Ecosystem stability: predator and prey simulation

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Abstract

This study explores the intricate predator-prey dynamics pivotal to ecosystem stability. We simulated an artificial ecosystem and focused on identifying and adjusting key factors to establish a self-sustaining, stable system. Our findings highlight the vital role of predator-prey interactions in maintaining ecological balance, providing insights for future studies in both artificial and natural ecosystems.

1 Introduction

Understanding the dynamics of predator-prey relationships is a fundamental aspect of studying ecosystems, given their crucial role in maintaining ecological balance. These interactions, which are central to the concept of ecosystem stability, provide valuable insights into the complex interplay of natural life. Simulating these interactions within a computer simulation, however, presents considerable challenges due to the multitude of factors that must be taken into account.

This study seeks to address this issue within the broader field of collective dynamics, a key area in artificial intelligence and computer science. Collective dynamics investigates how individual agents, when interacting in diverse environments, can collectively solve complex tasks or simulate behaviors that cannot be predicted from the study of individual elements alone.

In this context, we attempt to simulate the predator-prey dynamic. By applying the principles of the Lotka–Volterra model (Beals M., et al. 1999), we created an initial simulation and progressively incorporated additional adaptations related to movement and environment. Our goal was to understand which factors influence the simulation and how they can be tweaked to establish a stable ecosystem—a system capable of sustaining itself over time.

In the following sections, we provide a detailed overview of our research setup and methodology, discuss the modifications we applied to the simulation, and present the results of our investigations. Through this exploration, we aim to deepen our understanding of predator-prey dynamics and their pivotal role in promoting ecosystem stability. The focus research question for this study is '*How can ecosystem stability be improved in a predator-prey simulation?*'.

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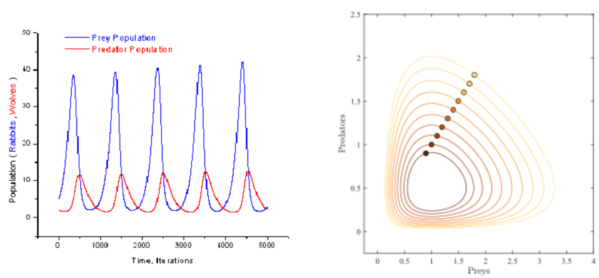
2 Methodology

2.1 Measuring ecosystem stability

The **Lotka-Volterra** equations are integral to the understanding of ecosystem stability in predator-prey simulations. This mathematical model provides valuable insights into the complex dynamics of species interactions by quantifying the cyclic relationships that exist between predators and their prey. The system of differential equations captures key biological assumptions: prey population grows exponentially in the absence of predators, and predator population decreases without prey. Moreover, the model highlights the idea of equilibrium in nature, showcasing how predator and prey populations can oscillify around a mean value, contributing to overall ecosystem stability. However, these equations are inherently simplistic and in practice there is too much stochastic variation in the environment to model this with simple agent behaviour. These equations will act as model results in the experiment.

Stability in an ecosystem is when all species survive over a certain period. We can visualize this through phase-plane plots, which graphically depict the sizes of predator and prey populations over time. Stability is indicated by a cyclical pattern in these plots, showing the natural ups and downs of species populations.

Phase plane plots are graphical representations and are instrumental in understanding stability. In an ideally stable system, the phase-plane plots will show a perfectly cyclic pattern. This means the predator and prey populations not only oscillate, but also return to their starting points after each cycle, demonstrating resilience.



(a) Population over time. (b) Phase-plane plot.

Figure 1: Lotka-Volterra model graphs.

2.2 Hypothesis and plan

The central hypothesis of our study is that integrating more complex behaviors into predators and prey in a predator-prey simulation will enhance the ecosystem's stability. This balance may be achieved by providing prey with the benefit of safety in numbers and improving the individual hunting capabilities of predators.

To demonstrate this, we will undertake the following methodological steps:

- Introduce adaptations to both predators and prey, and analyze areas of imbalance.
- Following identification of such imbalances, iteratively introduce new features to attain consistent cyclic results.
- Predator adaptations should improve strength of individuals, while prey adaptations should improve the strength of prey in groups.

