Conspecific Emotional Cooperation Biases Population Dynamics: A Cellular Automata Approach

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ABSTRACT

In this paper, the authors evaluate the benefit of emotions in population dynamics and evolution. The authors enhance a cellular automata (CA) simulating the interactions of competing populations with emotionally inspired rules in communication, interpretation, and action. While CAs have been investigated in studies of population dynamics due to their ability to capture spatial interactions, emotion-like interactions have yet to be considered. Our cellular stochastic system describes interacting foxes that feed on rabbits that feed on carrots. Emotions enable foxes and rabbits to improve their decisions and share their experiences with neighboring conspecifics. To improve the system's biological relevance, it includes inter-species disease transmission, and emotions encode data pertaining to both survival and epidemic reduction. Results indicate that emotions increase adaptability, help control disease, and improve survival for the species that utilizes them. Simulations support the hypothesis that the acquisition of emotion may be an evolutionary result of competitive species interactions.

Keywords: Cellular Automata, Population Dynamics, Emotion, Artificial Life, Predator-Prey

INTRODUCTION

Population dynamics study the development of either a single or multiple interacting species. In ecology, computational models are used to study the evolution within populations of plants and animals, such as which trees will survive in a forest over many hundreds of years, or what ratio of species is sustainable. A major topic of population dynamics is the cycling of predator and prey populations. Predator-prey dynamics relate to a wide variety of ecological situations, from microbial phagocytosis to lions and gazelles. Most often predator-prey systems are built to describe animal species, with at least one species as prey and one as predator; however, they are not limited to describing only two species. The Lotka-

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Volterra (Lotka, 1925) equations are based on the classic logistic equation, and commonly used to model this type of mutual interaction. However, it has been argued that these equations are not sufficient for truly modeling natural phenomena, as the expected fluctuations in species numbers are not sustained properly (Lehman, 1997).

Cellular Automata (CA) offer a popular mechanism to analyze population dynamics as they directly represent spatial interactions between entities (Hogeweg, 1988). CA allow the creation of rules for determining how an entity will interact with its neighbors. The most popular version of a self-regenerating cellular automaton is the Game of Life, developed by Conway (Gardner, 1970). In the Game of Life cells are created or removed for the next time step based on the number of neighbors the cell has in the current time step. Although the rules can be completely defined in a single sentence, the dynamics are complex enough that they are still not completely understood. This ability of CA to give rise to complex dynamics via simple rules enhances its desirability for modeling complex phenomena, assuming that the appropriate simple rules can be designed. Thus, in population dynamics models, entities can explicitly exist on a grid and interact with specific neighbors. The system not only knows how many of each species is in the system, but to what extent they are mixed. The world can either be viewed as a torus with periodic boundary conditions or a bounded box that may or may not be square. A torus is beneficial for analysis and computation as all cells have the same number of neighbors. However, in many ways a bounded region is more realistic, as the ecosystem of a set of species will not extend completely around the world but instead exist in some localized area.

We increase the realism of evolutionary dynamics models in CA by introducing intraspecies disease transmission and emotion-inspired rules for our predator and prey (foxes and rabbits). Real populations in nature are subject to epidemic diseases, a number of which can cross species. Such diseases have significant effects at the level of individual behavior and population dynamics. Evidence suggests that a primary contributor to the evolution of the emotion disgust is protection from the risk of disease (Curtis, 2004). We explore the relationship between disease transmission and emotional response. The development of emotions in higher animals has been conjectured to originate for purposes of survival in basic scenarios such as predator-prey (Blanchard, 2003; Löw, 2008), and thus emotionally-inspired rules are a natural extension to the traditional CA framework. Although they have been suggested previously for CA (Adamatzky, 2003), we are unaware of any work utilizing emotions in the context of predatorprey dynamics modeled within a CA framework.

Contradicting the older view that emotions typically interfere with decision making, in the last few years emotions were suggested to constitute an important part of adaptive decision making systems (Damasio, 1991; Sanfey, 2003). Case studies were reported describing people whose decision making was impaired when they suffered injury to or loss of areas of the brain related to emotion (Bechara, 2000). Instead of showing the benefit of decision making to an individual when emotions are involved as is done in these studies, we examine the benefit to the group when emotions are used.

