CS275 Artificial Life Course Project: Biological Ecosystem Simulation

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ABSTRACT

With the advance of machine learning and computer graphics, more and more researchers start applying similar techniques in biology. As such, simulating biological ecosystem with these techniques is widely popular. In particular, a 3D environment simulation helps provide a custom-made landscape and we could simulate the natural selection in an ecosystem through generations. For this project, we are interested in simulating a real world ecosystem to observe the influences of natural selection on the adaptability and survival of species, and the effects of overpopulation and competition on the whole ecosystem environment.

1 INTRODUCTION

Computer-generated ecosystem, through the real-time 3D environment, helps monitor great amounts of behaviors of different creatures and numerous events respectively. This could allow us to understand how and when animals eat, drink, reproduce, behave toward different species. For example, when animals feel hungry or thirsty, they would go to find and hunt food or drink water; when they are hunted by other animal species, they would flee from predators; when female animals meet male animals, they might reproduce, and so on. Learning from this kind of 3D ecosystem could make us greatly understand the relationship between different species' attribute value and behaviors, and how the real-life ecosystem works as a whole group.

In this ecosystem project, one of the biggest challenge is to reach a equilibrium state, which means the population of all the species in the ecosystem needs to be stabilized even though there might be some fluctuations at sometimes. Without the stabilization, some species might go extinct in a really short time period, and the species that prey on these extinct animals would also disappear in the future due to lack of food, while the species that are preyed on by such extinct animals would overpopulate since they have no natural enemies. Hence, in order to survive in the brutal ecosystem, animals must adapt to various environments and effects, so species will evolve by passing on the genes that could aid their success and removing those that could not. For instance, preys, such as antelopes and rabbits, would improve their survival skills and escaping speeds, and conversely, predators, such as eagles and snakes, would boost their hunting skills and sensitivity to preys.

All the living creatures in our 3D ecosystem inherit the physiological features including body colors, body sizes, and biological structures. They also inherit some behavior patterns from their ancestors, while other behavior patterns are learned from experiences by themselves, and this process is called evolution. The concatenation of the complex patterns leads to the genetic variation of the species, which would result in different responses and behaviors for each individual in different situations.

In this project, we built a 3D real-time ecosystem on Unity, which is based on a predator-prey chain model. Our goal is to observe the effects of natural selection on the adaptability and survival of species and how the whole ecosystem keeps stabilized during different generations. In Section 2, we would introduce some backgrounds of biological work and other related work about the implementations of ecological simulator. In Section 3, we would demonstrate several important methods we used in our project, including how to set up a ecosystem environment and how to pass on the genes to the next generations. In Section 4, we would present the evaluation of our ecosystem simulator by showing the changes of species' population and genes mutation over generations. In Section 5, we propose two improvements on the reproduction and genes passing.

2 BACKGROUND AND RELATED WORK

In order to simulate such biological ecosystem, we implemented an evolution simulator. However, the challenge of this kind of evolution simulator is that we need to build a ecological world that is complex enough for numerous interesting behaviors to happen, and the creatures will try their best to cheat and may even exploit bugs in the code. So we need to prevent that situations. From all the work we have seen in the previous section, almost all of them have different formulations. Depending on how sophisticated the physical simulation is, the degree of freedom that the creatures are allowed to evolve, and the amounts of human intervention, these simulations give different yet interesting results. One of the worlds we have seen has a very complex physics engine. It is 2D water world with fluid simulation and everything as shown in Fig 1 (left). Everything is purely determined by physics here. Each creature is made of particles and each particle has its own unique function. As a result, because everything is determined by physics, all one can see is a bunch of molecules bouncing around and running into each other, so it is impossible to see any complex behavior. Another extreme situation is shown in the right image, which has lots of human designs and interventions. After all these efforts, one can actually observe some complex interactions like predator-prey relationship and their co-evolution. However, none of them ends up reaching a stable ecosystem. It seems that mass extinction or domination of a single species are the most common ways things end, which is what we do not expect.

