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Interplay between social influence and competitive strategical games in multiplex networks

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We present a model that takes into account the coupling between evolutionary game dynamics and social influence. Importantly, social influence and game dynamics take place in different domains, which we model as different layers of a multiplex network. We show that the coupling between these dynamical processes can lead to cooperation in scenarios where the pure game dynamics predicts defection. In addition, we show that the structure of the network layers and the relation between them can further increase cooperation. Remarkably, if the layers are related in a certain way, the system can reach a polarized metastable state. These findings could explain the prevalence of polarization observed in many social dilemmas.

Social dilemmas are situations where individual interests are in conflict, like sharing resources or generating common goods. These situations are commonly modeled by the Prisoner's Dilemma¹ or the Stag Hunt game. Remarkably, cooperation in situations where individual interest are in conflict is surprisingly common in reality, although defection has been shown to prevail in many theories and controlled experiments^{2–4}. Several mechanisms have therefore been proposed to explain the emergence of cooperation in these scenarios, for example direct and indirect reciprocity (image scoring/reputation)⁵, kin and group selection^{6,7}, success-driven migration⁸, or punishment⁹.

Another mechanism responsible for the emergence of cooperation in social dilemmas could be the fact that strategic interactions between individuals or institutions do not occur in isolation. In particular, individuals that engage in strategic interactions are simultaneously exposed to social influence and, consequently, the spread of opinions. Following this line of reasoning, we assume that social influence impacts the decisions of the players^{10,11}, and that, vice versa, the decisions of the players impact the opinions that are propagated in the system. This consideration naturally raises the following questions: Can the interplay between social influence and game theoretical decisions enable cooperation in social dilemmas? And, what is the impact of the network topology and the relation between the structure of the social and strategical domain?

To answer these questions, we present a model where game theoretical decisions and social influence take place in different layers of a multiplex network^{12–18}. In such systems, each layer contains the same set of nodes, but links are usually different in different layers. However, the layers comprising real multiplex systems are not entirely independent, but exhibit certain relations¹⁹. As we will show, these relations can lead to interesting behaviors, and hence have to be taken into account when modeling such systems²⁰. On top of this topology, we model the dynamics taking place in the game layer by a replication dynamics, where individuals imitate the strategy of successful neighbors^{21–23}. Furthermore, we use a biased voter model²⁴ in the social influence layer as a proxy for the spread of opinions. These opinions can be seen as a proclamation of the intend of individuals regarding their choice of strategy in the game layer. We assume that there is a tendency for individuals to act in agreement with their proclamations, but allow, in general, that individuals deviate from them. The importance for individuals to be congruent in both domains constitutes the coupling strength between the different dynamical processes. Finally, the aforementioned bias of the voter model represents a general tendency towards the proclamation of cooperative intentions, which could be induced by appropriate media campaigns or similar measures.

We find that indeed the coupling between evolutionary game dynamics and social influence can sustain partial cooperation in the Prisoner's Dilemma, where total defection prevails in the isolated game dynamics, and partial or even full cooperation in the Stag Hunt game. In both cases, for appropriate parameters, the state of full

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defection can be avoided entirely. The role of the relation between the different layers of the system is especially interesting. In particular, only certain relations between the layers give rise to a metastable state in which nodes that adopt the same strategy self-organize into local clusters. This state could explain the emergence and prevalence of polarization observed in many situations that resemble social dilemmas.

Results

Coupling between game dynamics and social influence. In strategic games, individuals choose a strategy and then obtain a payoff that depends on their own and other players' strategies. Here, we consider the two possible strategies cooperate (C) or defect (D). The interactions are then governed by the payoff matrix

$$M = \begin{array}{c|cc} & C & D \\ \hline C & 1 & S \\ D & T & 0 \end{array}, \quad (1)$$

meaning that if player 1 chooses to cooperate and player 2 cooperates as well, both collect a payoff of 1. However, if player 2 defects, player 1 only collects the payoff S and player 2 collects the payoff T , and vice versa. Finally, if both players defect, both obtain no payoff.

