Evolution of Cooperation in Agent-based Simulations

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1 Introduction

Language provides us with the means for sophisticated communication and is arguably a key difference that sets us apart from non-human animals. An important function of communication is to coordinate cooperation. What are the necessary conditions for a species to evolve the capability to communicate and cooperate? As Számadó et al. (2021) note, this question is still left unanswered, although prior research suggests that reputation plays a key role in cooperation.

Prior research has investigated two distinct reputation-based systems: indirect reciprocity (IR) systems and reputation-based partner choice (RBPC) systems. In IR systems, if an agent helps another agent, they are more likely to receive help by a third agent in the future. Thus, agents build a reputation that has an influence on their future chances of receiving help. Similarly in RBPC systems, agents also build up a reputation based on their helping behaviour toward others. Unlike in IR systems, agents' reputations have an influence on their reproductive chances rather than receiving help. Roberts et al. (2021) compared these two systems and argued that the latter scenario is more relevant in interactions amongst humans, thus RBPC models deserve more attention.

A topic related to cooperation is gossip. Gossip occurs when a sender communicates information about a target to a receiver. In natural settings for example, gossip was often found to contain information about another person's cooperativeness and serves as a way to update that person's reputation (Dores Cruz et al., 2021).

This study follows the literature overview of cooperation by Számadó et al. (2021) and investigates the evolvability of the presented theories using agent-based simulations.

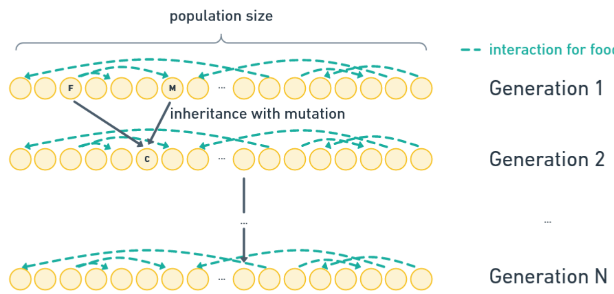
2 Biological Models of Cooperation

All models in this paper follow the general structure presented in Figure 1. The population size (how many individuals are in each generation) and the number of generations before a simulation concludes are arbitrarily chosen but can potentially influence the outcome of the simulation.

At a bare minimum, a biological model of evolution needs to implement the three main principles of evolution outlined by Darwin: variation, inheritance, and differential survival (Fitch, 2010). Variation and inheritance are loosely based on the biological process as seen in Figure 2. Differential survival is implemented by the fact that if agents do not acquire enough food they die and thus cannot reproduce.

Figure 1

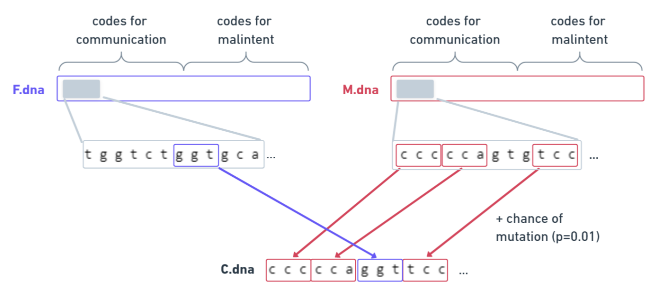
Simulation Setup



Note. Reproduction with inheritance occurs after all interactions of a generation have taken place.

Figure 2

Variation and Inheritance of Traits



Note. The DNA sequence is inherited in triplets.