Thus, we choose to include the six fundamental emotions as defined by Ekman (Ekman, 1999) to our rabbits and foxes, namely: happiness, sadness, fear, anger, disgust, and surprise. Emotions occur in response to specific world events, such as the happiness of food consumption the fear and of predator encroachment. Additionally, we enable conspecific communication of emotions to aid in coordination and cooperation. In other words, the emotional state of a member of a species will be communicated to a member of the same species within a restricted surrounding, and affect their emotional state. We consider this approach to emotional communication as an efficient way of transferring information that is crucial for the survival of the group. Our analysis shows that emotions enhance the realism of the simulation and offer increased utility to the modeled species. Additionally, we show that it is in the best interest of both rabbits and foxes to use emotion if they do not know if the other species will use emotion. This result is explained at a high level as a population dynamics version of the classic Prisoner's Dilemma, if we consider using emotion to be akin to defecting, and not using emotion as cooperating.

In this paper we first describe related work in the fields of population dynamics, cellular automata, and emotions. We then describe our model in detail, including our evaluation mechanisms. Finally we discuss results and conclude.

PREVIOUS WORK

Cellular automata have been modified to simulate and analyze many topics, with one of the first being von Neumann's description of selfreplicating automata (von Neumann, 1966), which has been built upon extensively. One such extension is the work of Petraglio toward creating a cellular automata capable of performing arithmetic operations by using self-replication of the cells (Petraglio, 1999). They have also been utilized for biological modeling of ants, where the floor is a set of CAs controlling the ant movement "above" them (Rosenberg, 2008).

Although these extensions maintained the traditional uniformity of all cells conforming to the same rules, CAs have also been extended such that each cell can run a different set of rules (Sipper, 1996). In Sipper's work this extension is used to evolve cellular automata capable of performing their desired computations. Additionally, all cells do not necessarily have to be updated synchronously, i.e. with all cells updating in parallel. However, the results of the system will vary based on the whether or not updates are synchronous (Schönfisch, 1999). Synchronous and asynchronous updates can also be combined, where many different asynchronous updates are performed within a single synchronous step (Gronewold, 1998). Arguments exist for the structure imposed by both synchronous and asynchronous CAs (Ingerson, 1984; Schönfisch, 1999). Step-driven methods for asynchronous updates include different strategies for sweeping the cells to perform updates. Directional sweeps provide a simple strategy whereby cells are according to their spatial order. updated Alternative sweeping techniques include fixed random sweeps and uniform choice, both randomization strategies. Both strategies are similar with the primary difference being replacement, which does not occur in the former, but does in the latter. A discussion of the practical implications of update ordering is presented in the next section.

An additional extension to CA is for population dynamics modeling, as CA allow the spatial environment to be directly modeled and thus for each entity to have specific neighbors with which to interact. The interaction of species living in symbiosis can be modeled with CA (Adamatzky, 2009), as well as the growth and death of single species (Tilman, 1997). Typical results exhibit dynamics of populations growing and declining over time.

Predator-prey models in particular often depend on spatial interaction and thus can benefit from CA modeling. Multiple interacting species move around the grid, with predator chasing prey. In some models, movement is purely defined by the birth of new entities into neighboring cells (de Carvalho, 2006; Farina, 2008), whereas other models allow individuals to actively move around the grid (Dewdney, 1984; Hawick, 2009). We will allow two of our species to actively move (rabbits and foxes), and one to only move by reproduction (carrots).

Predator-prey models are usually based on the Lotka-Volterra equations (Lotka, 1925), and thus they will allow for reproduction and death. Often the prey's need for food is either ignored or empty space is considered food (Dewdney, 1984; Farina, 2008; de Carvalho, 2006). It is also possible to require that reproduction occur during the same time step as eating (Hawick, 2009). Although a classic CA model would be completely based on neighbors for deciding actions, most predator-prey models are probabilistic (Dewdney, 1984). The interactions between predator and prey can be greatly influenced by how prey chooses between avoiding predators and finding food (Bell, 2009).

For predator-prey dynamics in a CA it can be useful to analyze the patterns created in the system. This can include how the number of predators and prev fluctuate in the system over time with differing parameters, as well as how mixed they are spatially (de Carvalho, 2006; Hawick, 2009). Results from (de Carvalho, 2006) indicate that a combination of Lotka-Volterra, an individual's ability to change, and the spatial structure of the CA give rise to both predators and prey selforganizing into self-sustaining patterns. It has also been proposed that taking the environment into account significantly affects results, potentially making them more realistic as living creatures naturally have outside influences other than a predator or prey (Farina, 2008).

