The coevolution of loyalty and cooperation

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Abstract—Humans are inclined to engage in long-lasting relationships whose stability does not only rely on cooperation, but often also on loyalty — our tendency to keep interacting with the same partners even when better alternatives exist. Yet, what is the evolutionary mechanism behind such irrational behavior? Furthermore, under which conditions are individuals tempted to abandon their loyalty, and how does this affect the overall level of cooperation? Here, we study a model in which individuals interact along the edges of a dynamical graph, being able to adjust both their behavior and their social ties. Their willingness to sever interactions is determined by an individual characteristic and subject to evolution. We show that defectors ultimately loose any commitment to their social contacts, a result of their inability to establish any social tie under mutual agreement. Ironically, defectors' constant search for new partners to exploit leads to heterogeneous networks in which cooperation survives more easily. Cooperators, on the other hand, develop much more stable and long-term relationships. Their loyalty to their partners only decreases when the competition with defectors becomes fierce. These results indicate how our innate commitment to partners is related to mutual agreement among cooperators and how this commitment is evolutionary disadvantageous in times of conflict, both from an individual and a group perspective.

I. INTRODUCTION

Cooperation has played a pivotal role throughout evolution, being an important prerequisite for the emergence of every new level of organization [1, 2]. As such, cooperation lies at the roots of human organization in societies. Understanding this ubiquity poses one of the most fascinating and fundamental challenges to date [3]. The problem is usually formulated in terms of metaphors like the two-person Prisoner's Dilemma (**PD**) [4], in which two interacting individuals decide simultaneously whether or not they help one another, i.e., whether they cooperate or defect. A cooperative act incurs a cost (c) to the individual, but confers a benefit (b) to his partner ($b > c$). Defecting does not involve any costs, but does not produce any benefits either. Self-regarding individuals try to maximize their own resources and are therefore expected to defect, creating the famous conundrum of cooperation. In the framework of evolutionary game theory [5, 6], the accumulation of received benefits and expended costs by an individual is associated with his fitness and this with his biological or social success. Several mechanisms that foster cooperation in this scenario have been identified over the years [2]. It has for instance been recognized that the

structure of the population (i.e., who interacts with whom) drastically affects the prevailing behavior [7–20]. Empirical studies of real life social networks indicate that some individuals interact more and more often than others, giving rise to heterogeneously structured populations [21]. Such environments lead to levels of cooperation that go far beyond those traditionally observed in well-mixed populations [5, 6, 16, 18, 20]. The reported network structures do, however, only constitute a fixed-time snapshot of a continuously evolving entity [22]. Indeed, our network of contacts is dynamic in the sense that we regularly engage in new interactions and abandon old ones. This particular aspect of our society has recently been recognized as a crucial ingredient in the viability of cooperative acts [23–30]. In a minimal setting [26], individuals are located at the vertices of a graph and decide selfishly on both their behavior (cooperate or defect) and their social connections. The two processes, behavioral evolution and network evolution, proceed simultaneously on separate time scales: the first (behavioral evolution) on a time scale τ_e, the latter (network evolution) on a time scale τ_a. It was shown that cooperation emerges, even in networks with high average degree, provided individuals swiftly change their adverse ties (i.e., the ratio $W = \tau_e / \tau_a$ is sufficiently high) [26]. Furthermore, the co-evolution of individual strategy and network topology leads to evolved networks whose structure agrees qualitatively with empirical analysis of real networks [21].

Until now, all individuals are assumed to react in the same way to adverse social ties — determined by the parameter W. We do, however, know from everyday life experience that differences in individual behavior are ubiquitous in our society. Our decisions are influenced by a wide range of stimuli (culture, family, friends,...) and associated with the social context in which we find ourselves. The combination of all these factors triggers behavioral diversity among individuals [31–33]. It is therefore natural to expect that some individuals have the propensity to swiftly change partner, whereas others remain connected even though they are dissatisfied with the situation. In other words, some people will be more loyal to their partners than others. Here, we introduce a model that takes this kind of behavioral diversity into account. Individuals have their own innate behavior for dealing with adverse ties, a characteristic that coevolves with

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the other features inherent to the entangled social dilemma. This allows us to investigate how individuals may react to inconvenient interactions, given the social conditions defined by the underlying game.