2.3 Agent adaptations

2.3.1 Base case

In the base case simulation, a simplified model was used, grounding it on the principles derived from the Lotka-Volterra equations. Both predator and prey agents were programmed with certain probabilities of death and reproduction respectively; and moreover had limits to increase in population per unit time. While these probabilities were inspired by the Lotka-Volterra model, the resulting interactions in the simulation generated a stochastic environment, introducing an additional layer of complexity that echoes the uncertainties found in the real world. For instance, the encounter between a predator and prey was not a guaranteed event, but instead, dictated by a probability that reflected various influencing factors such as location, timing, and environmental conditions. This aspect of the model added a level of realism, acknowledging that in nature, these encounters are not deterministic but are subject to various uncertainties. Furthermore, the base case incorporated a 'cooldown' period for predators, during which they were unable to consume prey continuously. This feature was designed to simulate digestion and rest periods, as observed in actual predators. For a visualization of the predator prey behaviour in the base case, refer to figure number 1, in section 7

2.3.2 Adaptation 1 : predator energy levels

Following the base case, the first adaptation involved endowing predators with an energy level attribute. Each predator was initialized with a set energy level, which would progressively deplete over time, leading to the predator's death upon exhaustion. To circumvent this, predators needed to consume prey to replenish their energy. Future enhancements could potentially include variable speed and reproduction rates for predators and prey based on energy levels. Refer to figure 6 in section 7 for a visual representation of the energy adaptation.

2.3.3 Adaptation 2 : huddling v1

For the next characteristic we wanted to model a huddling behaviour which can be observed in nature. Among other advantages, it acts as a defense mechanism against predators, as the sheer number of preys getting together fends them off. The initial version entailed that if there are 3 or more prey huddled together they cant die. Later on this was changed to a probability, based on the number of prey huddling. For a visualization of the predator and prey behaviour in the initial huddling adaptation, refer to figure number 7, in section 7

2.3.4 Adaptation 3 : huddling v2

In the following version of huddling we wanted to introduce some complexity into the mechanism. On the prey side, based on n, which is the number of neighbours of other prey, they would suffer a decrease in velocity: $velocity = velocity * 1/n$. For the predators, if they encountered a huddling group and based on the aforementioned probability, they failed to eat them, they would head to an opposite direction. For a visualization of the predator and prey behaviour in the improved huddling adaptation, refer to figure number 8, in section 7

2.3.5 Adaptation 4 : shelter

The last and the most influential addition was the shelter system. Both predators and preys got a safe-zone where they could only enter whether they belong to the given species. The main difference are the effect of said shelters. In the shelter, the predators would get their energy replenished, while on the other hand, preys would be safe in the zone when the predator population is high, as the species can not enter into the other shelter. The shelters ensures that a healthy population of both species persists going into each cycle. For a visualization of the predator and prey behaviour in the shelter adaptation, refer to figure number 9, in section 7

3 Results

After repeated running of the aforementioned versions of the simulation, we retrieved the graphs described in section 2, for each adaptation. The results represent a trial run, after running the simulation repeatedly in order to check the current adaptations stability:

Note: The plots included to represent the trial runs, have been run multiple times for each implementation, and are representative of the qualities; stability, stochasticity and periodicity of the runs.

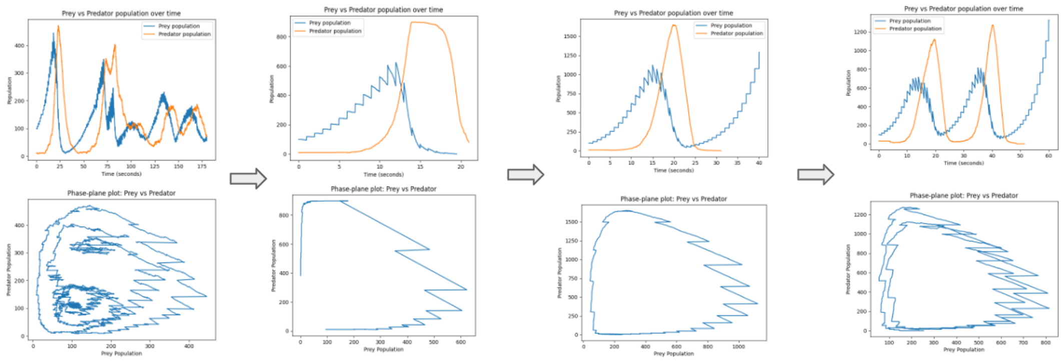


Figure 2: Phase- and population over time plots. The adaptations depicted, from left to right: Base case, Predator energy, Huddling v1, Huddling v2