CA models do not always have a single entity in each cell, although that is the most common approach (Dewdney, 1984; Hawick, 2009). It is also possible to superimpose several layers, each corresponding to a different entity, similar to a population dynamics meta-population model (Dong, 2010; Farina, 2008). In this case there will be fluctuations in the percentage of a cell that is each type of entity. It is unclear whether this approach is more or less realistic than a single entity per cell model, although this multi-layer structure allows an easier approximation of differential equations to model fluctuations within each cell (Dong, 2010; Farina, 2008). However, it has been argued that a CA model can provide better results than a partial differential equation model (Hawick, 2009), and they are viewed as the norm for spatial predator-prey models.

A goal within the predator-prey modeling community is to move toward more realistic models. One possible previously unexamined direction is to include emotion-based features for each species in the environment. Although there are a number of human psychological theories of emotion (Ekman ; Plutchik, 2001; Rolls, 2005), it is generally agreed that emotions serve the purpose of increasing our ability to interact with our environment in a successful manner. CA have been studied with emotions in the past for investigating the behavior of an individual. For instance, the interaction of individual emotions within a single person was studied using a CA to determine how they work together to influence an behavior individual's (Adamatzky, 2003). Emotions have also been studied as part of an artificial entity modeled with a CA (Davis, 2001). The goal of our study is to introduce emotions to a species by including rules on how each individual gains and updates emotions, how the emotions of the individuals are shared with other conspecifics. and how each member changes its behavior locally based on its emotional state. The outcome is a coordinated group of individuals that act like a complex system with shared emotions. Such experimentation may be of importance both in understanding evolution of competing species as well as in the future of coordinating multi-robot systems.

Rolls has argued that human emotions have ten functions, including reflexive behaviors and motivation (Rolls, 2005). These functions are advantageous for predators and prey as well, causing them to react quickly when near the other. It has been suggested that human emotions were initially evolved due to the need to survive, showing many commonalities with both the reaction of prey to predator and predator to prey (Plutchik, 2001; Löw, 2008). Although there have been arguments that any defensive action in a prey represents emotions, more recently that view has been modulated to instead argue that although this may not always be the case, it is still likely that initial reactions to threat in animals can precede emotions (Blanchard, 2003).

We therefore study computational emotions in the predator-prey context via a CA. We propose a mechanism for communicating emotions among nearby species members. Groups of prey in real situations will exchange information about their surroundings, increasing their likelihood of survival (Sirot, 2009). In the proposed model, the communicated emotions will include hints about a variety of survival conditions such as satisfaction (from food), fear (from predator), and disgust (from food poisoning). These emotions will result in behavior directing the individual to move in the best direction for survival. Our paper therefore discusses new ways for how emotions can be added to a predator-prey cellular automata, and analyzes the resulting population dynamics.

OUR MODEL

We use a CA based model to examine predatorprey dynamics in an environment that represents diseases and where emotions are developed individually and communicated to neighboring conspecifics. For ease of description we will label our species as rabbits, foxes, and carrots. All are able to reproduce, with foxes attempting to catch rabbits and rabbits attempting to find carrots. All species movement is based on individual preferences that take into account knowledge about the environment gained through the shared emotions from their neighboring cells.

The model is defined as a four-species CA. Entities are able to reproduce, move, and die. Empty spaces (the fourth species, vacancies, as described in the literature) represent an area where any of the other species may reproduce or move. Our grid structure is defined as a torus, and thus there are no corners requiring special treatment. Each individual's next step is determined based on probabilities and their neighbors within the Moore neighborhood (8 neighbors), as suggested to be ideal by Chen (2003). The implementation of the CA is asynchronous. The model world is shown in Figure 1 to demonstrate the non-uniformity of the distribution of entities within the simulation. By using stochastic movements on a toroidal grid the potential for structure induced by directional sweeps is essentially removed.

All species are given the ability to reproduce after they reach maturity (defined in time steps), and then the individual may reproduce probabilistically. Reproduction may occur only



Figure 1. Simulation world at multiple time steps shows the dynamics of model, and how it may differ between a world (a) without emotion, (b) without fox emotion but with rabbit emotion, (c) with fox emotion but without rabbit emotion, and (d) a world with fox and rabbit emotion. Vacant squares are in black, carrots are in dark gray, rabbits are in gray, and foxes are in white.



Figure 2. Population dynamics of the system with different parameter settings. In (a) all population sizes tend towards non-zero attractors. In (b) the fox population crashes while the rabbit and carrot population sizes continue to tend towards non-zero attractors.

when there is at least one vacant surrounding location. After reproduction, the age of an individual is reset to zero and the individual has to wait again before another reproduction is possible. The reproduction in rabbits and foxes is affected by emotions, and for simplicity all reproduction is asexual. Some aspects of the model results may be slightly less realistic as a result, but as the goal is to examine the use of a modeling technique instead of directly modeling a specific environment, our hypotheses can be equally tested in either case.