In reality, individuals make many successive strategic decisions and adapt their strategies over time. This behavior is commonly modeled by a replicator dynamics^{21–23}, in which individuals copy the strategy of a randomly selected neighbor with a probability that depends on the difference of the payoff of the two involved players. In general, individuals tend to copy the strategy of players who have earned a higher payoff compared to themselves. Here, we use synchronized updates, meaning that after each round of the game, in which each node plays one game with each of her neighbors and payoffs are distributed according to the aforementioned payoff matrix, every node i chooses a neighbor j at random and copies her strategy with the probability²⁵

$$P_{i \leftarrow j} = \frac{1}{2}(1 - \tanh[\pi_i - \pi_j]), \quad (2)$$

where π_i and π_j denote the payoffs of node i and j .

Depending on the values of $S \in [-1, 1]$ and $T \in [0, 2]$, there are different stable choices of strategies. In the Stag Hunt game, for which we have $S < 0$ and $T < 1$, we have bistability: both full cooperation as well as full defection are stable stationary solutions. In the Prisoner's Dilemma, i.e. for $S < 0$ and $T > 1$, full defection is the only stable strategy. In the Snowdrift game, $S > 0$ and $T > 1$, the only stable solution is an intermediate density of cooperators. Finally, in the Harmony game, $S > 0$ and $T < 1$, only full cooperation is a stable solution.

However, in reality, individuals do not make decisions exclusively based on the payoffs of their neighbors. Instead, individuals are simultaneously exposed to social influence and hence the opinion of the peer group of an individual cannot be neglected in understanding what drives cooperation in strategic games. Opinions of individuals propagate through a contact network. This behavior is widely described by the voter model²⁴, where individuals adopt the opinion of a randomly selected neighbor. We assume that propagating an opinion that is considered anti-social, like defection in our model, is less likely than propagating opinions which are socially accepted, like cooperation in our model. This could be the result of media campaigns or similar measures. We take this effect into account by introducing a bias, $\beta \in [0, 1]$, into the voter model. Individuals then adopt the opinion of a randomly selected neighbor with probability β if this opinion is cooperation and $1 - \beta$ if it is defection. Values of $\beta > 0.5$ hence reflect a positive bias towards cooperation in the opinion dynamics. The opinion of an individual can be understood as her proclamation of intent regarding her choice of strategy in the game layer.

As mentioned before, social influence has an impact on the decision of individuals. To mimic this fact, we couple the opinion propagation and game dynamics. In particular, we define a parameter γ , which represents the tendency of individuals to act in agreement with their proclamations, and hence constitutes the coupling strength between social influence and game dynamics. In particular, at each update step, with probability γ a node copies her state from one layer to the other. This means that each node either copies her state from the opinion to the game layer or, vice versa, copies her state from the game layer to the opinion layer, where each of these options is chosen with 50% probability. The copying process can be understood as the tendency of individuals to pursue congruence between their actions and proclaimed opinions. Finally, with the complementary probability $1 - \gamma$ each node updates the strategy in the game layer according to the game dynamics and in the opinion layer according to the biased voter model (see Fig. 1).

Mixed populations. In reality, individuals or institutions interact in strategic games via a contact network, like a network between firms or countries. We will discuss the influence of the structure of the contact network and of the correlations between different networks later. For now, we study the model on a mixed population, in other words, we assume a homogeneous and infinite population in the absence of dynamical correlations and noise.

The mixed population (meanfield) assumption allows us to derive differential equations for the evolution of the density of cooperators c_I in the game layer and c_{II} in the opinion layer (see Supplementary Materials),

$$\begin{aligned} \partial_t c_I &= (1 - \gamma)c_I(1 - c_I)\tanh[\langle k \rangle(c_I(1 - T) + S(1 - c_I))] + \gamma(c_{II} - c_I), \\ \partial_t c_{II} &= (1 - \gamma)(2\beta - 1)c_{II}(1 - c_{II}) + \gamma(c_I - c_{II}), \end{aligned} \quad (3)$$

where S and T denote the parameters from the payoff matrix, equation (1), $\gamma \in [0, 1]$ controls the strength of the coupling between the opinion and game dynamics and $\beta \in [0, 1]$ is the bias of the opinion dynamics. Finally, $\langle k \rangle$ denotes the mean degree of the contact network.

