Cellular Automata Model Illustrating Prey Predator Dynamics

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Abstract

In this paper, I have developed a simple algorithm to simulate the prey predator dynamics in nature using a cellular Automaton (CA) in the Python language. To do this, we check the health of the prey and predator and consider unlimited food resources for the prey species. The cellular automaton works on the basis of the health of prey and predator species which can either be '1' or '0'. The prey is depicted by blue color and predator species with a red color in the cellular automaton model. A simulation is performed in the python language using the 'pygame' module. Different topologies were studied and their results were compared and analyzed. In addition to different topologies, another important question was also investigated in the simulation describing what happens if the prey species suddenly starts dying. It turns out that the predators are the first ones to die instead of the prey. In this paper, we shall also discuss the Lotka Volterra equations which are also called the prey predator equations.

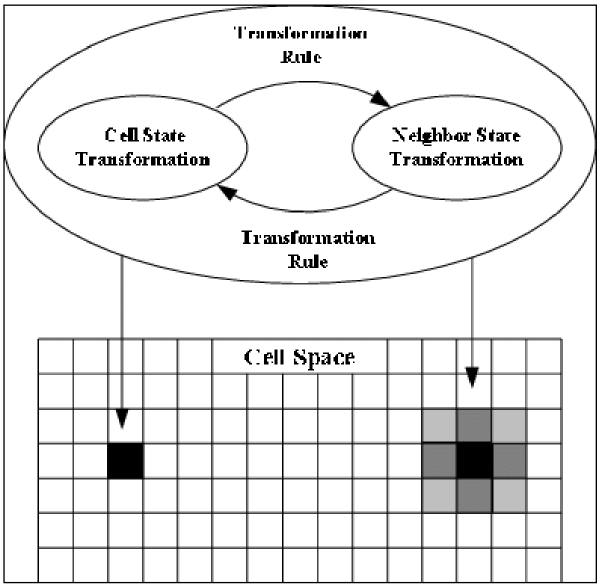


Figure 1: Cellular automata schematic diagram

I. INTRODUCTION

A regular cellular automaton is a set of cells or squares in a grid or matrix like structure that changes and updates its states every generation according to some set of rules applied to every cell which are based on the neighbourhood of the cell. The rules are then applied iteratively for as many time steps as desired [1][2]. John von Neumann along with Stanislaw Ulam and discovered/invented the concept in the 1940s at Los Alamos National Laboratory. von Neumann then tried to implement the cellular automata in the 1950s as a possible model for biological systems by incorporating a cellular model into his "universal constructor". During that period, cellular automata were considered a plausible model for biological systems. [3, p. 48]. Even though the subject matter had been studied by a few people during the 1950s and 1960s, it wasn't until 1970, when Conway developed Game of Life, a 2-D cellular automaton, that interest in the subject exploded outside the confines of academic research [4]. The cellular automaton can be used to simulate a variety of real-world systems, including those involved in biology and chemistry which is why it has such a wide usage for implementation and simulation of biological models like prey predator dynamics, tumor growths, pollination etc.

In Prey Predator dynamics, predators and prey are capable of interacting and influencing each other's evolution and population. In the case of predatory species, it is the traits that enhance their ability to locate and capture their prey that are selected for, while for prey species it is traits that enhance their ability to avoid being eaten that are selected for. As a result, the "goals" of these traits are incompatible, and the dynamics of the predator and prey populations in an ecosystem are determined by the interaction of these selective measures. Additionally to understanding how species interact, biologists also find it insightful to predict what will happen when communities are formed and sustained.

Predator-prey dynamics are best described by the Lotka-Volterra model. It is a set of differential equations used to describe predator-prey dynamics based on the assumption that there is one predator per prey population. It postulates that predators and prey populations oscillate at the same time, but the peak of the predator's oscillation lags behind the peak of the prey's. The theory was developed independently by Alfred Lotka and Vito Volterra in the 1920s. This model relies on several simple assumptions/limitations:

1. Population of the prey grows exponentially when there is no predator population present;
2. Population of predator will decrease when the prey population is not present as it basically dies of hunger (instead of switching to another prey because we assume that one prey per predator population);
3. Predators can consume infinite number of preys;
4. Both the population move randomly in the stable environment. There is no additional environmental factor hindering the population growth of the species. [5][6]

Hence, the Lotka-Volterra equations were studied and taken into account to construct the population dynamics in the Cellular Automaton model. These define the coordination between prey and predator and their interaction and how the population is further affected by their food habits and consumption.