Within the model rabbits and foxes are mobile, with each attempting to move toward their food source. A predator eats a prey when it moves to the prey's position. Once all of a species have been eaten, no more of that species can come into being in the system. An example of this situation can be seen in Figure 2(b). However, as long as there is still at least one of a species alive it is possible for it to reproduce to create a new one (Figure 2(a)).

Both rabbits and foxes may starve, and therefore the number of carrots in the model can strongly affect the overall dynamics of the system. We choose an adequate reproduction rate and initial number of carrots such that rabbits are unlikely to starve due to inability to find food. Each entity is also capable of becoming diseased. Disease initiates in the carrot population, and moves to the rabbits and then the foxes when eaten. A diseased rabbit or fox will become hungry at double the rate of a healthy rabbit or fox, thus increasing their chance for reaching starvation and die.

Rabbits and foxes can exist either with or without emotions. Carrots are not affected by emotions. We will first describe the model without emotions, and then describe how emotions are generated and how they modify individual behaviors within the model.

Probabilistic and Neighbor-based Rules

At every time step, each cell occupied by a carrot will update following these rules in this order:

- *Reproduction:* All carrots at the maturity age will produce a new carrot into an adjacent square, and the age of both carrots will be reset to zero. If there are no empty adjacent squares for a carrot at maturity age, then no reproduction takes place and its age is still reset to zero.
- *Disease:* When a new carrot is produced it has a probability (0.1) of being diseased, unless the parent is already diseased in which case the probability is doubled to 0.2.
- *End of disease:* Disease will last for a minimum of 2 timesteps. After that minimum time has elapsed, there is a fixed probability *Cure* of disease being cured at each timestep.
- *Aging:* After all reproducing carrots have been updated, the age of all carrots is incremented by 1.

Rabbits and foxes follow slightly more advanced rules at each time step:

• *Movement:* Movement occurs by computing a local gradient of preference for the surrounding cells that do not contain another individual of the same species, as seen in Eq 1. Species can only move to a cell with another individual there if that individual is their food source.

$$g_{d,sp}(t,x,y) = food_{sp}(t,x_d,y_d), \qquad (1)$$

where *d* in D = {NW, N, NE, W, E, SW, S, SE}, *t* is the current time, $g_{d,sp}(t,x,y)$ represents the preference for each direction d at time t for

an individual at location (x,y), $sp \in \{$ rabbits, foxes}, and food_{sp}(t, x_d, y_d) returns the existence of prey for a given species, sp, at locations in direction d from position (x,y) at time t calculated on that gridpoint and its two neighbors. For instance, $food_{sp}(t, x_N, y_N)$ will be equal to 2 if there is food source at the N direction and either the NE or NW direction. For rabbits this is taken to be the sum of all carrots, and for foxes it is the sum of all rabbits. These preferences are converted to normalized probabilities that bias the individual's otherwise random movements.

- *Movement rate:* When a rabbit/fox is diseased it will have a decreased probability of movement each timestep (*DiseaseMove*).
- *Hunger level:* Every rabbit/fox gets hungrier by a value of 1 each timestep if it doesn't eat, unless it is diseased. If diseased, it gets hungrier by a value of 2. Hunger is decreased to 0 when it eats.
- *Food/Disease:* When a predator eats a prey its hunger is returned to 0. However, if the prey was diseased the predator becomes diseased as well.
- *End of Disease:* Disease will last for a minimum of 2 timesteps. After that minimum time has elapsed, there is a fixed probability *Cure* of disease being cured at each timestep.
- *Reproduction:* If the rabbit/fox is of maturity age there is a fixed probability *Rep* of a new rabbit/fox being created in an adjacent vacant square. The individual's age will continue to increase until it eventually reproduces, and then it will be reset to count to the next reproduction opportunity. However, reproduction can only occur if a vacant square exists.
- *Aging:* After all reproducing rabbits/foxes are updated, the age of every rabbit and fox is increased by 1.

Emotion Calculations

Emotions for rabbits and foxes are included in the model for individuals and as communication to improve realism and applicability, as described in the previous work section. Carrots do not have emotions. Emotions are calculated at the end of the sequence described in the previous subsection, and are used by rabbits and foxes when determining the next movement direction as well as their probability of reproducing. They are based on Ekman's original six basic emotions (fear, anger, sadness, happiness, disgust, surprise; Ekman, 1999). Individuals communicate their emotion, which can influence the emotions of other nearby individuals from their own species. Communicated emotions of one species cannot be seen or interpreted by the other species.