Moreover, we also retrieved during our trial runs, the average survival time per species:

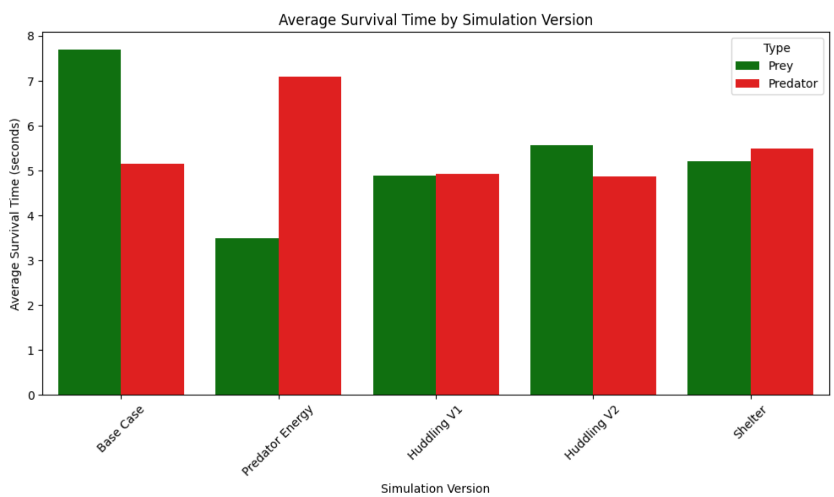


Figure 3: Average survival time by simulation version

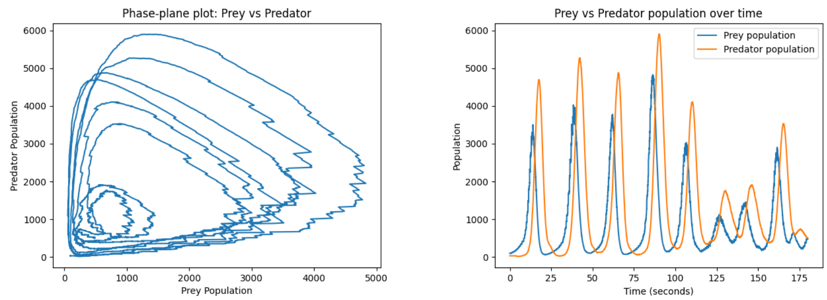
The last and most complicated simulation version results, where the shelter system was introduced are the following:

4 Analysis

During the implementation of the base case simulation, we observed inherent stability and cyclic behaviour within the population dynamics, consistent with traditional predator-prey models. However, this was not consistently upheld, as the inherent randomness of agent behaviour led to irregularities in the expected patterns.

In an attempt to introduce more predictability and control, we incorporated predator energy levels into the first adaptation. While this refinement served to increase the mean survival time of predators and decrease some randomness, the introduced advantage proved excessive, ultimately destabilizing the ecosystem.

To counterbalance the predator advantage and restore equilibrium, the concept of 'huddling' was introduced in the prey behaviour in our first version of this modification. By providing a defensive



(a) Phase plane plot

(b) Population plot

Figure 4: Population plots for the shelter version of the simulation

mechanism for the prey, we succeeded in significantly increasing their mean survival time. However, this adaptation overcompensated for the prior imbalance, shifting the advantage excessively towards the prey and leading to a decrease in predator numbers.

In the second iteration of the huddling adaptation, we sought to strike a better balance between predator and prey survival. The prey's huddling mechanism was strengthened, providing a more robust defense. Simultaneously, we introduced a behavioural modification for predators, wherein their velocity would change following unsuccessful predation attempts. This enhanced exploratory behaviour resulted in more sustainable predator populations, leading to more cycles of population fluctuation and an improvement in overall ecosystem balance.