II. BACKGROUND

A. Prey Predator Relationship

Predator-prey relationships involve the interactions beween two species and how they impact each other. Species live in predator-prey relationships as one feeds on the other. The organism that consumes another is known as a predator, and the organism that is being devoured is known as a prey. It is this simple relationship that nature has developed over time in various species, so much so that we have food chains in which we have predators who eat lower-level predators and so they affect each other's survival. Each population evolves to become fitter as its adaptations increase. Scientists have found that predator-prey relationships greatly affect population dynamics and changes over time within a species' population, which in turn causes population fluctuations in an environment. One species might be a predator or prey depending on the circumstance, and the other might be the opposite depending on the circumstance, especially when interacting with other species. One such example that can be found among birds are blue jays that prey on insects and snakes that prey on the blue jay birds and hawks who then prey on snakes for food. Such arrangements are known as food chains. Prey Predator dynamics are studied as an individual topic because they influence the environment greatly and the equilibrium and sustainability of any given fauna and flora area.

In a classification scheme, predators are categorized by how they hunt, kill, and consume their prey. A "true" predator hunts and kills the prey and then feasts on it. Grazing cattle are not considered predators because only a small portion of the grass is consumed, and the intact roots allow the grass stalks to grow back.

There are some examples of predator-prey relationships in nature where the predator actually preys only on one type of prey species. So, in such a situation, the changing population of the prey and predator species have a direct relation and influence with each other. Let's consider a basic example of the prey-predator relationship between the rabbit and the fox. Since the fox mostly consumes rabbits as part of its diet, they make up a significant part of its diet. A fox wouldn't be able to survive without them. The fox reproduces by consuming rabbits or a variety of rabbits and because of this, the fox population increases. When the fox population increases, the rabbit population also increases rapidly. The graph in Figure 2 explains the population dynamics of fox and rabbit population in an area over a period of almost 100 years.

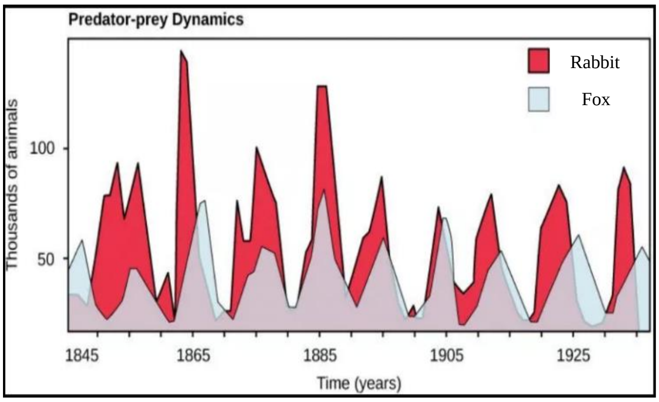


Figure 2: Graph showing population dynamics between prey and predator over a period of time (Pilovsky et al., 2001)

A blue line indicates fox populations, while a red line indicates rabbit populations. At the starting of the graph i.e. in year 1845, the population of fox was high which is indicated by the blue peak and the rabbit population was low. Due to less availability of rabbit species to hunt, the fox population significantly declined over time. When there was no fox population left to hunt the rabbits, the rabbit population continued to increase to a very high number. Then the fox population also increases as the prey increases because when there is availability of prey, the predator hunts and eats it and ultimately reproduces new healthy offspring. The cycle is the repeated again and again every 10 years since 1845. Hence, a pattern is seen in this fox- rabbit population graph. If you average out the peaks and the valleys of the graph, it is observed that both populations remain almost stable showing only a slight increase or decrease over the period of time. Furthermore, it is important to point out that rabbits and the plants on which they feed have an almost predator-prey relationship. When the rabbits grow, their diet exceeds the nutritional capacity of their environment, and they are forced to starve. The combination of these factors, along with the predator-prey relationship with the fox, makes population shifts very volatile. There is an intricate relationship between predators and prey. In response to the abundance of prey in the food chain, the number of foxes increases when there are more rabbits. Over-exploited or disease-ravaged rabbit populations will soon decline, resulting in a decline of the predator population. During a period of time, the rabbit and predator populations fluctuate.