Each individual maintains values of their own emotions. Emotions are independent for both rabbits and foxes, and each emotion is affected by different experiences. For rabbits, **fear** increases with the number of surrounding foxes. For foxes, **fear** increases with the amount of anger felt by surrounding foxes. **Anger** for each species increases exponentially based on hunger level. **Sadness** increases the longer the individual has gone without reproducing. **Happiness** increases after food consumption. **Disgust** increases when an individual is diseased. **Surprise** increases by the average amount of change in all of the other five emotions from one time step to the next. The numerical values used to represent these experiences when calculating emotions can be seen in Table 1.

Emotion	$X_{e,sp}(t,x,y)$	
Happiness	1 if ate prey,	
	0 otherwise	
Sadness	t – [timestep of last reproduction]	
Anger	exp^(hunger)	
Fear (fox)	Anger of neighboring foxes	
Fear (rabbit)	Number of neighboring cells with foxes	
Disgust	1 if ate diseased prey,	
	0 otherwise	
Surprise	$Sum_e(E_e(t,x,y)-E_e(t-1,x,y))/5$, where e does not include surprise	

Table 1. Experience values affecting each emotion. For each emotion the corresponding value of the experience variable is listed.

An individual's emotions are based on these experiences, as well as their previous emotion and the emotions being communicated nearby. They are computed at each time step as seen in Eq. 2. The previous emotion and communicated emotion are both discounted, to prevent them from overpowering newer experiences or causing monotonically increasing emotions over time.

$$E_{e,sp}(t+1,x,y) = (1 - c_{m,sp}) * (X_{e,sp}(t,x,y) + c_{c,sp} * CE_{e,sp}(t,x,y)) + c_{m,sp} * E_{e,sp}(t,x,y) , \quad (2)$$

where $e \in \{\text{fear, anger, sadness, happiness, disgust, surprise}\}, sp \in \{\text{rabbits, foxes}\}, X_{e,sp}(t,x,y)$ is the unique experience of each emotion for each species (Tbl. 1), $c_{m,sp}$ is the memory discounting coefficient that determines what percent of the new emotion is based on new versus old emotional information and is calculated as in Eq. 3, $c_{c,sp}$ is the discounting coefficient for communicated emotion, and CE_{,sp}(t,x,y) is the communicated emotion at

position (x,y) at time *t* as shown in Eq. 4. The coefficient $c_{m,sp}$ is bounded to [0.1,0.5] and $c_{c,sp}$ is bounded to [0,1).

$$c_{m,sp} = 0.1 + 0.4 *$$

$$\frac{abs(E_{surprise,sp}(t,x,y) - E_{surprise,sp}(t-1,x,y))}{(E_{surprise,sp}(t,x,y) - E_{surprise,sp}(t-1,x,y))}$$
(3)

Emotions are computed for each individual and remain at that location decaying iteratively every timestep; however, an individual will overwrite old emotions at their location when they move to a new location. The calculation of communicated emotion can be seen in Eq. 4.

$$CE_{e,sp}(t,x,y) = \sum_{d \in D} \left(S_{sp}(t,x_d,y_d) * E_{e,sp}(t,x_d,y_d) \right)$$
(4)

where $e \in \{\text{fear, anger, sadness, happiness, disgust, surprise}\}$, sp $\in \{\text{rabbits, foxes}\}$, D

represents all directions, $S_{sp}(t,x_d,y_d)$ returns 0 or 1 denoting the existence of species sp in direction d from position (x,y) at time t, and emotion $E_{e,sp}(t,x_d,y_d)$ is the amount of emotion in direction d from position (x,y) at time t. After emotions and communicated emotions have been calculated for all entities in the system, all emotions are decayed linearly by a small value denoted in Tbl. 2.

Rules Enhanced by Emotions

Rabbits and foxes with emotions have altered reproduction rates, and movement direction preferences from their unemotional counterparts. Other aspects are calculated the same as shown in the Probabilistic and Neighbor-based Rules section.