Another related work, PolyWorld (PW) [6], was done by Larry Yaeger in 1994. PolyWorld, as shown in Figure 2, is an ecological simulator of a simple flat world with a few impassable barriers, inhabited by a variety of organisms and freely growing "food". These organisms and all other visible stuffs of the world are represented by simple polygonal shapes. The organisms use vision, provided by a pixel map of the world from their point of view, as input to a neural network brain. The outputs of this brain fully determine

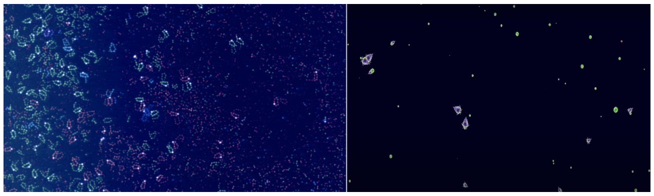

Figure 1: ALIEN [1] and The Bibites: Digital Life [2]

the organisms' behaviors. The artificial neural systems employed in PW are based on Hebbian learning, a learning algorithm where correlated activation of two neurons leads to the strengthening of the connection between the two neurons. The organisms' metabolic rates, neural architectures and other stats are determined from an underlying genome. When two nearby organisms both express their mating behaviors, reproduction occurs and the genes are passed to the next generation.

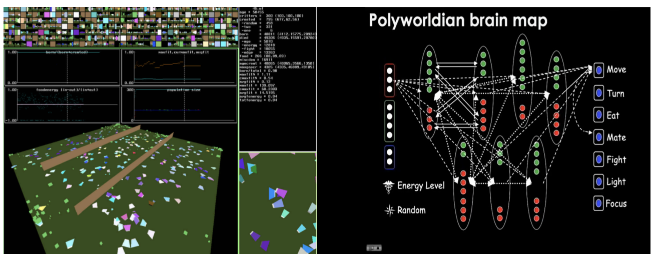

Figure 2: PolyWorld[6] and Polyworldian Brain Map

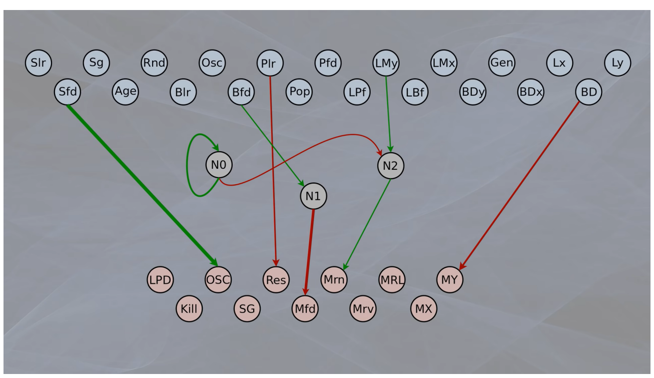

Figure 3: An example of the creature's neural network[4]

3 METHODOLOGY

In this section, we will present the detailed implementation of our project. We will discuss the approach from three major aspects: (1) how we build the environment with computer graphics, (2) how we model the internal states of our selected animals, and (3) how we determine the behaviors of our selected animals. Example of our ecosystem is shown in figure 5.

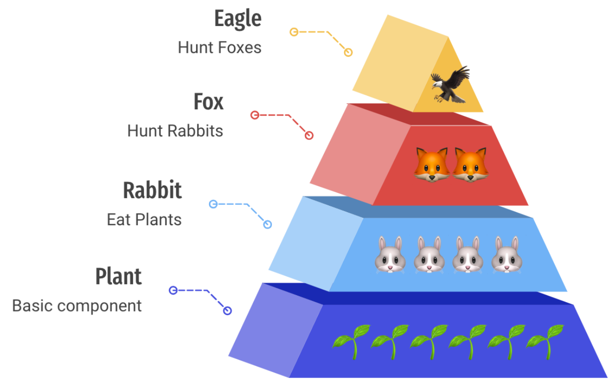

Figure 4: Food Chain

3.1 Environment

To build the environment, we first utilize Unity game engine's built-in models to create and manage a closed ecosystem environment with trees, grasses and rivers. While trees serves for pure decoration purpose, grasses and rivers (water) are resources for animals to survive. Although the growth rate of grasses is determined by many factors in real life, we modeled them without these factors for simplicity. We also modeled water as an unlimited resource for the same reason.