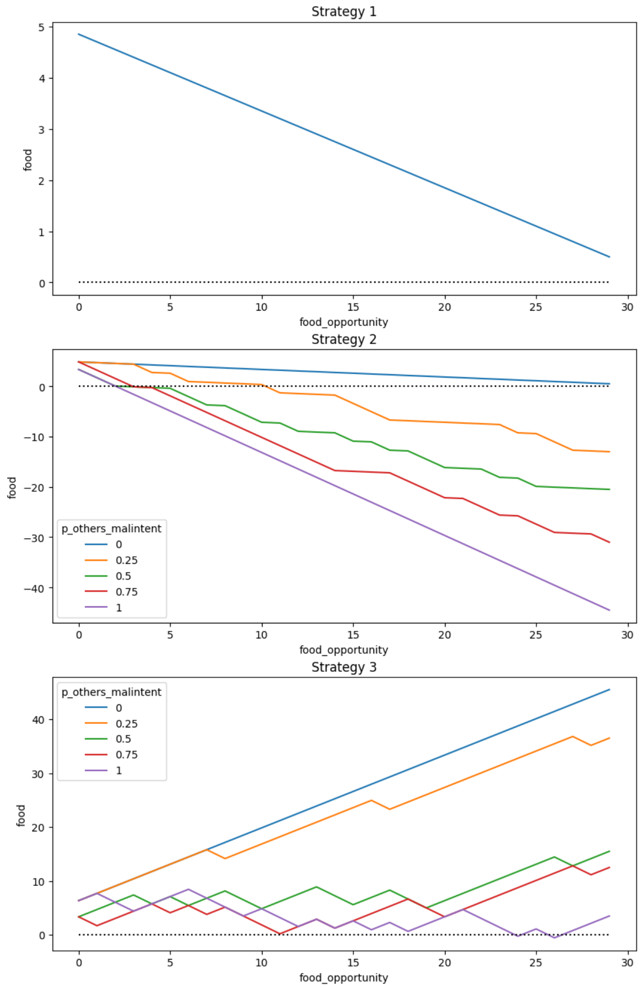
Since we are interested in cooperation, agents have two continuous traits: communication and malintent. Agents are repeatedly presented with food opportunities, in which they have the following three options:

1. Do not communicate and acquire food by themselves.
2. Communicate with intentions of sharing food.
3. Communicate with intentions of taking all food for themselves.

The long-term outcomes of using either one of the three strategies in the is presented in Figure 3 below.

Figure 3

Effects of Strategies on Long-term Food Reserves



Note. The dotted line denotes the threshold at which agents starve.

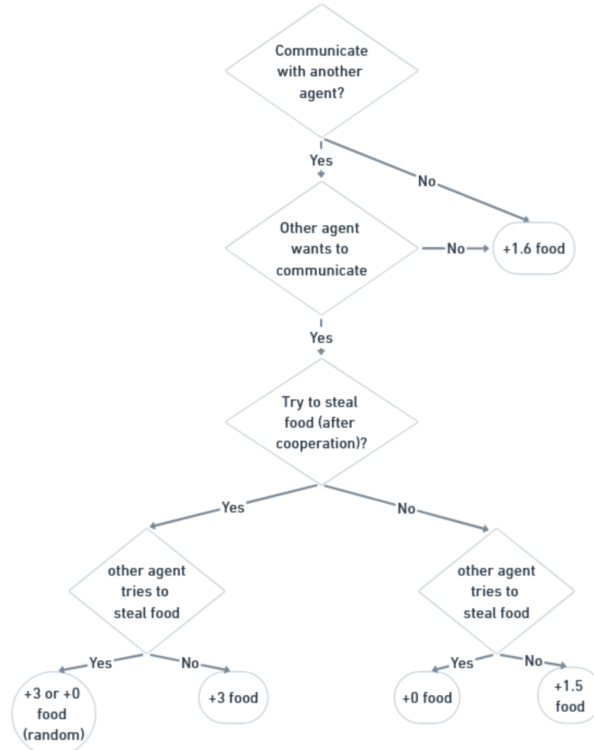
Cooperation occurs when both agents communicate with good intentions. I adopt the definition of cooperation by Számadó et al. (2021): "The production of mutual benefits at a cost to the individual". Following this definition, the cost for the individual for cooperating is that they receive slightly less food or none at all if the other agent steals the food than if they had simply not communicated. The mutual benefit of cooperating is that both individuals gain reputation. All potential outcomes for one interaction are shown in Figure 4

2.1 Reputation-based Partner Choice (RBPC)

This model assumes that reputations have an influence on the choice of the sexual partner. Agents can gain reputation by cooperating with other agents. The reputation is used to calculate the reproductive chances for each individual using a categorical distribution.