Reproduction Rates: Rabbit and fox reproduction rates are altered positively by their happiness, and negatively by their disgust and anger. Additionally, rabbits will not reproduce at all while their fear is above a threshold. The calculation of reproduction rate can be seen in Eq. 5.

$$R(t) = Rep * (1 - Rep) * (E_{happiness}(t, x, y) - Rat * E_{disgust}(t, x, y) - (1 - Rat) * E_{anger}(t, x, y))$$
(5)

where R(t) is the probability of reproducing at time t, *Rep* is the initial probability of reproducing after the maturity age has been reached, *Rat* is the ratio of how much disgust versus anger decreases reproduction, and $E_{happiness}(t,x,y)$, $E_{disgust}(t,x,y)$, and $E_{anger}(t,x,y)$ represent the current emotional value of the listed emotion.

Movement Preference: The local preference gradient for movement considers emotions, where an individual will move toward the highest positive value $g_{d,sp}(t,x,y)$. This differential is taken to be the difference between the emotion in a given direction and the current emotion of the individual, as seen in Eq. 6.

$$g_{d,sp}(t,x,y) = \text{food}_{sp}(t,x_d,y_d) + \sum_{e} \left(\text{valence}_{e} * \left(\mathsf{E}_{e,sp}(t,x_d,y_d) - \mathsf{E}_{e,sp}(t,x,y) \right) \right)^{(6)}$$

where (x,y) represents the individual's current location, (x_d, y_d) represents locations in direction *d*, *e* is taken over all emotions except surprise, and

 $valence_e$ is -1 for a negative emotion e (fear, anger, sadness, disgust) and 1 for a positive emotion e (happiness).

Emotions are used to encode and communicate various features of the environment to modulate the behavior of individuals. The components of the environment incorporated into emotions are intuitively useful for survival, which suggests that emotions should modify the behavior of individuals in a way that is beneficial for their species.

Simulation Details

The simulation is run on a grid world of size 100 x 100. Each point on the grid interacts with its Moore neighborhood of radius 1. Simulations are run for a total of 2000 time steps with an initial random placement of individuals on the grid. Each of the twenty initial placements are tested on the four emotion scenarios: no emotions, only foxes using emotions, only rabbits using emotions, and both species using emotions.

Initial population sizes for foxes, rabbits, and carrots were 1000, 2000, and 6000. Initial parameter searches were done on both population parameters and emotion parameters for all populations. The initial parameter searches for emotion were done for when only rabbits have emotion or only foxes have emotion, to determine how the individual parameters affect the overall population dynamics. From these parameter searches the most promising parameters were taken to combine and investigate further; those parameters are used in the results section and can be seen in Table 2 and Table 3.

	Carrot	Rabbit	Fox
Rep	n/a	0.75	0.75
Maturity Age	2	6	7
Cure	0.8	0.8	0.8
DiseaseMove	n/a	0.8	0.8
Starvation	n/a	2	6

Table 2. Non-emotion parameters for each species. Rep is the probability of reproducing after reaching the Maturity Age, Cure is the probability of being cured from, DiseaseMove is the probability of an individual moving if it is diseased, and Starvation is the hunger level that causes death.

	Fox	Rabbit
Decay rate	0.45	0.45
Rat	0.4	0.4
$C_{c,sp}$	0.55	0.75
Fear threshold	n/a	0.5

Table 3. Emotion parameters used in experiments. Decay rate linearly decrements the emotion value at every point, Rat denotes the ratio of how disgust and anger affect reproduction rate, $c_{c,sp}$ discounts communicated emotion from surrounding conspecifics, and the fear threshold denotes the level of fear necessary to pause rabbit reproduction.

RESULTS

The basic dynamics of the system can be seen in Figure 3 for the four scenarios: without emotion, with foxes only having emotion, with rabbits only having emotions, and both populations having emotions. In Figure 3(a) we see that rabbits benefit the most if they are the only population using emotions, and suffer the most when foxes are the only population using emotions. We should also note that the rabbit populations in the rabbit-only emotion scenario are hitting what we have seen to be a glass ceiling in the system for this particular amount of initial carrots. Thus, rabbits have the most evolutionary benefit when foxes do not use emotions, whether or not rabbits use emotion. As will be explained by later figures, this disparity is due to emotions enabling foxes to eat rabbits much quicker, and emotions only marginally increasing a

rabbit's ability to flee from foxes. As would be expected, this directly impacts the carrot population (Figure 3(c)): the ordering of best to worst scenario for carrots is a direct inverse of the population size ordering for rabbits.

Figure 3(b) shows the corresponding fox population. Again the most intuitive aspect is that fox-only emotion gives the fox the best situation, and rabbit-only emotion gives them the worst situation. The scenarios of both populations having emotion or neither having emotions are in the middle, although with no significant distinction between them unlike for rabbits. Emotions increase a fox's ability to find rabbits to eat, but do not decrease its disease rates. The following figures will examine this disparity further.