As explained above the fox is an example of a traditional predator. It hunts, kills and then eats its prey i.e. rabbit. Foxes are usually solitary predators that means they hunt individually, but there are other species that hunts in groups and can also be commonly called social predators like lions, wolfs etc.

In addition to the conventional predators, there are various other types of predators that are not predators in the traditional sense and follow a different approach to predation. One such type of predators are scavengers which have a predator prey relationship with the species that they hunt. The most popular example of a scavenger would be a vulture. They don't hunt the water buffaloes directly but their food comes from them. So, when the buffalo population decreases, the population of lions don't have a lot of prey population to kill which affects the vulture population in turn because they rely on the leftover dead water buffalo hunted by the lions. It is an indirect relation between the predator and prey but still the population dynamics of the relation are still maintained.

Another example of a non-conventional predator would be the Parasites which basically latches on to the host organism and then feeds off of it. They don't necessarily kill the host organism. Also, there usually very microscopic in nature and are significantly smaller than the prey, they still display a predator-prey dynamics with their host. The most common example of such a relation would be of deer and ticks. When the deer population declines due to any external factors, the ticks have very less to eat and hence survive. Also, if ticks increase in number, they will reduce the number of deer population by spreading diseases to the deer and if ticks reduce in number, the deer population will thrive in the area. This is another non-traditional type of prey-predator relationship between ticks and deer.

Almost all predatory species that are successful and have survived have developed several strategies in order to capture their prey. Predators utilize a variety of methods including speed; stealth (being quiet and deliberate while moving, or approaching from upwind); camouflage; a highly developed sense of smell, sight, or hearing; tolerance to poison produced by the prey; producing its own poison that kills the prey; or an anatomy that allows them to consume the prey. In the same manner, prey has strategies to avoid being killed by predators. Additionally, prey species can use the aforementioned predator characteristics to avoid being caught and killed.

By controlling the predator population, the prey population is able to maintain its fitness, including the number of individuals, their chances of breeding, and their chances of surviving.

B. Lotka Volterra Equations

Lotka–Volterra equations are a set of non-linear differential equations which are used to describe and illustrate the relationship between prey and predator population. The rate of change of populations according to the set of equations is:

$$dx/dt = \alpha x - \beta xy \qquad (1)$$

$$dy/dt = \delta xy - \gamma y \qquad (2)$$

where,
x is the number of prey (for example, rabbits);
y is the number of some predator (for example, foxes);
dy/dt and dx/dt represent the growth rates of the two populations at a particular instant;
t represents time;
α, β, γ, δ are positive real parameters describing the interaction of the two species.

In 1910, Alfred J. Lotka proposed this model in his theory of autocatalytic chemical reactions. The model was extended in 1920 by Lotka, through Andrey Kolmogorov, to the study of "organic systems", using a plant species and an herbivorous animal species as examples, and in 1925 he applied the equations to the study of predator-prey interactions in his book. Volterra, a mathematician and physicist with an interest in mathematical biology, published the same set of equations in 1926. Figure 3 shows the graph that was generated by the Lotka- Volterra equations which is pretty similar to Figure 2.

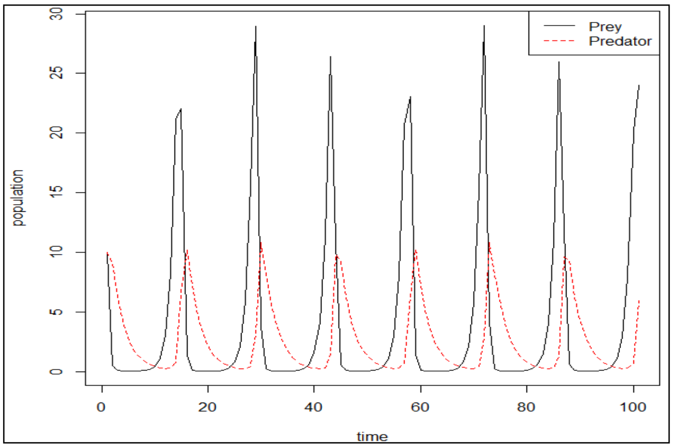


Figure 3 : Lotka Volterra equations generated graph (Ian Alexander, December 2018)

III. METHODOLOGY

A. CA Model Of Predator Prey Dynamics

Cellular automata (CA) models are a more biologically accurate approach to modeling predator-prey interactions. The lattice sites in the CA context are updated synchronously. It is easy for the model to monitor individual movements with the small cardinality of the CA neighborhood.