The final adaptation entailed the introduction of species-specific shelters, a modification that provided both species with survival benefits and served to further equalize the environment. This adaptation was crucial for predators, in particular, as it significantly increased their chance of surviving each population cycle by providing a reliable source of energy replenishment. The shelters, combined with the huddling behaviour, effectively balanced competition between species, fostering a stable ecosystem marked by predictable, nearly perfect cyclic behaviour.

5 Conclusion

The research confirms our initial hypothesis: creating an advantage for prey in numbers and for predators on an individual level, while maintaining a balanced competition, results in a consistently stable ecosystem.

Complex behavioural adaptations were introduced, reducing environmental randomness and enhancing survival times for both species. These observations highlight the importance of tuning species' advantages for maintaining ecological equilibrium.

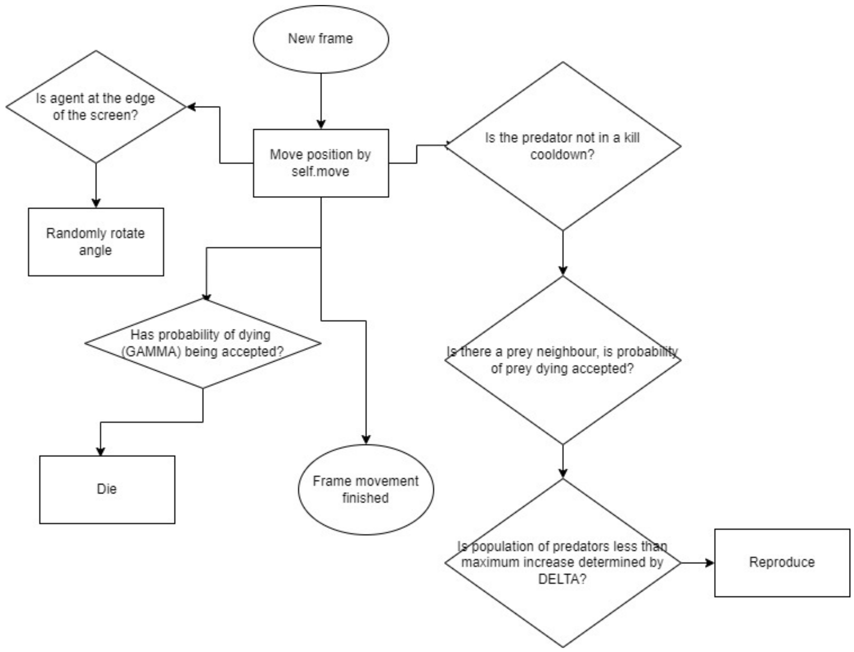
The study further emphasizes that for stable predator-prey dynamics, predators must sustain themselves individually and prey must thrive in groups. This balance contributes significantly to ecosystem stability.

In conclusion, while these results provide insights into predator-prey interactions, they also outline directions for future research. More nuanced behavioural features for predators and prey could yield further insights into maintaining balanced competition and ecosystem stability.