Figure 1. Graphical illustration of the multiplex model. Different layers denote the different networks that individuals participate: on the top the Game Network (GN) and on the bottom the Opinion Network (ON). Intra-links (black solid lines) correspond to the individuals' connections within each network, while inter-links (green solid lines) indicate the coupling between layers. On the right, the pictures show a simplification of the dynamic occurring on each network.

Parameter γ controls the strength of the coupling. For $\gamma = 0$, the dynamics in the different layers are independent, and for $\gamma = 1$ there are only copying events between the layers such that the individual layer dynamics become inexistent. Therefore, the most interesting behavior is observed for intermediate values of γ , and hence in the following we specifically investigate $\gamma = 0.2$ (see Supplementary Materials for details).

Parameter β controls the bias in the voter model. For $\beta = 0.5$, one recovers the classical voter model, which has no stable fixpoint, but only two absorbent states (full consensus on opinion 1 or 0). In the meanfield approximation, in this case the behavior of the coupled system ($\gamma > 0$) is equivalent to the isolated game dynamics, and the game dynamics enslaves the opinion layer. This means that in the final state of the system both layers have the same cooperation density which is equivalent to the isolated game dynamics. We anticipate that while this behavior is confirmed in Erdős-Renyi networks, complex layer topologies and the organization of the multiplex, in particular geometric correlations intertwining their layers, increase cooperation. For $\beta > 0.5$ ($\beta < 0.5$), the opinion dynamics in isolation has one stable fixpoint, which corresponds to full consensus of opinion 1 (opinion 0). Therefore, the meanfield behavior of the system is different to the isolated game dynamics, which we discuss in the following.

Let us now consider the dynamical properties of the system described by equation (3) for fixed values of $\beta = 0.7$ and $\gamma = 0.2$. We find three regions of different qualitative behavior, depending on the values of parameters T and S . In particular, we find a region in which the system effectively behaves like the harmony game (red region in Fig. 2a), which means that only full cooperation in both layers is a stable solution (see Fig. 2d). Furthermore, we find a region where the system effectively behaves like the snowdrift game (blue region in Fig. 2a). In this region, the only stable solution is a mixed state, where a finite fraction of the population cooperates (see Fig. 2f). In this region, in general, the density of cooperators in the game dynamics and those who proclaim cooperation are not the same. Finally, there is a region which can be described as a mixture of the two above cases (green region in Fig. 2a). In this region, the system exhibits a bistable behavior. Full cooperation in both layers is a stable solution as well as a mixed state as described above (see Fig. 2e). The bistable region emerges as the system undergoes a saddle-node bifurcation. Let us fix $S = -0.2$ and increase the value of T . At $T = T_{c,1} \approx 0.77$ the system undergoes a saddle-node bifurcation as a pair of fixed points, one stable and one unstable, appear (see Fig. 2b and c). Increasing T further, at $T = T_{c,2} \approx 1.03$ the system undergoes a transcritical bifurcation and the solution which corresponds to full cooperation becomes unstable. In the supercritical regime, only the mixed state is stable.

To sum up, we have shown that the coupling to the biased opinion dynamics shifts the effective behavior of the game dynamics compared to the isolated case. The coupled system exhibits effectively a harmony-like behavior, a Snowdrift-like behavior, or a mixture of both. Interestingly, the coupling to the biased opinion dynamics successfully avoids the situation of complete defection. So far, we have considered a fully mixed, homogeneous population. In the following, we discuss the impact of the topology of the underlying contact networks as well as the relationship between the two layers of the system.

Impact of the structural organization of the multiplex. Using the assumption of a fully mixed, homogeneous population we have shown how the coupling to the biased opinion dynamics can effectively transform the behavior of the system. However, in reality, networks are heterogeneous and highly clustered, which can have a significant effect on the outcome of dynamics taking place on the network²⁶.

