the absolute value symbols in equations 1 and 2. We drop this hereafter, and assume $a >= 0, g >= 0$. It is of course interesting to consider what happens when the two populations do interact, and ignoring spatial distribution effects, we model this through a coupling term assumed to be proportional to the product RF which is related to the probability of a predator-prey encounter. We then obtain:

$$\frac{dR}{dt} = aR - bRF \tag{3}$$

$$\frac{dF}{dt} = hRF - mR \tag{4}$$

In fact we can extend these equations to incorporate a third species ("wolves"), that eat both rabbits **and** foxes so that:

$$\frac{dR}{dt} = aR - bRF - cRW \tag{5}$$

$$\frac{dF}{dt} = hRF - gF \tag{6}$$

$$\frac{dW}{dt} = xRW - yW \tag{7}$$

We now have some extra parameters x, y to adjust. These will depend upon the frequency or probability of encounter between our species in the spatial model. It is a matter of future work to incorporate the spatial diffusion properly, but we can investigate some simple bulk behaviour for the 3-species system once it is roughly equilibrated.

Solving this equation numerically, one can obtain equilibrium periodic solutions ($a = 2; b = c = g = h = x = 1; y = 1.1$) where the rabbit population reaches a high mean value with boom-bust periodic oscillations superposed on it. The fox population attains a lower mean oscillating value that lags behind the rabbit booms and a wolf population of even lower mean value that lags behind both rabbit and fox booms.

For comparisons with our spatial animat model and simplicity we can set $c \equiv 0$ so that wolves do not eat rabbits directly but do eat foxes (which eat rabbits). This does not change the stable solution found qualitatively, only the periodic length of the boom-bust cycles.

Our spatial model does indeed show this **average** effect after some long term spatial fluctuations. It remains to link the equation parameters to the microscopic properties of our animat model, using diffusion constants.

6 Discussion and Conclusions

We have described our introduction of a third species into a spatial animat model. The model can attain a bulk equilibrium in the sense that all three species can survive at appropriate mean population levels. There will be the usual superposed boom-bust periodic cycles with appropriate lag time delays up the feeding chain.

The starting configuration requires more fine tuning than we have encountered with our 2-species model This is simply because the top predator species exists in quite a precarious position in the model system. While we have found our 2-species systems relatively forgiving in that local fluctuations of prey diminish the predators but they can typically recover as animats drift in from other spatial regions.

In the three-species model the animats arrange themselves in a very interesting spatial pattern. Rabbits generally form arbitrary clumps with a spatial dimension close to that of the embedding space - nearly two dimensional. Strictly speaking if measured this dimensions would be some fractal value between 1 and 2. Foxes tend to form spatial structures that are line-like or have spatial dimension of one less than that of the rabbits' structures. The third and top predator tends to form almost point-like zero-dimensional structures at the tail end of the fox fronts.

It appears therefore that the spatial model can really only support three species in this hierarchy. It is interesting to speculate whether these hypotheses about the dimensionalities would scale up to an embedding dimensionality of three. Furthermore, would it then be feasible to introduce a fourth species that could be supported in a similar spatial hierarchy?

These observations seem consistent with observed natural populations of top predators such as tigers or polar bears. They need a large territory and are spatially sparse and are therefore very susceptible to changes down the food chain.

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