Figure 4

Decision Flowchart for Food Opportunities



The simulations that were performed suggest that in RBPC systems communication emerges over time while malintent does not (Figure 5). Varying hyperparameters such as simulation length, population size, number of interactions, and food decay gave similar results.

2.2 Indirect Reciprocity (IR)

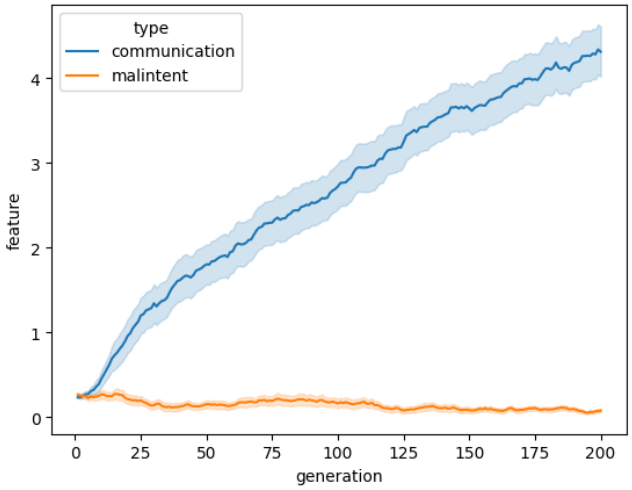
In the IR model, agents also gain reputation which improves their chances to communicate instead of their chances to reproduce. In the simulations that were performed, neither communication nor malintent emerged over time (Figure 6). Similar to the RBPC model, running the IR model with different hyperparameters yielded similar results where neither of the traits emerged.

2.3 Limitations of Biological Models

In the biological models, reputation is treated as a white box: every agent knows the reputation of another precisely, even when it results from interactions that the . This is unrealistic since animals in the real world do not have perfect information about the behaviour of others.

Figure 5

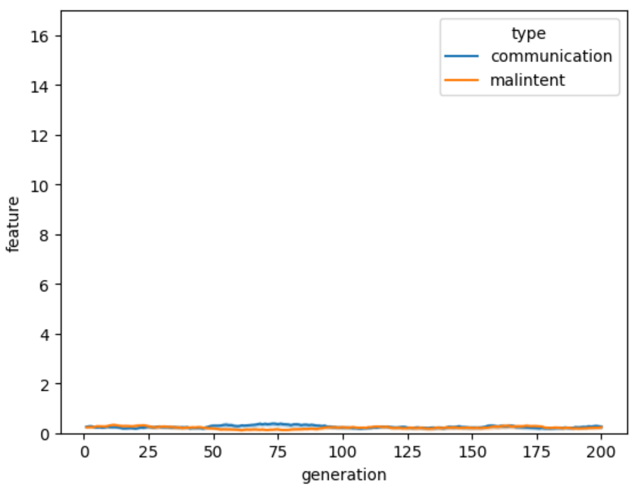
Communication emerges in the RBPC model



Note. Based on 30 replications of the RBPC model. The error bands represent 1 standard error from the mean.

Figure 6

Communication does not emerge in the IR model



Note. Based on 30 replications of the IR model. The error bands represent 1 standard error from the mean.

Agents have a fixed probability to communicate with any other agent. This is unrealistic because most animals are capable to adapt their behaviour based on prior interactions.

These shortcomings will be addressed by the next model.