Furthermore, in reality, the social influence layer and the strategic game layer are neither independent nor identical. In other words, real multiplex networks are not random combinations of their constituent layer's topologies¹⁹. Hence, the contexts—or domains—in which individuals make strategic decisions and by whom they are influenced are related. In ref. 19 the authors have shown that these relations are given by geometric correlations in hidden metric spaces underlying each layer of the system. These correlations come in two flavors: popularity correlations, which are correlations between the degrees of nodes, and similarity correlations, which determine how likely an individual is to connect to the same nodes in different layers. In simple terms, these correlations

Figure 2. Behavior of the system for $\gamma=0.2$ and $\beta=0.7$ and $\langle k \rangle=6$. **(a)** Shows the phase diagram. In the red area, full cooperation is the only stable solution and we effectively observe the behavior known from the harmony game. In the opinion layer, “cooperate” is the only prevailing opinion. This behavior is illustrated in the stream plot shown in **(d)** for $T=0.6$ and $S=-0.2$. In the blue area in **(a)**, the only stable solution is a mixed state with $0 < C_I < 1$ and $0 < C_{II} < 1$, and in general we have $C_I \neq C_{II}$. This region corresponds to $T > T_{c,2} \approx 1.03$. **(f)** shows this behavior as a stream plot for $T=1.2$ and $S=-0.2$. In the green area in **(a)**, we have a bistable behavior, where either full cooperation is approached in both layers, but the mixed state is stable as well. **(e)** shows this behavior as a stream plot for $T=0.9$ and $S=-0.2$. In the bifurcation diagrams in **(b)** and **(c)** this region corresponds to $T_{c,1} < T < T_{c,2}$, where $T_{c,1} \approx 0.77$. Green solid lines represent stable fixed points and dashed red lines unstable fixed points.

control how “similar” the different contexts represented by the layers of the system are. For further details on geometric correlations between layers of real multiplex networks we refer the reader to ref. 19. Here, we focus on the impact of these structural properties on the dynamics of our model. What is, in general, the impact of geometric correlations on the behavior of the system? In particular, do stronger correlations favor or hinder cooperation? To answer these questions, we perform numerical simulation using the geometric multiplex model (GMM) developed in ref. 19 (see Methods 5). The model generates networks with a power-law degree distribution and a tunable level of mean local clustering. Furthermore, we can control the popularity correlations (by tuning parameter $\nu \in [0, 1]$) as well as the similarity correlations (by tuning parameter $g \in [0, 1]$) independently from the individual layer topologies, which allows us to study their impact in isolation. We calculate approximated phase diagrams similar to Fig. 2a using the generated networks by performing numerical simulations. In particular, to capture the bistable region of the system, we perform simulations starting from different initial conditions, in particular $C_{I,II} = 0.01$ and $C_{I,II} = 0.99$ respectively. The regions are separated by critical lines, above (below) which the harmony (full defection) state is reached with a probability of more than 50% (dashed black lines in Fig. 2 in the Supplementary Materials). The difference between the critical lines for the different initial conditions is an approximation of the bistable region (see Supplementary Materials for details).

Let us first consider the unbiased voter model, hence $\beta=0.5$, and $\gamma=0.2$. The system either reaches full cooperation and consensus (“harmony state”), i.e. $C_I^{\text{final}}, C_{II}^{\text{final}} = 1$, a state where a mixed strategy prevails and full consensus is not reached (“snowdrift state”), or full defection (“PD”). Furthermore, by comparing the outcomes from the different initial conditions, we are able to approximate the bistable region (“SH”), where both full cooperation and full defection are possible solutions. Indeed, for Erdős-Rényi networks the approximated phase diagram, see Fig. 3a, closely resembles the meanfield prediction for the isolated game dynamics. Whereas it is well known that heterogeneous topologies favor cooperation^{27–32}, here we show that the structural organization of the constituent layers to the multiplex plays an important role. Specifically, the existence of geometric correlations