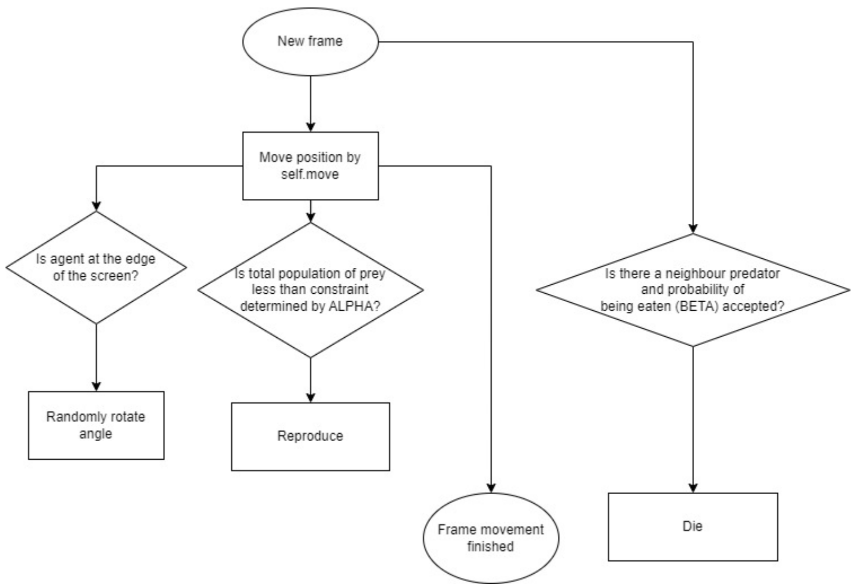
6 References

[1] Beals M., Gross L. & Harrell S. (1999) *PREDATOR-PREY DYNAMICS: LOTKA-VOLTERRA*. NIMBioS. http://www.nimbios.org/ gross/bioed/bealsmodules/predator-prey.html

7 Appendix

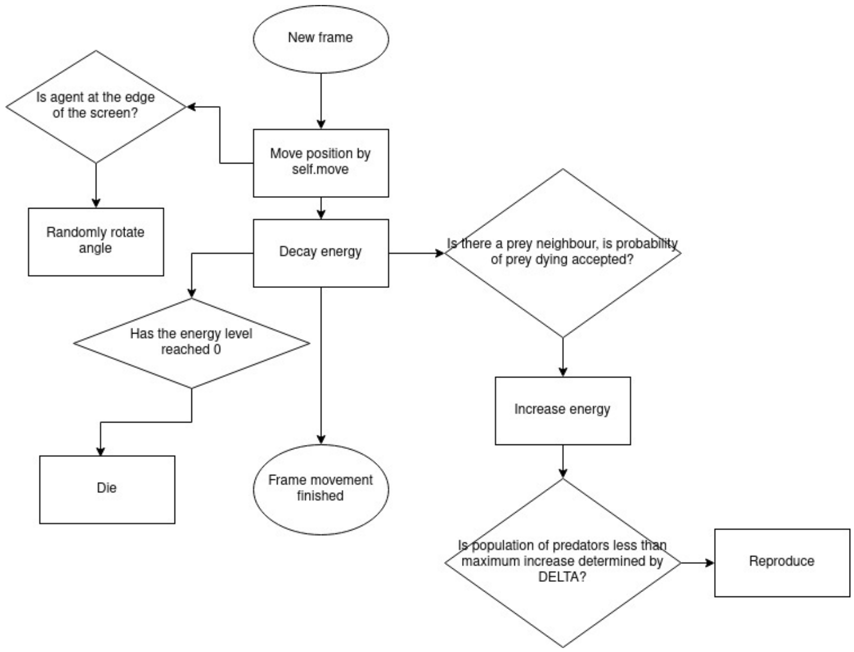


(a) Predator flow chart

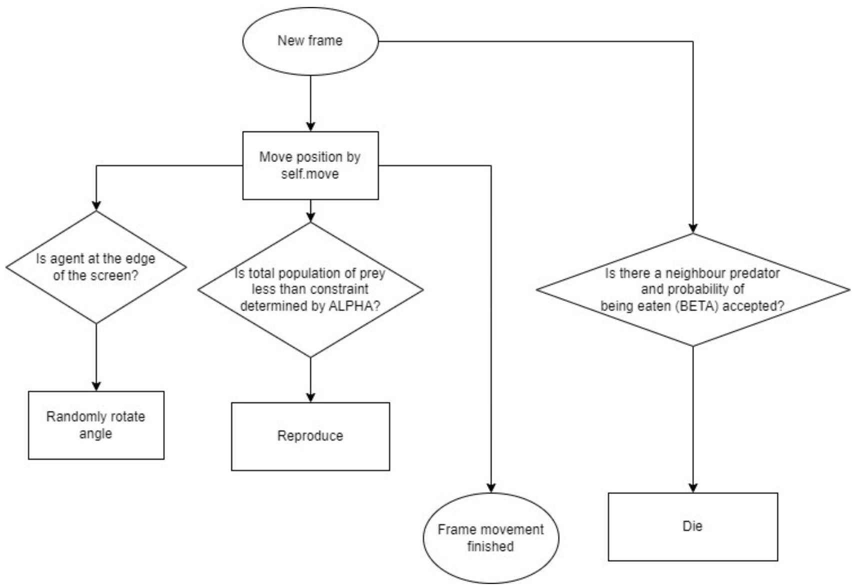


(b) Prey flow chart

Figure 5: Flow chart for the base simulation.