As for the creatures living on this field, we introduce a food chain as demonstrate in figure 4. We include rabbits, foxes and eagles. Although plants are also living entities in our ecosystem, they do not have any "behavior" other than self-replicate based on their growth rate. The creatures' reproduction rates, feeding/hunting rates (percentage of creatures choosing to eat whenever they encounter their food), as well as the amount of food they need to survive, are determined by their underlying genes and neural network brain, which are described in detail in the following section. We did not assign an "age" or lifespan to our creatures as most creatures' cause of death are not old age. The ecosystem environment created by Unity can directly show how these creatures feed and how they interact with each other.

3.2 Genes and Brains

After we establish the external features, we need to build "internal" features for our selected animals. We select several key features for all animals that are genetic, including gender, diet, max HP, attack, defense, agility, speed, number of babies per pregnancy and neural network weights. For evolution to happen, these features need to be able to self-replicate and passed down to the next generation as genes. At the same time, these genes also need to be able to mutate occasionally. For the first generation, the genes are initialized at random.

We modeled the "brain" of our creatures with the above idea in mind. Like Tierra[5] and Avida[3], each of our creature is associated with its own set of genes that allows it to self-replicate and mutate. The genes will only affect the creature's physical appearance slightly for certain animals. Currently, only rabbits would present as different shade of browns based on their gender and