II. MODEL DESCRIPTION

We model social dilemmas of cooperation in terms of the well-known one-shot two-person **PD** game, in which players can either cooperate or defect during an interaction. In general, mutual cooperation leads to a *reward* R for both individuals, mutual defection to a *punishment* P. A cooperator receives the *sucker's payoff* S when interacting with a defector, who in turn obtains the *temptation to defect* T. Different dilemmas of cooperation arise depending on the ordering of these payoff values [34]. We enter the realm of the **PD** whenever $T > R > P > S$, the cost-benefit dilemma introduced in the introduction constituting the prototypical example. In that case, mutual cooperation leads to $R = b - c$, whereas mutual defection leads to $P = 0$. When a cooperator and defector interact, the cooperator gets $S = -c$, whereas the defector gets $T = b$, automatically satisfying the inequality above. We adopt the convention of [18] and normalize the advantage of mutual cooperation over mutual defection to 1, taking $R = 1$ and $P = 0$. This leaves us two parameters, T and S, to tune the intensity of the social dilemma inherent to the **PD**. Together T and S define a 2D parameter space, of which we consider the diagonal defined by T (and $S = 1 - T$). This diagonal corresponds exactly to those games that can be associated with a cost-benefit parameterization of the **PD**: With $T = b$ and $S = -c$, the assumption $R = 1$ leads to $T + S = 1$.

We construct a social network by assigning individuals to the vertices of graph. Each edge of the graph represents an interaction between the two connected individuals. These interactions are modeled in terms of a **PD** game as described above. Individuals' behavior in this game is governed by their game strategy (cooperate or defect). They may decide to alter this strategy, based purely on their self-interest, using only information on their direct partners. When an individual is dissatisfied with the behavior of a certain neighbor, he may also decide to change partner (rewire their connecting edge). His willingness to do so is given by his loyalty parameter $\lambda \in [0, 1]$. The higher the value of λ of an individual, the more loyal, i.e., less willing to change partner, he will be. The coevolution of strategy and network structure is implemented asynchronously. The type of update event — behavior or partner — is chosen according to the ratio W between the time scale associated with strategy evolution (τ_e) and the one associated with network evolution (τ_a). Assuming $\tau_e = 1$ (without loss of generality), a strategy (behavioral) update event is chosen with probability $(1 + W)^{-1}$, a structure (partner) update event being selected otherwise. As such, the frequency of structure update events increases with the value of W.

A *strategy update* event is defined by the pairwise comparison rule [9, 35]. An individual A is drawn randomly from the population. Another individual B is drawn randomly from
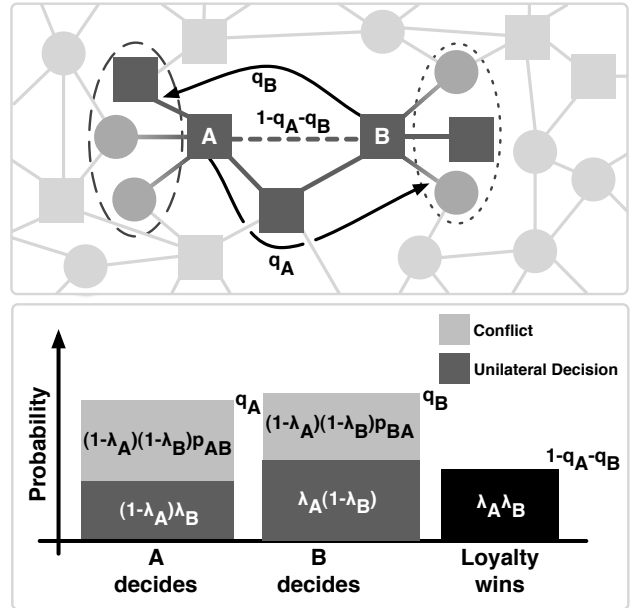

Fig. 1. **Loyalty and network evolution.** The upper panel illustrates a detail of a hypothetical graph, whose edges define the interactions between individuals. Cooperators are indicated by circles, defectors by squares. The dashed edge represents an interaction selected for evaluation during a structure update. In this particular example, both interacting individuals A and B are dissatisfied with each other's defecting behavior. Being dissatisfied, each of them may be willing to change partner (i.e., rewire the edge), depending on his loyalty λ. Concretely, A would like to change with probability $1 - \lambda_A$, B with probability $1 - \lambda_B$. The actual rewiring decisions are outlined in the lower panel. When both A and B would like to rewire, a situation that is indicated by the light gray zones, fitness determines the winner of the conflict: A rewires the edge with probability p_{AB}, B with probability p_{BA}. The dark gray zones, on the other hand, indicate the situation in which one individual decides to remain loyal to his partner, whereas the other would like to change. If this is case, rewiring becomes fitness independent and the one who would like to change partner is given the opportunity to do so. Altogether, A rewires the edge with probability $q_A = (1 - \lambda_A)(1 - \lambda_B)p_{AB} + \lambda_B(1 - \lambda_A)$, B with probability $q_B = (1 - \lambda_A)(1 - \lambda_B)p_{BA} + \lambda_A(1 - \lambda_B)$. When A (B) redirects the edge, he chooses his new partner randomly from the immediate neighbors of B (A), excluding those he is already connected to. The potential new partners of A (B) are surrounded by the dotted (dashed) circle in the upper panel. Note that the edge between A and B remains untouched when both individuals remain loyal to each other, which happens with probability $\lambda_A \lambda_B$.