3 Bayesian RBPC Models

In this model, agents can update their probability to communicate with other agents based on the outcome of communication. Their prior is still informed by their DNA, however, they can learn to treat another agent differently based on the outcomes of their interactions. For example, agent 1 communicates with agent 2 $c(a_1, a_2)$ based on their prior:

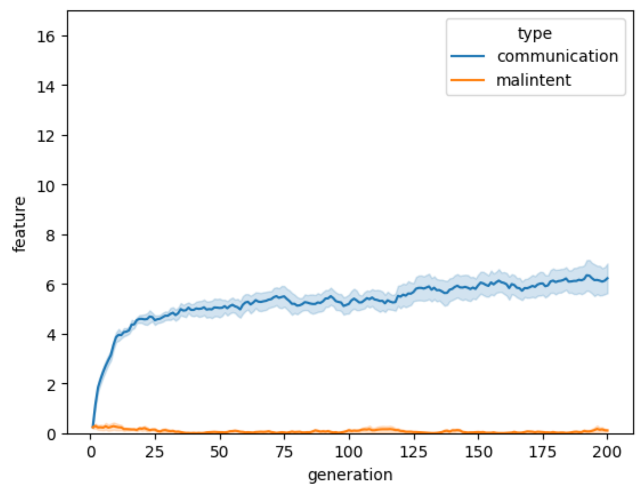
$$P(c(a_1, a_2)) = Beta(\alpha, \beta)$$

This prior is determined by their inherited DNA sequence. Based on the outcome of their interaction, agent 1 can update their probability to communicate with agent 2 ($Beta(\alpha + 1, \beta)$ for a positive outcome, $Beta(\alpha, \beta + 1)$ for a negative one) [1].

Reproduction also works differently now to address the unrealistic assumption that agents have perfect knowledge of other agents' reputations. Instead, pairs of agents are sampled. Then their probabilities to communicate with each other are used to reflect partner choice.

Figure 7

Communication emerges in the Bayesian RBPC model as well



Note. Based on 5 replications of the Bayesian RBPC model. The error bands represent 1 standard error from the mean.

3.1 Gossip

A topic we have not yet touched upon is gossip. Gossip can be simulated by letting agents share information about their last encounter with other agents.

Generally, all RBPC models lead to competitive altruism where agents compete to be the most cooperative in order

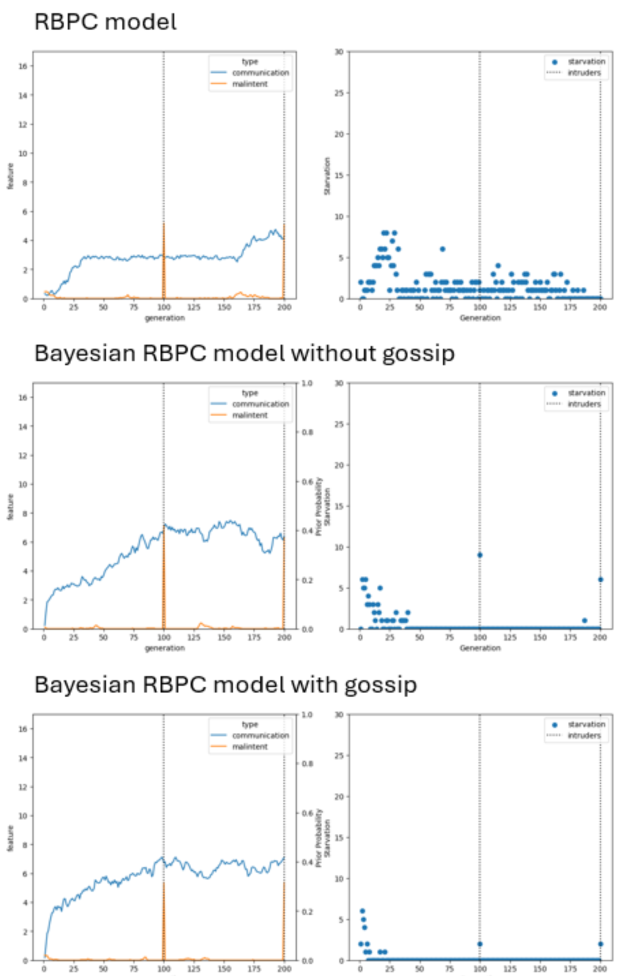
[1]For a detailed explanation, see https://www.youtube.com/watch?v=hKYvZF9wXkk