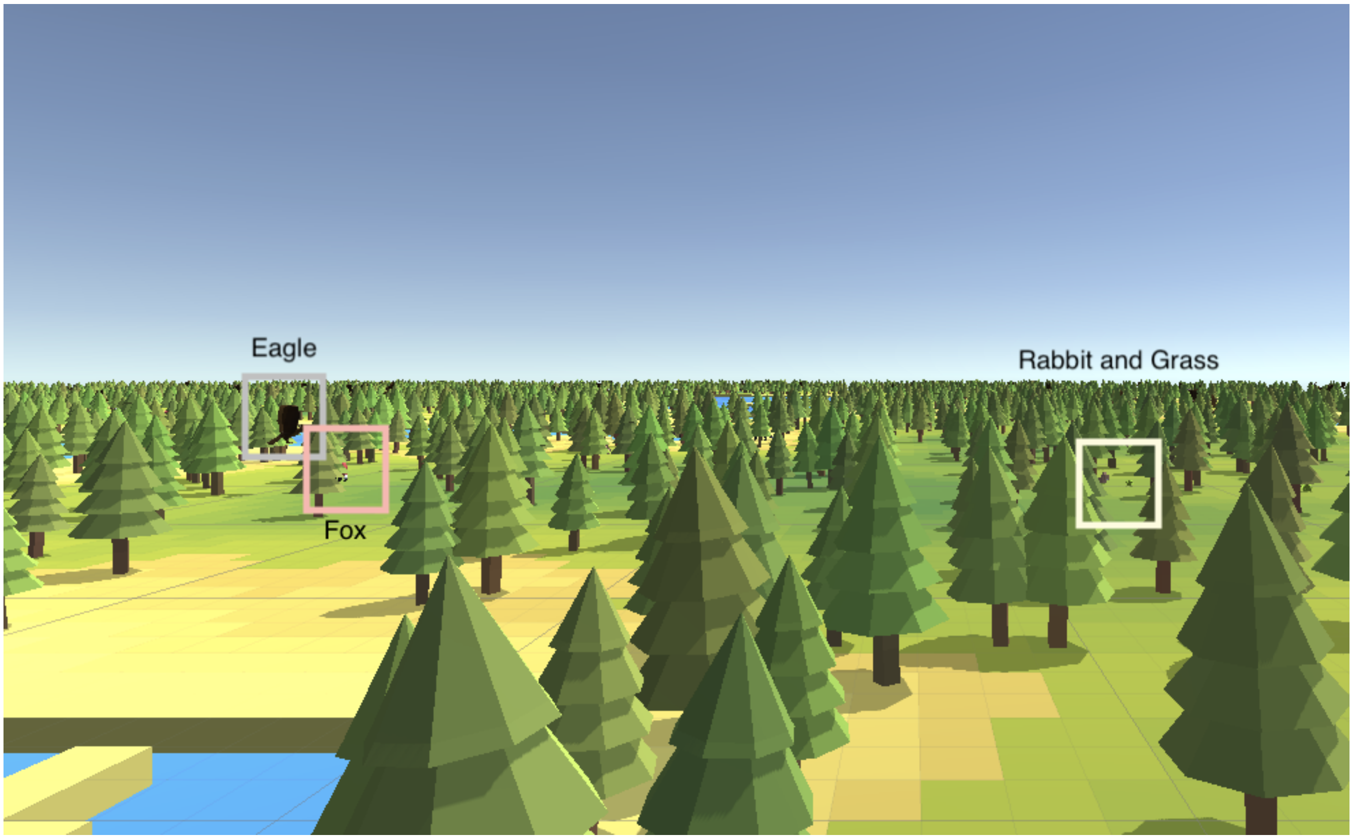

Figure 5: Example

other animals remain the same physical appearance regardless of their genes. However, physical appearance is not our focus here.

More importantly, genes determines weights of the creature's neural networks. For large scale simulation, we use a simple feed forward fully connected neural network with a single layer as the brain structure. As shown in Figure 6, the neural network takes the current status of an animal as inputs and output a single behavior that enables the animal to act accordingly. It is worth-noting that the output behavior is only a direction. For example, the neural network would direct an animal to find nearest water, but the animal is not guaranteed to find one.

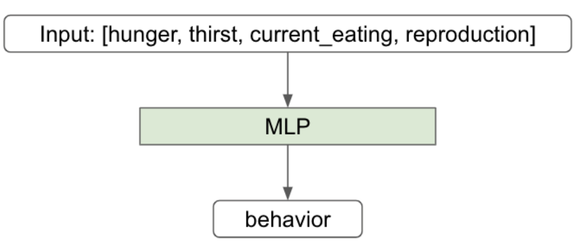

Figure 6: Neural Network

3.3 Behaviors & Other Mechanisms

3.3.1 Hunger & Thirst. In nature, every animal needs food and water. This is also true in our simulated ecological environment, represented by a hunger/thirst value, which accumulate over time in the following way:

$$hunger+ = consumptionRate * maxHp * 1/timeToDeathByHunger$$

$$thirst+ = consumptionRate * maxHp * 1/timeToDeathByThirst$$

where *consumptionRate* is defined as:

$$consumptionRate = (speed/1.5) * attack * defense * maxHp$$

Intuitively, in order to be faster and stronger, one has to pay the price of higher metabolic rate.

These values are also the input to the neural network which is used to produce the next action for each animal. If the neural network output is *Find Food*/*Find Water*, the animal will attempt to find food/water in the following way: First, check if there is a prey/a water tile inside the view of the animal. If so, go to the tile and start eating/drinking. Otherwise the animal will keep exploring the environment until the next action is chosen. After eating/drinking, the hunger/thirst level are reduced accordingly:

$$hunger- = foodConversionRate * resourceLevel * damage$$

$$thirst- = resourceLevel * \frac{timeBetweenFrame}{eatDuration}$$

where *foodConversionRate* determines how much energy this type of food contains. *damage* depends on the attacker and the target, and is calculated as follow:

$$damage = \frac{attacker.maxHP}{target.maxHP} * \frac{attacker.attack}{target.defense} * \frac{timeBetweenFrame}{eatDuration}$$

This gives a way for both the predator/prey to evolve against each other.