the immediate neighbors of A. The strategy of B will replace that of A with probability given by the Fermi function (from statistical physics) $p_{BA} = [1 + e^{-\beta(\Pi(B) - \Pi(A))}]^{-1}$, where $\Pi(X)$ represents the accumulated payoff of individual X after interacting with all his neighbors. The quantity β (≥ 0), which in physics corresponds to an inverse temperature, controls the intensity of selection. The limit $\beta \to 0$ leads to neutral drift, the limit $\beta \to \infty$ leads to the so called imitation dynamics, often used to model cultural evolution. Note that not only the game strategy is transferred during a strategy update, but also the loyalty parameter λ.

At each *structure update* event, a random edge is selected for evaluation, as illustrated in Figure 1. The two individuals at the extremes of the selected edge — A and B — both

decide whether they are satisfied with the interaction or not. As interacting with a cooperator always leads to a higher payoff than interacting with a defector ($S \leq R$ and $T \geq P$), A (B) will be satisfied when B (A) is a cooperator and dissatisfied otherwise. A satisfied individual would like to maintain the interaction, whereas a dissatisfied one may want to change partner (rewire the edge). A potential conflict over an edge arises as soon as at least one of the individuals is dissatisfied with the interaction. In that case, both A and B compete for whatever they wish to do (i.e., maintain or rewire the edge) with probability dependent on their loyalty parameter λ. As such, λ_A and λ_B — the loyalty of A and B, respectively — define three possible outcomes for the competition over the edge between A and B. First, both A and B refuse to compete with probability $\lambda_A \lambda_B$. They remain loyal to each other so that the social tie remains unaffected, despite, for instance, mutual dissatisfaction. Second, both A and B decide to compete for the edge with probability $(1 - \lambda_A)(1 - \lambda_B)$. Individual fitness ultimately dictates the winner of this conflict. The decision of B prevails with probability p_{BA}, the decision of A with probability $p_{AB} = 1 - p_{BA}$, where the probabilities are defined by the payoff-dependent Fermi function. If the decision is to redirect the edge, the new destination is chosen randomly from the immediate neighbors of the previous partner, adding realistic spatial and cognitive constraints [22]. In order to prevent the graph from becoming disconnected, we impose that individuals connected by one single edge cannot lose this edge. This assumption ensures that *all* individuals remain subject to strategy evolution. The final possibility encompasses the situation in which one individual decides to remain loyal, whereas the other does not. Concretely, A (B) competes while B (A) does not with probability $\lambda_B[1 - \lambda_A]$ ($\lambda_A[1 - \lambda_B]$). In this case, A (B) decides the fate of the interaction unilaterally. Taken together, A's decision prevails with probability $q_A = (1 - \lambda_A)(1 - \lambda_B)p_{AB} + (1 - \lambda_A)\lambda_B$ and B's decision with probability $q_B = (1 - \lambda_A)(1 - \lambda_B)p_{BA} + (1 - \lambda_B)\lambda_A$.

III. SIMULATIONS

We start each simulation with a homogeneous random graph [36] with N vertices and N_E edges. All vertices in such a graph have the same degree, $z = 2N_E/N$, and are randomly linked to arbitrary other vertices. This configuration mimics a well-mixed population with limited connectivity. The average connectivity z remains fixed since we do not add or remove any edges. The degree distribution of the graph, on the other hand, changes over time as individuals change their ties. We use networks of size $N = 10^3$ and average connectivity $z = 30$. The latter value reflects the average connectivity of a plethora of empirically studied social networks [37, 38], whose average connectivity values range between 2 and 170.

