Coevolution of individual perception and cooperative behavior in the Norm Compliance Dilemma

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Evolutionary game theory studies the behaviour of populations of rational agents that repeatedly engage in strategic interactions. It differs from classical game theory in that it focuses more on the dynamics of strategy change. Such change occurs since the agents can modify their strategy with the aim of maximizing their payoff. The success of a given strategy depends on how well it performs in the presence of competing strategies, and on the frequency with which those strategies are used in the population. This field has recently proven to be a powerful tool for studying human decision-making processes. In my thesis work, I combined the framework of mathematical epidemiology with evolutionary game theory to model human behaviour in the face of a potential epidemic.

In this context, individuals may take containment measures specific to the disease characteristics to prevent its spread. However, their adoption often entails a cost that is heterogeneously perceived by the population. There are many real-world scenarios in which the payoff of an agent participating in an interaction, i.e. a game, depends on its perception of the game itself. Nevertheless, most models in this framework assume homogeneous interactions both between agents and over time. In this work, the Norm Compliance Dilemma (NCD) is introduced to investigate the effect of distinct, timeevolving perceptions of interactions propagating in different population structures. In doing so, an alternative and general methodology to study heterogeneous coevolving perceptions is proposed. It is also pointed out how this model can be applied to different types of epidemic spreading and norm compliance scenarios.

In this framework, the adoption of a disease containment measure, or norm, is considered as a cooperative act, while the perception, i.e. "opinion", of an agent corresponds to its individual effort in adopting the norm. The control parameters of the model are the overall presence of the disease in the population, and the maximum cost of compliance to the norm, whereas are kept fixed the disease cost discount for a cooperating agent and for the agents interacting with a cooperator. The relevant variables of the model are the fraction of cooperators and the average opinion in the population, and the individual strategies and opinions of the agents. An interaction between two individuals choosing between cooperation and defection is generally characterized by a 2×2 payoff matrix, where the values of the payoffs are formed by the cost relative to the possibility of getting the disease and the cost of adopting the containment measure. While the former is fixed and equal for all individuals, the latter is purely subjective and varies according to the agents' opinion on the given norm.

In infinite well-mixed populations with homogeneous opinion, the evolution of strategies is governed by the replicator equations. On the other hand, the opinion-update is influenced by the relative abundance of cooperators and defectors in the population. Under these assumptions, the coevolution of individual perception and cooperative behavior is described a set of ordinary differential equations, which describe the influence of the other agents' behaviour on individual strategies, and of the present number of cooperators in the population on opinion change. This simplified population model (ODE model) was employed to predict the game equilibria and to study how these are affected by the overall presence of the disease in the population and the maximum cost of compliance to the norm. I investigated the transitions between the different types of games and calculated the areas of the basins of attraction of relevant fixed points.

One of the purposes of this study was to investigate the impact of the two parameters that are kept free: the presence of the disease in the population, and the maximum cost of compliance to the norm. I found that a high presence of the disease favors cooperation and causes the preponderant opinion in the population to be in favor of the norm, or "pro-norm". On the contrary, a high cost of compliance results in less cooperation and a higher presence of "anti-norm" individuals. This result holds qualitatively for all population structures, regardless of spatial arrangement or heterogeneity of opinions. A possible implementation of this model could be to let the presence of the disease change dynamically as the number of cooperators changes in time. This could be done by coupling this evolutionary decision-making model to a disease-spreading model, as suggested by the Vaccination Dilemma of Jun Tanimoto.

Subsequently, I compared the theoretical results with those obtained in finite-size populations having heterogeneous individual perceptions and organized in network structures. To this end, I studied the evolution of cooperators and opinion over repeated iterations of the NCD game, by recasting the ODE model into a stochastic discrete-time model. I found that the two models are generally in agreement, but that stochastic oscillations may compromise the convergence of the system to the fixed points predicted by theory.

Another purpose of the study was to assess the effect of the population structure on the evolution of cooperation, since previous works have shown that certain network structures promote cooperative behaviour, especially if they have a low connectivity. To this end, I performed multi-agent simulations on networked populations, focusing on the structures of a random regular graph (RRG) and a random geometric graph (RGG). According to my results, I found that networked structures hinder and slow down the evolution of cooperation with respect to well-mixed populations. In particular, the formation of strategy clusters in the RGG may prevent convergence towards a homogeneous strategy distribution. In fact, the spatial arrangement of individuals in the RGG is responsible for the survival of cooperation communities in a society almost entirely made of defectors. Symmetrically, defection communities arise and endure in cooperative societies. It is interesting to note how this reflects reality: people who exchange relevant interactions reinforce each other's opinions and often end up acting in the same way. For this reason, spatial networks have once again proven to be a powerful tool for shaping real-life social interactions.