Figure 3. Approximated phase diagrams (see Supplementary Materials) from numerical simulations for $\gamma = 0.2$ and $\beta = 0.5$ (a–d) as well as $\beta = 0.7$ (e–h). (a) Erdős Rényi network with mean degree $\langle k \rangle = 6$ and $N = 10000$. (b) Using GMM multiplexes with $N = 10000$ nodes, mean degree $\langle k \rangle \approx 6$, a power-law exponent 2.9 and temperature $T_{\text{GMM}} = 0.4$. Layers are uncorrelated, i.e. $g = v = 0$. (c) same as (b) but with geometric correlation, in particular $g = v = 1$. (d) shows the size of the “harmony” area in the phasespace for different parameters, i.e. the size of the red area in (a–c). The blue bar is for the Erdős Rényi networks as shown in (a), the yellow bar represent the GMM model without correlations as shown in (b), and the green bar denotes the GMM model with correlations as presented in (c). (e–h) shows the same as (a–d) but for $\beta = 0.7$.

intertwining the layers of realistic multiplexes¹⁹ significantly increases cooperation (compare Fig. 3b,c). In particular, in Fig. 3d we compare the area of the harmony region, which is largest if geometric correlations are present. To conclude, the interplay between the dynamics, the complex layer topologies, and—last but not least—the structural organization of these layers into the multiplex leads to an increased cooperation.

Let us now consider $\beta = 0.7$ and $\gamma = 0.2$. The bias in the voter model shifts the system towards cooperation and, for these parameters, the region of full defection disappears. Furthermore, the behavior of the system in the bistable region is now different from the aforementioned case. Full cooperation still is a possible solution, but instead of full defection the other stable solution is given by a finite cooperation density (“mixed region”). This region has no classical analogue. We observe that heterogeneous and clustered topologies in single layers increase cooperation (compare Fig. 3e and f). The presence of correlations between the layers increases the region in the parameter space where the harmony solution is approached, and hence further increases cooperation (compare Fig. 3f and g). To facilitate this comparison, in Fig. 3h we show the size of the harmony region in the $T = S$ phase-space. Interestingly, the harmony area is larger for the heterogeneous multiplexes with geometric correlations and the unbiased voter model compared to the biased voter model on Erdős-Rényi random multiplexes. We take this as further evidence for the importance to consider the structural organization of the individual layers into the multiplex.

The impact of correlations in the bistable region is especially interesting. We find that in this region angular correlations lead to a metastable state in which nodes that adopt the same strategy self-organize into local clusters. These clusters are sets of nodes that are located at small angular distances in the underlying metric space. They emerge spontaneously and are metastable in the sense that they can exist for very long times despite the noise present in the system. This behavior is shown in Fig. 4 and in the Supplementary Video. The emergence of these clusters can be interpreted as a polarization of society into defecting and cooperating groups. Finally, the amount and size of the clusters is highly random and, as a consequence, we observe a broad range of final cooperation densities in this parameter region (see Fig. 5).

Discussion

Cooperation is common in reality in social dilemmas where many theories predict the prevalence of defection. This contradiction could be resolved by taking into account further domains of interactions between individuals, in particular social influence.

We have presented a model based on multiplex networks with two layers. One layer represents the domain in which individuals engage in repetitive strategical games. The second layer corresponds to the domain of social influence, which we model using a biased opinion dynamics. The opinions can be understood as the proclamations of individuals regarding their strategy. The coupling between the game and opinion dynamics mimics the

Figure 4. Polarization of the system in the presence of angular correlations between the layers ($g = 1$, $v = 0.2$) for a multiplex with $N = 5000$ nodes, a power-law exponent 2.9, temperature 0.2, and mean degree 6 in both layers. Parameters of the game are $T = 0.8$ and $S = -0.4$, the bias β is 0.7 and the coupling strength is 0.2. Results are for a single realization of our model starting with a density of cooperators of 0.1 in each layer. A visualization of this realization is shown in the Supplementary Video. The top row shows visualizations of the network layers. Color coded is the mean state of each node, averaged over time. Each time step denotes 1000 update steps of each node. The bottom row shows the evolution of the density of cooperators in each angular bin. Numbers indicate selected clusters of nodes that tend to adopt the same strategy. Each timestep t denotes 10^3 rounds.