to maximize reproductive chances. A population that is too cooperative, however, is vulnerable to be taken advantage of. Therefore, agents who do not learn from interactions (i.e., the biological RBPC model) should be least capable to adapt to agents with malintent. Agents with the capability to learn from their experience (i.e., the bayesian RBPC model) should be more capable to adapt to adapt to agents with malintent and agents that can learn from their experience and gossip about their past interactions should be most adept.

To test these hypotheses, simulations were run on all three models where in two generations, a third of all agents' probabilities to steal food (malintent) were set to 1. Since getting your food stolen results in a higher chance of dying, how adept a generation was to intruders can be inferred by how many agents of that generation starved.

Figure 8

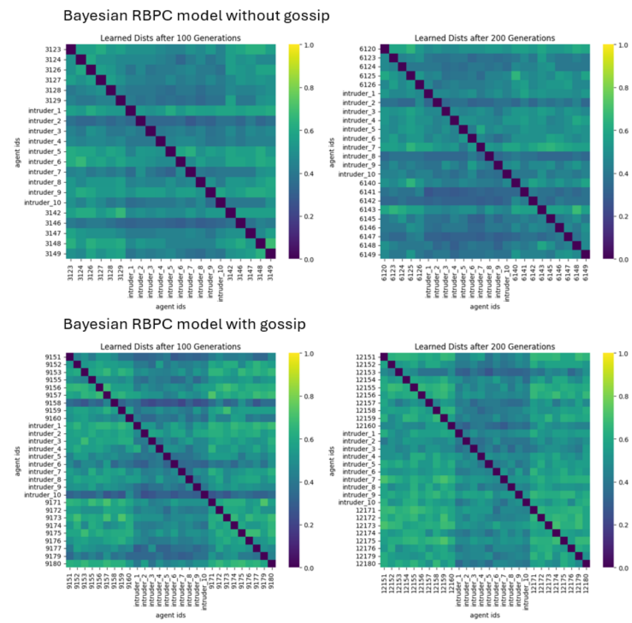
Intruder simulations



The simulations indicate that gossip helps agents that are very cooperative to protect themselves from agents with malintent as they show higher survival rates compared to the agents in the bayesian RBPC model without gossip. Surprisingly, survival rates in the biological RBPC model are not affected by the intruders. This might be due to a generally lower probability to communicate which leads to less opportunities for the intruders to steal food.

Figure 9

Gossip helps reduce the probability to communicate with intruders.



Note. Each cell refers to the probability of $agent_{col}$ communicating with $agent_{row}$ at the end of this generation.

The communication matrices in Figure 9 indicate that agents in the simulation with gossip learned more easily to avoid communication.

4 Conclusions and Discussion

The results indicate that the evolution of cooperation is evolutionarily more plausible due to reputation-based partner choice (RBPC) rather than indirect reciprocity (IR). Given the assumptions for all models, RBPC models consistently showed an emergence of cooperation while IR models did not. Consequently, these results also imply that cooperation is much easier to evolve from sexual selection rather than natural selection. This is because indirect reciprocity provides an agent with more food opportunities, however, these are only advantageous if they prevent the agent from starving.

However, this could also be a potential shortcoming of the presented models since differential survival does not exert much selective pressure. For example, there are cases in nature where hoarding food can be advantageous for survival, such as long droughts where food opportunities are sparse and in which natural selection is a stronger evolutionary pressure. Simulations that explore these types of scenarios could be explored by future research.

Secondly, the results suggest that when cooperation is prominent in a population gossip can be an effective tool to protect cooperative agents from agents that try to take advantage of them.

References

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