We next investigate the trends in Figure 3. Population changes are directly affected by death and reproduction. The causes of death are highly inter-related and cannot be examined completely separately. For rabbits and foxes death is caused by starvation, which is less likely with higher food consumption, and more likely with higher disease rates. Rabbit death is also caused by foxes eating them, so fox consumption is related to rabbit death as well. Reproduction is highly affected by hunger, disease, and nearby predators due to emotions. A rabbit will pause reproduction when it has high fear, and both rabbits and foxes reproduce less frequently when they have not eaten recently, or have recently eaten diseased food. Thus, we must examine death and reproduction for rabbits and foxes to fully understand the population changes.



Figure 3. Population variation over time. The population over time is shown for no emotion, rabbit-only emotion, fox-only emotion, and both species emotion. The rabbit population (a) is highest when only rabbits have emotion with no emotion as a close second, and lowest when only foxes have emotion, and all emotion as second worst. The fox population (b) and carrot population (c) are both highest when only foxes use emotion, and lowest when only rabbits use emotion, with all emotion and no emotion close in the middle.



Figure 4. Rabbit consumption, disease, and starvation are all correlated. (a)Rabbits eat most frequently when foxes use emotion. This graph is the inverse of Figure 3(a), as rabbits eat the most when they have the lowest population size. (b) Rabbits are the most diseased with fox-only emotion, and the least diseased with rabbit-only emotion. Disease is highly correlated to amount of carrots eaten. (c) Although rabbits starve at a very low rate overall, they starve the fastest in the scenario where they eat the least and are the most diseased. These trends are very similar to the trends in Figure 3(a).

We first examine rabbit population changes. Rabbits eat most frequently (Figure 4(a)) and are the most diseased (Figure 4(b)) when foxes use emotion. Disease is highly correlated to the amount of carrots eaten and fox emotion. Rabbit-only emotion minimizes rabbit disease, so disgust is allowing rabbits to avoid diseased carrots. Rabbits may have the lowest population size when they eat the most due to less food being available for other rabbits. Rabbits starve at a very low rate overall, the fastest being with rabbit-only emotion, where they eat the least and are the most diseased (Figure 4(c)). The rabbit population is not highly dependent on rabbit starvation rates though, as the scenario of highest starvation (rabbit-only emotion) is also the scenario of highest population. Starvation rates are inversely related to population, and thus reproduction must play a vital role.

Rabbits reproduce the least when they use emotion (Figure 5(b)), likely due to fear, disgust, and anger significantly decreasing their probability for reproduction. In the highest population scenario of rabbit-only emotion, rabbits are reproducing the least, eating the least, having the lowest disease, and starving the most. It therefore is most likely that rabbits are best off with rabbit-only emotion because it allows them to escape foxes the easiest, as reproduction rates and death by starvation



Figure 5. Fraction of individuals reproducing over time. (a) Carrots reproduce most frequently when only rabbits use emotion, and least frequently when only foxes use emotion, corresponding to rabbit population size (Figure 3(a)). This suggests that higher carrot growth is due to less competition for carrots among rabbits. (b) Rabbits reproduce most frequently with fox-only emotion, closely followed by no emotion. Rabbits reproduce the least when they use emotion, likely due to fear, disgust, and anger significantly decreasing their probability for reproduction. (c) Foxes reproduce most frequently when they do not use emotion, most likely due to disgust and anger decreasing their reproduction probability. The effect is less pronounced than for rabbits as there is no fear level that stops them from reproducing completely.



Figure 6. Fox consumption, disease, and starvation are correlated. (a) Foxes eat the most frequently when they use emotion. (b) Foxes are the most diseased when the use emotion, and thus when they eat the most. Thus, emotions are not improving a fox's ability to avoid diseased food. (c) Foxes starve fastest when they do not use emotion, corresponding to when they eat the least and are the least diseased. Starvation rate does not directly correspond to population size.

do not explain the population changes. This hypothesis is supported by Figure 6(a), where the rabbit-only emotion and no emotion scenarios are seen to decrease fox consumption.