3.3.2 Reproduction. Plants will grow at the same rate. A plant has a chance to regenerate every twenty seconds. For animals, reproduction requires two individuals of opposite sex. Both of them must first express their mating desire before they manage to find each other. An internal counter keeps track of the time since the last mating behavior and this value is passed as an input to the neural network brain:

$$reprod+ = \frac{maxHp}{timeToReproduce}$$

It is worth noting that while reproduction is crucial for the species, it is a burden on the individual. There is a cost on hunger/thirst for reproduction:

$$hunger+ = consumptionRate * reprodHungerCost * maxHp$$

$$thirst+ = consumptionRate * reprodThirstCost * maxHp$$

There is also a constraint on the minimum amount of time between two pregnancy.

If reproduction succeeds against all odds, a child is born with genes obtained from combing the genes of both parents: most attributes are the average of that of the parents with a few exception like gender and diet. For example, gender is always randomly assigned while diet is always fixed within the same species. Genes also have a chance to mutate by adding a Gaussian noise to certain attributes.

3.3.3 Death. For animals, there are three causes of death: starvation, dehydration and killed by predators. The first two are straightforward: the creature dies once hunger/thirst reach a certain level. For the third one, a creature takes damages when attacked by predators and dies when their hp reaches zero. As mentioned before, the damage taken is determined by a number of factors: maxHP, attack, defense, and the duration of the attack. It can also be avoided by fleeing, where speed and agility play a major role.

4 EXPERIMENTS

While most of the parameters that control the creatures' behaviors are determined by genetic algorithm, there are many other hyper-parameters that we can use to shape this world:

- **Resource Level**: determines the amount of resources in the world.
- **Initial Population**: initial population of different species.
- **Food Chain**: defines the predator-prey relationship.
- **Plant Regeneration Rate**: determines how fast plant regenerate.
- **Hunger/Thirst Tolerance**: determines how long does it take for a creature to die of hunger/thirst.
- **Reproduction Cost**: determines the hunger/thirst cost for reproduction.
- **Time Between Reproduction**: determines the minimum amount of time between two reproductions.
- **Food Conversion Rate**: determines the percentage of energy that can be transferred from one level of the food chain to another.
- **Mutation Chance**: determines the chance of mutation when genes are passed down to the next generation.

In this section, we will first choose a setting as a baseline and analyze the creatures' behaviors in depth. Then, we will play with some of the hyper-parameters and observe their impact on this simulated world and the evolution direction of different species.

4.1

In this baseline world, all hyper-parameters are set to what is considered the "normal level" - a setting that doesn't lead to immediate ecological disaster followed by the end of the world. We start off with 2500 plants, 1000 rabbits, 400 foxes and 200 eagles. The food chain is set as follow:

- **Plant** Prey: None | Predators: Rabbit
- **Rabbit** Prey: Plant | Predators: Fox, Eagle
- **Fox** Prey: Rabbit | Predators: Eagle
- **Eagle** Prey: Fox, Rabbit | Predators: None

As shown in Figure 7, the population change of the species is quite similar to what would happen in the real world: In the abundance of food and absence of predators, rabbits' population skyrockets at first, consuming a large amount of plants. In response, one of the rabbits' major predators, foxes, also see a sudden increase in population. Following that, eagles' population also increases for the same reason. Then, due to lack of food and increased number of predators, rabbits' number plummets, follows by foxes and eagles' decline in population. Meanwhile, plants start to grow back. As the number of predators decreases, rabbits' number bounces back a little for a while and but inevitably decline. In the end, the three species reach an equilibrium.