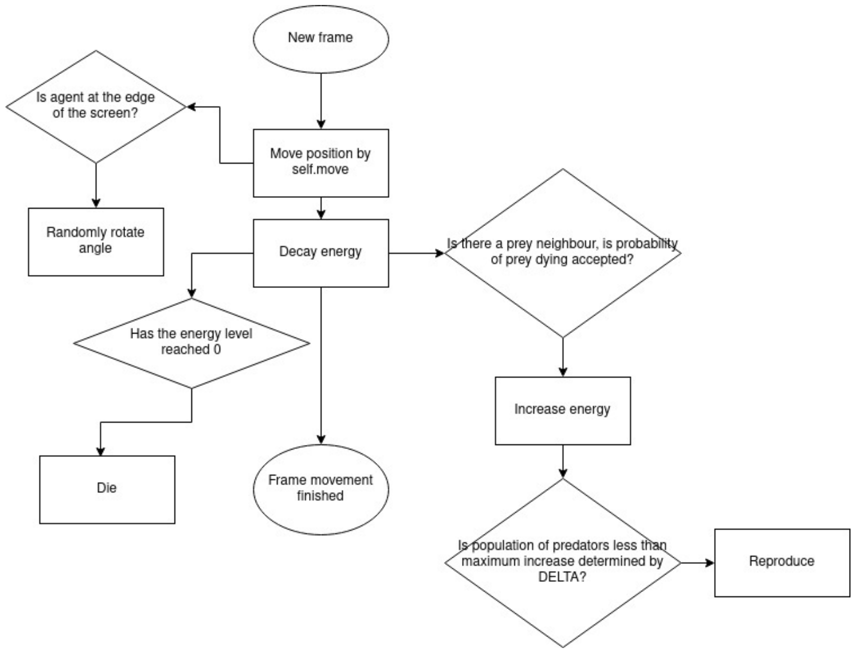


(a) Predator flow chart

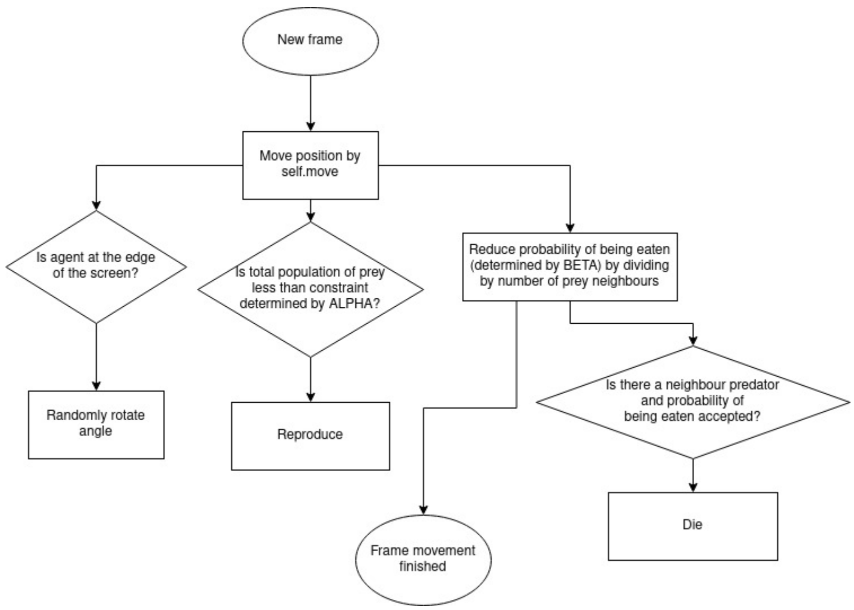


(b) Prey flow chart

Figure 6: Flow chart for the predator energy level adaptation.