tendency of individuals to be congruent with respect to their actions and opinions. Even in the absence of a bias in the opinion dynamics, the coupling of the different dynamics combined with complex layer topologies and geometric correlations governing their organization into the multiplex increases cooperation. In reality, a positive bias towards cooperative attitudes could be achieved by media campaigns that promote pro-social behavior. Such a bias shifts the system towards cooperation and can avoid full defection. Furthermore, we have shown that the coupling of these dynamics in combination with geometric correlations between the layers of the system can lead to a metastable state of high polarization, in which nodes that adopt the same strategy self-organize into local clusters. These findings could explain the emergence and prevalence of polarization observed in many social dilemmas. Our findings show that taking into account the multiplex nature of human interactions and the structural organization of these system is important to understand the emergence of cooperation in social dilemmas and that the interplay between different processes can significantly alter the behavior of the system.

Real social and strategic interaction networks evolve in time, and their evolution could depend on the strategic choices of individuals^{33,34}. Hence, the inclusion of an evolving and adaptive topology constitutes an interesting task for future work. Furthermore, one could include the competition^{14,35,36} between different strategic networks, or incorporate external noise⁸. Finally, our findings suggest that hidden geometric correlations between different layers of multiplex networks can alter the behavior of the dynamics taking place on top of them significantly, and hence such correlations should be taken into account in future research on dynamical processes on multiplex networks²⁰.

Figure 5. Distribution of final cooperation (after 5×10^5 rounds) in the game layer among 50 realizations of our model. The parameters are $\gamma = 0.2$ and $\beta = 0.7$, $N = 10000$ nodes, and mean degree $\langle k \rangle \approx 6$. Network layers have a power-law exponent of 2.9 and temperature $T_{GMM} = 0.4$. Here, we have fixed $T = 0.6$. Plots (a–c) show the uncorrelated case ($g = v = 0$) and (d–f) show the case of angular correlations ($g = 1$, $v = 0$). The value of S is shown in the respective plot title.

Methods

Geometric multiplex model (GMM). The geometric multiplex model is based on the (single-layer) network construction procedure of the newtonian $\mathbb{S}^1$ ³⁷ and hyperbolic $\mathbb{H}^2$ ³⁸ models. The two models are isomorphic and here we present the results for the $\mathbb{H}^2$ version. The construction of a network of size N proceed firsts by assigning to each node $i = 1, \dots, N$ its popularity and similarity coordinates r_i , θ_i and subsequently, connecting each pair of nodes i, j with probability $p(x_{ij}) = 1/(1 + e^{\frac{1}{2T}(x_{ij}-R)})$, where x_{ij} is the hyperbolic distance between the nodes and $R \sim \ln N$ (see Supplementary Materials). The connection probability $p(x_{ij})$ is the Fermi-Dirac distribution where the temperature parameter T_{GMM} controls the level of clustering in the network³⁹. The average clustering c is maximized at $T = 0$, linearly decreases to zero with $T \in [0, 1]$, and is asymptotically zero if $T > 1$. As $T \rightarrow 0$ the connection probability becomes the step function $p(x_{ij}) \rightarrow 1$ if $x_{ij} \leq R$, and $p(x_{ij}) \rightarrow 0$ if $x_{ij} > R$. It has been shown that the $\mathbb{S}^1$ and $\mathbb{H}^2$ models can build synthetic networks reproducing a wide range of structural characteristics of real networks, including power law degree distributions and strong clustering^{37,38}. The use of these models for the single-layer networks allows for radial and angular coordinate correlations across the different layers. The level of these correlations can be controlled by model parameters $v \in [0, 1]$ and $g \in [0, 1]$, without affecting the topological structure of the single layers. The radial correlations, related to the node's degree, increase with parameter v —at $v = 0$ there are no radial correlations, while at $v = 1$ radial correlations are maximized. Similarly, the angular correlations increase with parameter g —at $g = 0$ there are no angular correlations, while at $g = 1$ angular correlations are maximized. See ref. 19 for details.

Finally, we extract the mutually connected component of the system to avoid disconnected nodes.

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Author Contributions

K.-K.K. and R.A. designed the research. K.-K.K. and R.A. performed numerical simulations. K.-K.K. performed meanfield calculations and prepared the figures. All authors wrote the manuscript and discussed the research.

Additional Information

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