The automaton used in this project is a 2-dimensional discrete square lattice space $G = \{0,...,P-1\}\times\{0,...,Q-1\}$ having P cells in the horizontal direction and Q cells in the vertical direction with some boundary conditions. Each cell can assume a value in $Z = \{0, 1, 2\}$, where 0, 1 and 2 mean that either the cell is empty, it contains a predator or it contains a prey, respectively. The neighbourhood that has been defined and used in this project is the Moore neighbourhood i.e., it considers all 8 neighbours of the cell and implements the simulation and rules on all the 8 neighbours of each cell in a synchronous manner.

B. Language

The language the code has been written in is the Python language. The code uses the pygame module to run the prey-predator simulation in a more graphical manner. This is an open-source library for Python that enables you to create games, multimedia applications, and other applications using the Python programming language. pygame is built using the highly portable SDL (Simple DirectMedia Layer) development library and is compatible with a wide variety of platforms and operating systems. It is possible for you to control both the logic and the graphics of your games with Python's pygame module without having to worry about the backend complexities of interacting with video and audio.

C. Neighbourhood

For simulating prey predator dynamics, two types of neighborhoods can be used: the von Neumann neighborhood with a 4-cell grid and the Moore neighborhood with an 8-cell grid. The neighborhood in the von Neumann model consists of four cells such as left, right, up, and down, which surround the central cell. But the Moore neighborhood considers eight cells surrounding the central cell. These cells include the left, the right, the up, the down, the top-left, the top-right, the bottom-left, and the bottom-right. In this model, since species are interacting with each other in all directions, so it makes more sense to use the Moore neighbourhood in the simulation of the project. Based on the comparison, we will then assess the results from each scenario.

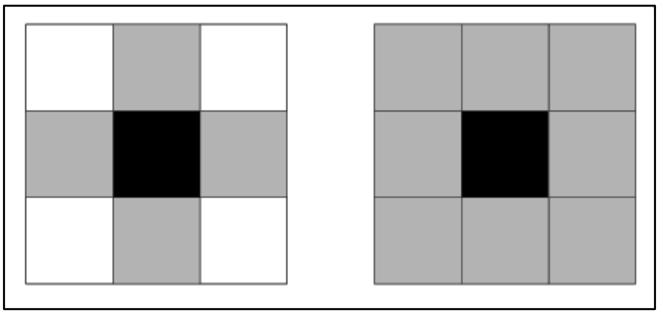


Figure 4: von Neumann neighbourhood (left) and Moore neighbourhood (right) (Szymon Skoneczny, 2017)

D. Algorithm Used

The cellular automaton lattice is a grid of cells with 3 possibilities for each cell which are as follows:

i. Predator (Red or 1)
   a. The predator moves in a random direction inside the grid. Whenever they move, their health starts to decrease.

   b. Once, the health reaches zero, they die and turn into nothing i.e. black cell or 0 state cell.

   c. If the adjacent square is a prey i.e. blue cell or 2 state cell, then the predator cell will consume the prey and turn the eater prey cell into "predator" cell.

   d. The health of the predator cells depends upon the amount of prey cells the predator has eaten.

ii. Prey (Blue or 2)
   a. The prey moves in a random direction inside the grid. Whenever they move, their health starts to increase.

   b. Once their health reaches a threshold value "$H_{threshold}$", they will reproduce and give birth to new offspring which leads to creation of new "prey" or blue cell.

   c. The new cells thus formed will have their health reset to one.

iii. Empty (Black or 0)
   a. The cell becomes empty or zero when the predator dies due to lack of prey.

   b. The cell becomes empty when prey is eaten by a predator and then that predator's health reaches 0