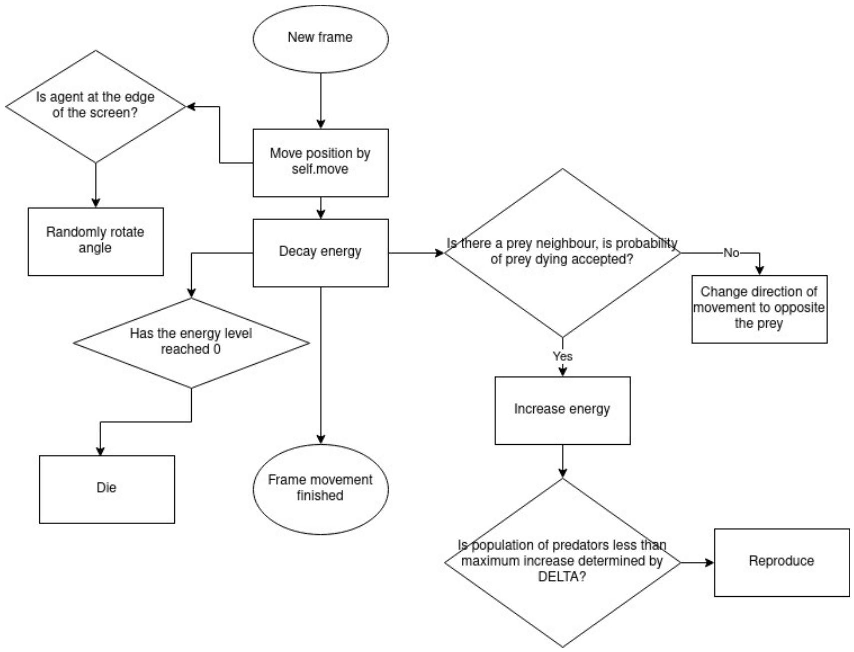


(a) Predator flow chart



(b) Prey flow chart

Figure 7: Flow chart for huddling v1.