The fox population is benefited the most by fox-only emotion, but no emotion and both rabbit and fox emotion scenarios are tied for second. Foxes consume the most rabbits when they use emotion to enable them to track rabbits (Figure 6(a)), but they are also the most diseased when they use emotion (Figure 6(b)). Fox disgust does not appear to be successful in allowing foxes to avoid eating diseased rabbits, although it is successful in allowing rabbits to avoid diseased carrots. Most likely this is due to the fact that a fox's food is mobile, while a rabbit's food is not. If a fox is seeing high disgust to the south from other foxes, that does not mean that the diseased rabbits are currently in that direction, only that they recently were in that direction. Rabbits do not have this problem as carrots are stationary, so their diseased relatives will stay near where a diseased carrot was recently eaten.

Foxes starve slowest when they use emotion, corresponding to when they eat the most and are thus the most diseased. Fox starvation is close to completely describing the trends seen in Figure 3(b), however the case of no emotion results in a

higher population count despite also resulting in higher starvation. Therefore reproduction must play a significant role in population numbers as well. Foxes reproduce the most when they do not use emotion (Figure 5(c)). Anger and disgust are thus noticeably decreasing fox reproduction. Fox reproduction is not as significantly decreased by emotion as rabbit reproduction is since fox reproduction is not paused by fear. If we take both starvation and reproduction into account, however, the trends in Figure 3(b) are logical. Fox reproduction has a stronger affect on the fox population than rabbit reproduction has on rabbit population because there is no predator to counteract reproduction, so it is only slowed by lack of prey. This result is expected in predatorprey dynamics.

We conclude that emotions are a mechanism that can propel a species toward the lead of the evolutionary race by analyzing our results as an instance of the Prisoner's Dilemma problem. Table 4 shows the rankings of each scenario for rabbits and foxes. If foxes choose to use emotion, then rabbits are in either their ranking 3 or 4, and are better off if they also have emotion (ranking 3). If foxes choose not to use emotion, rabbits are in their ranking 1, so both are equal. Likewise, if rabbits choose emotion, then foxes are either in

	Fox Emotion	Fox No Emotion
Rabbit Emotion	R3, F2	R1, F4
Rabbit No Emotion	R4, F1	R1, F2

Table 4. Prisoner's Dilemma diagram showing the ranking of each situation for rabbits (labeled R) and foxes (labeled F). The rankings are based on the ordering in Figure 3, with 1 as the best scenario and 4 as the worst; ties are denoted appropriately. Both foxes and rabbits should choose emotion if they are trying to maximize their own population's payoff.

their ranking 2 or 4, and are better off if they also have emotion (ranking 2). If rabbits choose not use emotion, then foxes are either in ranking 1 or 2, and are better off if foxes choose to use emotion (ranking 1). Thus, the logical choice for rabbits and foxes if they do not know if the other species uses emotions is to use emotions themselves, as it always maximizes their situation. It thus appears that rabbits and foxes are both better off if they choose to use emotions.

CONCLUSIONS

Predator-prey dynamics are frequently modeled by cellular automata due to the spatial ordering of entities within the system. This spatial ordering allows each member of the population to exist in a specific place on the grid and interact with its neighbors, potentially giving a more realistic dynamic among individuals. As some emotions have been found to evolve for survival in a predator-prey environment, we enhance the model by adding computational emotions based on Ekman's six basic emotions to our predator and prey. Conspecific communication of emotion allows individuals to transmit relevant local information to other members of its species.

Representing a biological system as a model always leaves some features of the environment unexplained or oversimplified. This has been true ever since the first use of physical laws to describe the real world. The use of cellular automata to model a biological system is no different. CAs approximate decisions based upon complex state information with simplified rule sets. In studying this model it is important to consider that the model describes approximations of behaviors for rabbits, foxes, and carrots. It is also important to consider that the emotions are the authors' interpretations of previous studies and observations. Nevertheless, the model is constructed to serve as a useful tool for exploring the population dynamics and behavioral effects of interacting species.

Our introduction of emotion to a predator-prey model has shown multiple biases in the population dynamics: increased food consumption; reduced predation; and increased population sizes. These biases are not guaranteed by the introduction of emotion as the dynamics of the system links system attributes, i.e. too many rabbits can lead to overcrowding, decreased growth, and increased starvation. Nevertheless, the introduction of emotion to a species generally increases its population size, and the use of emotion within a species has a dynamic akin to the Prisoner's Dilemma.

conspecific The use of emotional communication can be thought of from a game theoretic perspective. By being the only species to use emotion it is possible for a species to gain an advantage in the world. Being the species not using emotion leads to a disadvantageous position. Further work is required to understand the cooperative mode in the context of conspecific emotional communication; however, in our results we see favor towards neither species using emotion as the cooperative mode. This suggests that the acquisition of emotion may be an evolutionary result of competitive species interactions.

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