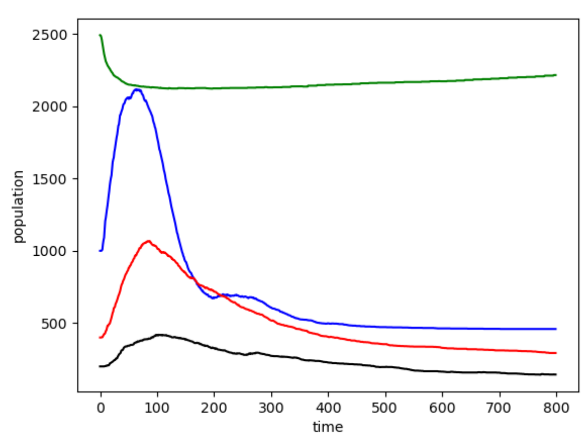

Figure 7: Population (Green: Plant, Blue: Rabbit, Red: Fox, Black: Eagle)

Figure 8 shows how some of the species's stats evolve over time. Rabbits, in the bottom of the food chain, evolve to have the highest defense and the lowest attack. To avoid their predators, they are the fastest species by a large margin for quite some time. Rabbits have low consumption rate during their baby boom period but it increases later as they have to keep up with the game when they don't have the numbers. Foxes, as both predators and preys, have a more balanced attack/defense. They are slower than rabbits at first but manage to catch up in the end. Eagles, as the apex predator, have a surprisingly low consumption rate and speed. The most probable explanation is that they only need to work hard enough to feed themselves and have no reason to spend extra energy on avoiding predators.

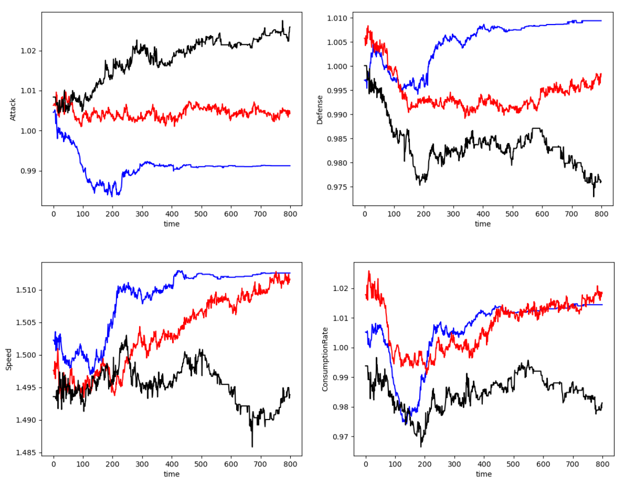

Figure 8: From left to right, up to bottom: Attack, Defense, Speed, Consumption Rate (Blue: Rabbit, Red: Fox, Black: Eagle)

Figures 9 shows the birth rate change over time. The birth rate of all three species are high at first but then slowly declines. The reason is that, reproduction, while being beneficial to the species, puts individual at a disadvantage. Therefore, creatures with relatively low reproduction tendency are more likely to survive. After many generations, the species as a whole has a low birth rate. As a result, even when food is abundant again (for rabbits), their number would never bounce back to the previous level.

4.2

Now, we will play with the hyper-parameters - resource level and reproduction cost, and compare worlds under different settings.

Figure 10 compares the population change over time under different resource settings (low/normal/high resource level). The higher the resource level, the more energy a creature can get from one unit of food. All settings exhibit similar curve shape for population change, except that the low resource setting one has a lower peak. Interestingly, the curves for normal and high setting are nearly the same, indicating that once resources reach a certain level, it plays very little role in affecting the population of the species.

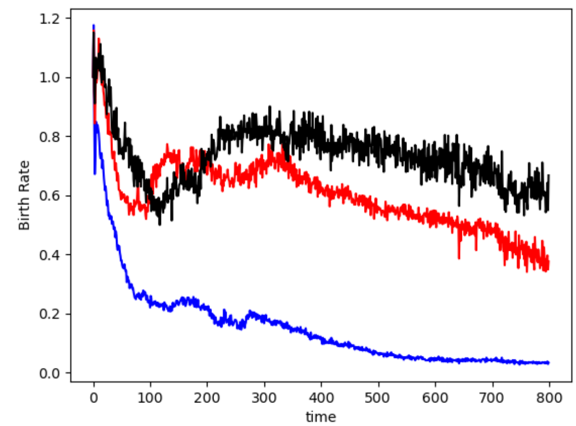

Figure 9: Birth Rate (Blue: Rabbit, Red: Fox, Black: Eagle)