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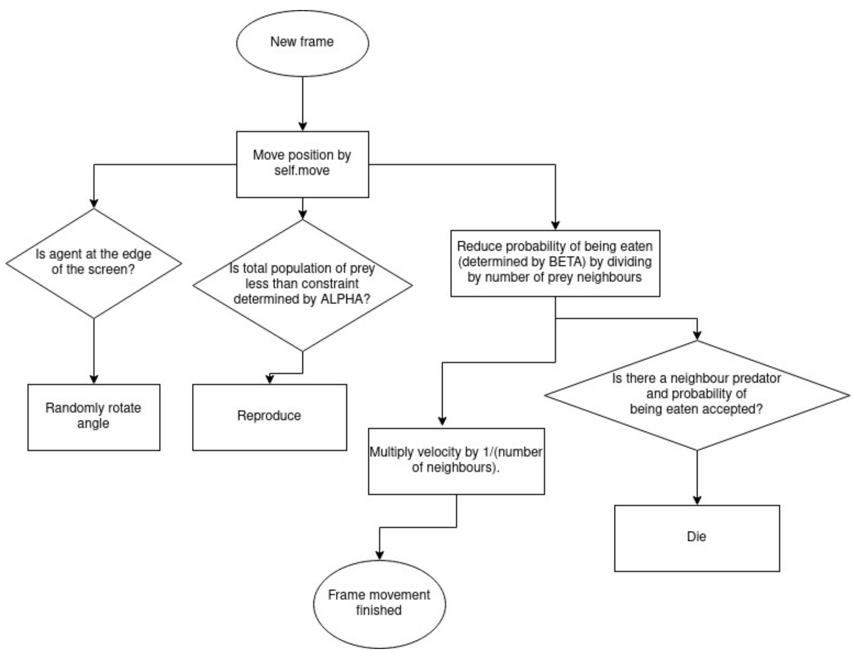
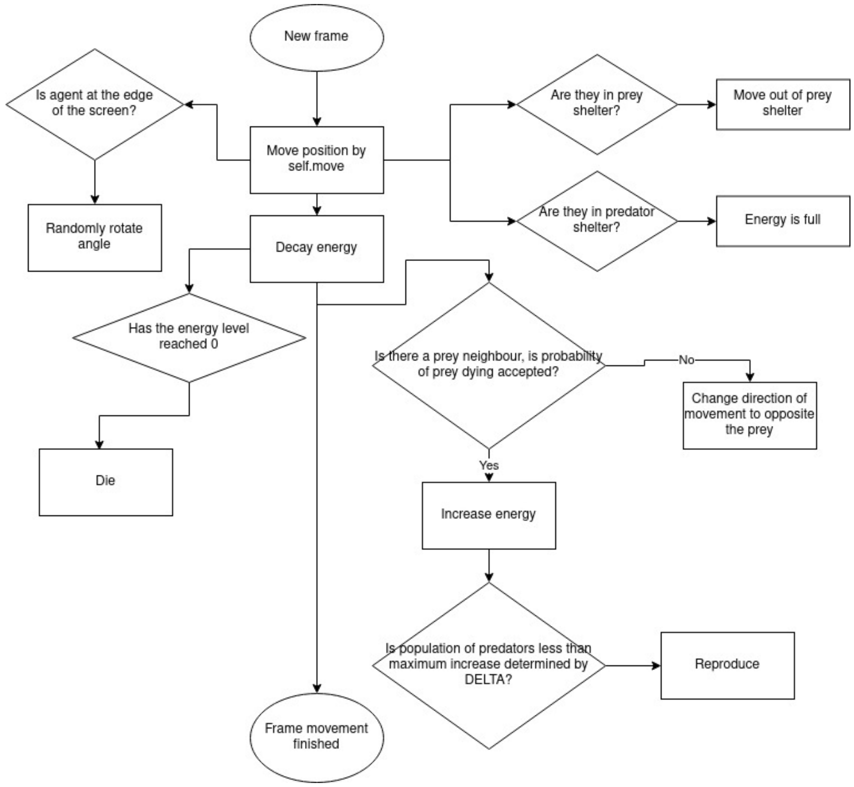
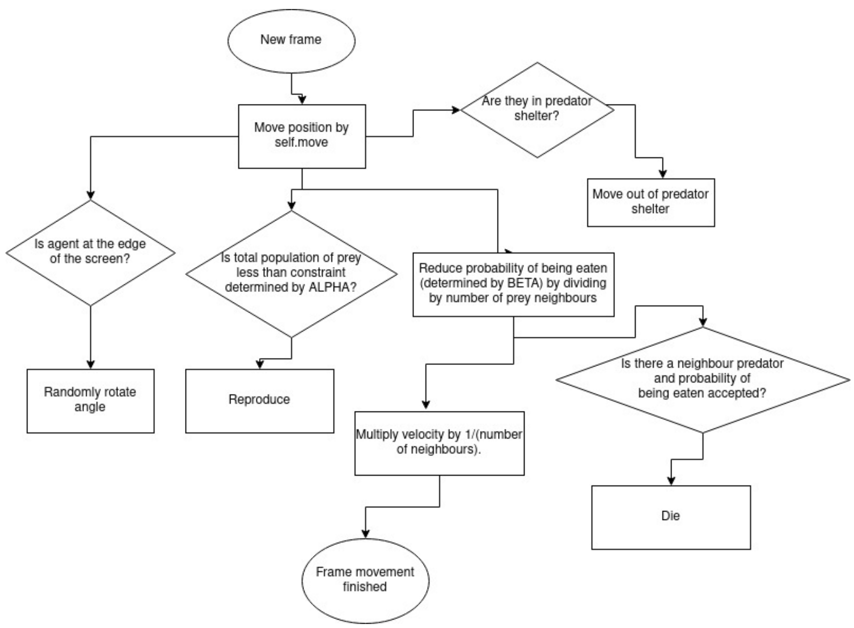


(b) Prey flow chart

Figure 8: Flow chart for huddling v2.



(a) Predator flow chart



(b) Prey flow chart

Figure 9: Flow chart for shelter addition.