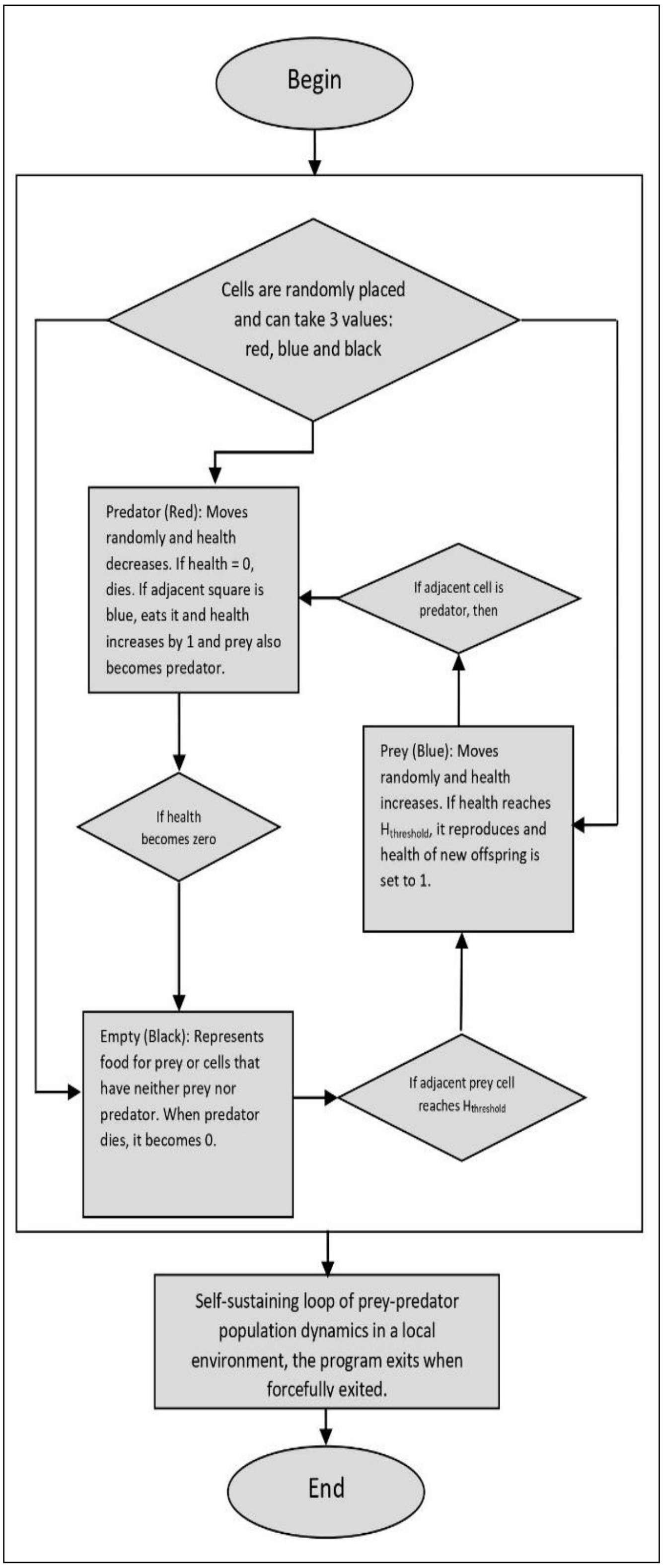


Figure 5: Code flow of the project

and then it dies off.

An important thing to note is health of a cell is different from its state. Health of a cell increases or decreases due to the neighbourhood. The current health of the cell then defines the state of the cell. The state of the cell can be only in {0, 1, 2} but as explained health can be from {0,…n} where n depends upon prey and predator rules accordingly.

Another assumption that has been made for thew purpose of this project is that the food for prey (herbivores) is unlimited. The topology that was used in the first simulation is a random blob and are defined randomly. The figure 5 describes the flow of the code that has been designed.

E. Research Questions

Some of the research questions that are answered after the evaluation of the running the simulations are:

i. What pattern is formed by the population dynamics in each simulation?
ii. How do different prey and predator death rand birth rate influence the populations scenarios?
iii. What happens to any one species when the other one dies off?
iv. What are the suitable parameters to make the population of an area a stable community?

IV. OBSERVATIONS

A. Simulation 1 : Random topology

After the code was constructed and simulation was run, the observations that were made are:

i. The simulation begins with a random population of prey and predator cells with a very few empty cells (black)
ii. The rules explained in the methodology section are applied on the cellular automata grid.
iii. The next significant change is predator cell (red) eat/kill almost all of the prey cells (blue) except a handful of predator or prey cells
iv. Then using a handful prey cells (blue), they reproduce and again expand by moving randomly in the neighbourhood.
v. The predator cells are also increase as the prey cells continue to increase.
vi. This simulation runs infinitely with continuous ebb and flow in population.