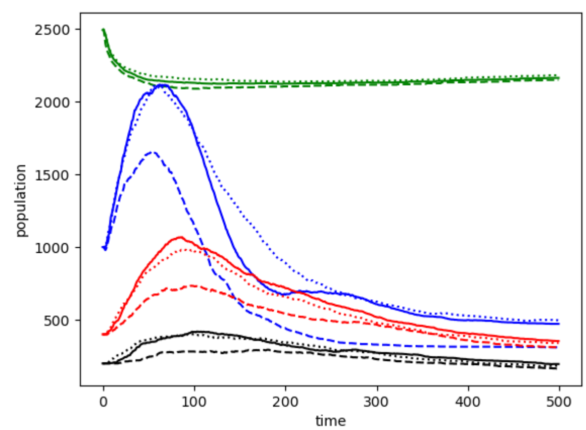

Figure 10: Population under different resource setting (Blue: Rabbit, Red: Fox, Black: Eagle; Dash: low resource, Regular: normal resource, Dot: high resource)

Figure 11 compares the population change over time under different reproduction cost settings. The normal and high reproduction cost settings exhibit similar curve shape, except the peaks are different. The low reproduction cost setting, however, has a second peak following the first baby boom period. The curve also fluctuates a lot more compared to the others. When we examine other stats in this setting, we find that the creatures also have a noticeably higher number of babies per pregnancy, lower attack, lower consumption rate and lower max HP (which further reduces the cost of reproduction). This means that under this setting, the best survival strategy changes from "being faster and stronger" to being able to produce more off-springs.

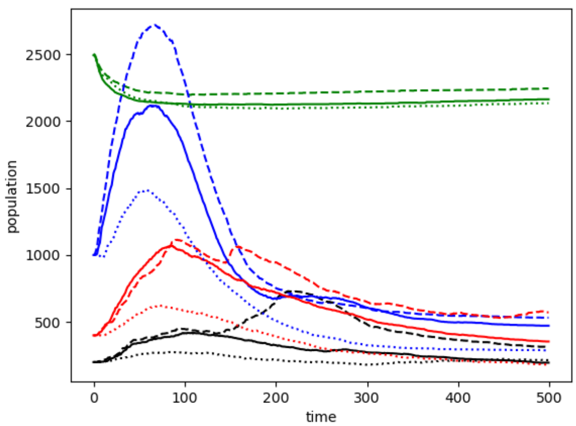

Figure 11: Population under different reproduction cost setting (Blue: Rabbit, Red: Fox, Black: Eagle; Dash: low reproduction cost, Regular: normal resource, Dot: high reproduction cost)

5 FUTURE WORK AND DISCUSSION

One main improvement we would like to make is the addition of acquired behavior. In our current implementation, the animals' behaviors are purely determined by their genes. Ideally, animals should be able to learn from their parents or by interacting with their environment. To make our simulation of the ecosystem more realistic, this ability would be a great addition. In order to achieve this, we would need to enable communications between neighboring creatures and add some kind of online learning mechanism. More details should be investigated for completing this task.

Another future direction we would like to work on is to model animals' brains more "realistically". Currently, the animals' brains are modeled as a simple feed forward network with relatively few neurons. Therefore, animals' behaviors are simply directed by the level of their desires, which are determined with respect to time. However, animals' brains are much more complex than that. Additionally, we did not differentiate among different types of animals. In other words, we assume all creatures have the same level of intelligence and suppose to act the same. Yet, this situation does not apply to animals in real world. One of the future direction of our project would be adding certain rules or advancing the neural networks behind creatures. For instance, we would pause the likelihood of reproduction and only increase it after a certain age for each type of animals to mimic the real world.

A PROJECT GITHUB LINK:

https://github.com/ZuerWang/CS275-Ecosystem.git

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