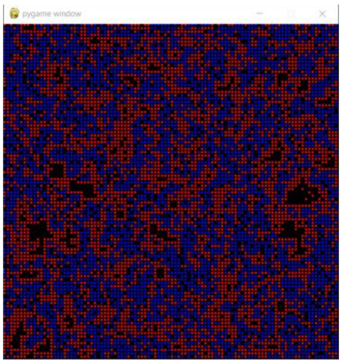
B. Simulation 3: Wave Topology

In the next topology, instead of random assignment, we use a wave i.e., in the grid 2 vertical columns of cells are prey cells and then one vertical column for predators on the right of the prey cell columns. Within 25 generations in the CA, the wave transforms to a random pattern between the prey and predator and it follows the same pattern as the random topology and henceforth following the same results for it.

C. Simulation 2: Blob Topology

The next topology that was tested is a blob i.e. a small grid of cells i.e. a 3X3 grid is assigned with prey and predator cells instead of the whole grid. Within 50 generations the graph expands to a randomized pattern reproducing results similar to the random topology. Hence, it also follows the same rules.

Figure 6 shows the approximate output of the simulation.



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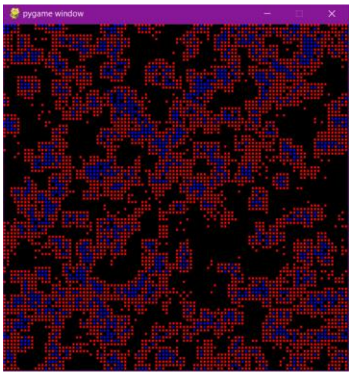

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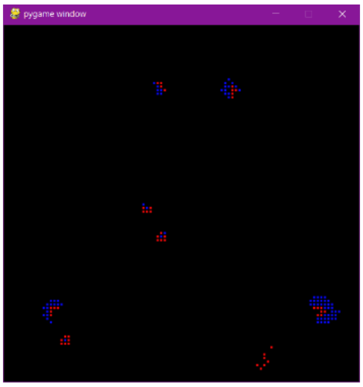

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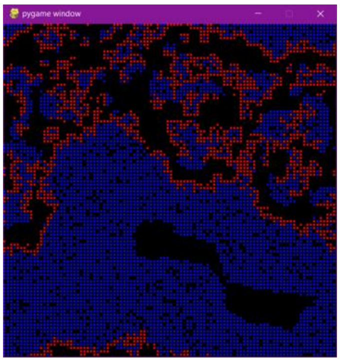

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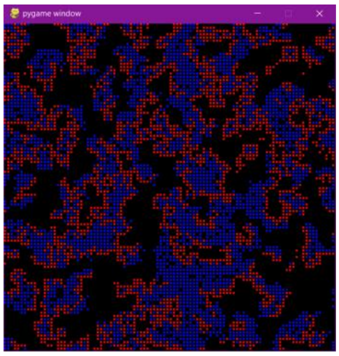


(v)

Figure 6: Snapshots for steps for simulation

V. RESULTS

The results and conclusions that are found are as follows:

i. The prey will continue to increase without the presence of predator which can be seen using the Figure 7.

ii. The predator will die off without the presence of the prey which is evident from the graph Figure 8.

iii. The simulation runs independently in the pygame module without any help which points to the fact that in a local environment for a basic pair of prey and predator species, they can survive and maintain their populations in accordance with each other without any interference from the nature i.e. it is a stable local community.

iv. Another thing that can be observed and concluded from the simulation, even if a handful of prey and predators are left in an environment, they will be able to grow and maintain their populations provided there is no external interference.

v. Another very important question that this simulation answers is the result of what happens if we increase the prey death rate. For example, there is an internal or external factor that kills off all the prey cells, the crucial observation is that the predator cells are the ones that die out or empty first rather than the prey cells.

vi. Even though the dynamics are studied using various topologies, it always becomes a repetitive random pattern in a few generations always displaying similar patters as a repeating cellular automaton.

vii. The graph that is plotted from the population dynamics (Figure 9) is very similar to the one that was observed naturally in an area over a long period of time (Figure 2) as well the graph generated from the Lotka Volterra equations (Figure 3)

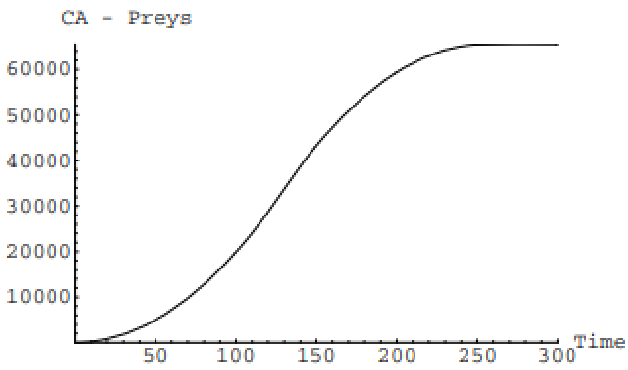


Figure 7: Population of prey species without presence of predator

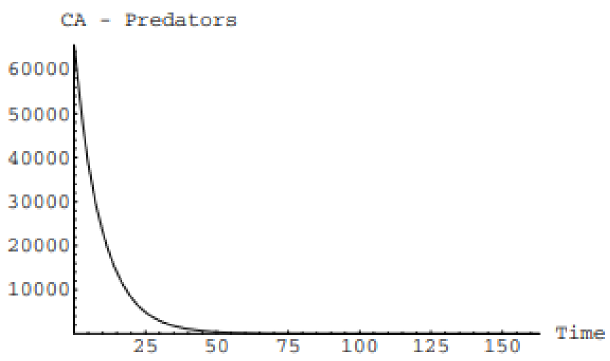
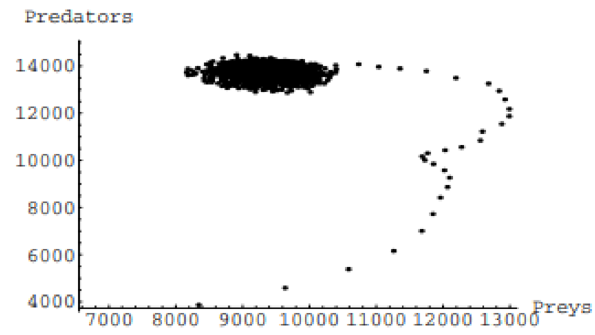


Figure 8: Population of predator species without presence of preys

VI. Future work and Limitations

Although this study simulated the population dynamics for a stable community in great detail, it does have its own limitations. As we know, there are various types of prey and predator species, we are considering only one of each and in nature a predator doesn't prey on single species but in nature a range of prey species exist for the



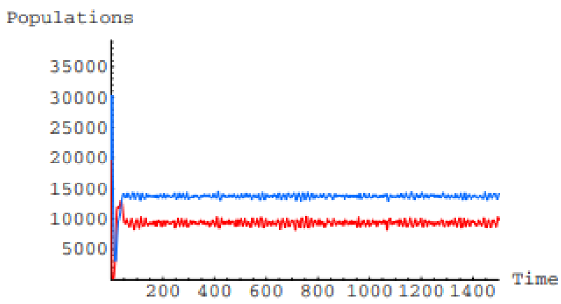


Figure 8: Cellular Automata graph for prey (blue) and predators (red)

predator to eat off of. If one species of prey dies off, the others are still available to the predator species. So, this was an assumption made in the model that only one species of prey and one predator species are considered.

Another important limitation is the availability of food for prey is not unlimited. The results would be different when the food for the prey is also limited which can significantly influence the population dynamics in different environments. In this project, a very general methodology is being implemented to model the population dynamics of predator and prey species.

VII. Conclusion

This project aimed to extend and illustrate a cellular automata model simulation for the relationship between the prey and predator species in a local environment with unlimited food resources as a stable community. A few experiments were conducted by creating and studying various simulations of differing birth and death rate of prey/predator species and differing the topology in the cellular automata. Data was collected for various scenarios, and it was found that the stability of an area depends upon the predator population. The rate of birth of prey and the death rate of prey etc. all depend upon fitness function of the predator, if predator is fitter than prey then predator dies off first and prey becomes the majority and if predators are less fit than prey then also the same situation arises, the predators die off and prey population increases infinitely. The Lotka Volterra equations also validate the results of the model.

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