We measure the chances of cooperators for certain parameter settings by calculating the fraction of simulations that end in 100% cooperation. The stochastic nature of the adopted strategy update rule [35] ensures that full cooperation and
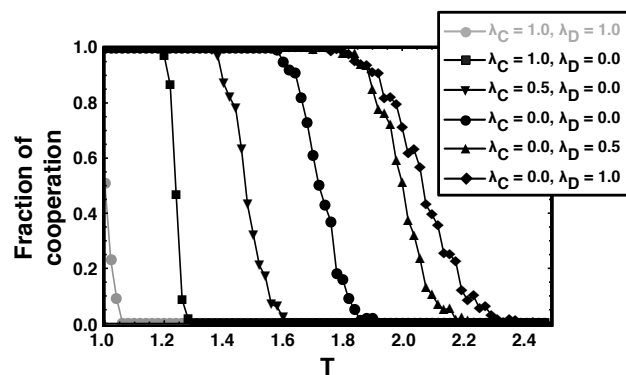

Fig. 2. **Strategy-dependent loyalty and cooperation.** Fraction of simulations that end in cooperation as a function of T for different values of λ_C (the loyalty of cooperators) and λ_D (the loyalty of defectors). The remaining parameters are $W = 2.5$, $\beta = 0.005$, $N = 10^3$ and $z = 30$. The situation in which $\lambda_C = \lambda_D = 0.0$ can be regarded as the baseline here. Increasing the loyalty of cooperators makes it harder for them to wipe out defectors. Increasing the one of defectors, on the other hand, has the opposite effect. When comparing with the situation in which both cooperators and defectors are completely loyal ($\lambda_C = \lambda_D = 1.0$), the presence of individuals who are willing to change adverse social ties always has a positive effect on cooperation.

full defection are the only two absorbing states of the strategy evolutionary dynamics. Whenever the full cooperation absorbing boundary is reached, the coevolutionary dynamics stops, as all social ties rely on mutual satisfaction. Whenever the full defection absorbing state is reached, only strategy dynamics stops, as mutual dissatisfaction will compel myopic defectors to search uninterruptedly for other partners, leading ultimately to a stationary regime in which the average properties of the network structure remain unchanged.

IV. RESULTS

As a first step to investigate the effect of individual differences in loyalty on the evolution of cooperation, we assume that either cooperators or defectors have a fixed and pre-defined λ. We run 100 simulation for each set of parameters $(T; \lambda_C; \lambda_D)$, each simulation starting with 50% of cooperators, randomly distributed in the population. Figure 2 shows that when defectors are more loyal to their partners ($\lambda_D = 1.0$ and $\lambda_D = 0.5$) than cooperators ($\lambda_C = 0.0$), cooperators ensure the stability of favorable interactions while avoiding adverse ones more swiftly; hence, assortment of cooperators becomes more effective, enhancing the feasibility of cooperation [39]. When cooperators are more committed to their partners than defectors ($\lambda_C = 0.5$ and $\lambda_C = 1.0$ versus $\lambda_D = 0.0$), the level of cooperation decreases with respect to the situation in which any loyalty is absent in both cooperators and defectors ($\lambda_C = \lambda_D = 0.0$). Increasing the loyalty of cooperators leads to their own demise. On the other hand, if we compare these results to those in which all social ties remain immutable (leading to a static network, shown also in Figure 2), the feasibility of cooperation actually increases. Why does the rewiring of only defector-links already improve the survival of cooperators?
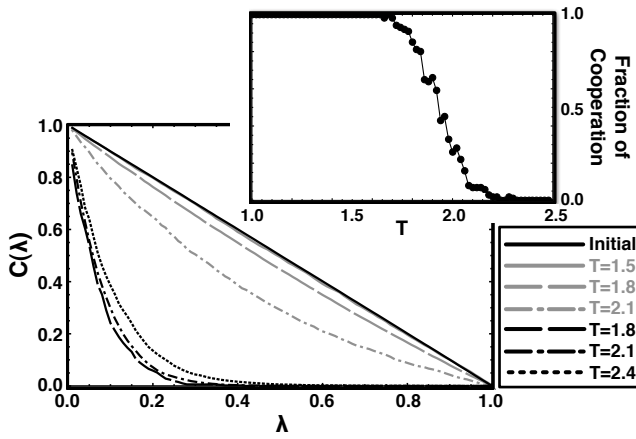
Fig. 3. **Evolving loyalty for both cooperators and defectors.** The gray (black and non-solid) lines shows $C(\lambda) - C(\lambda_0)$ being defined as the fraction of individuals with loyalty $\lambda \geq \lambda_0$ — of cooperators (defectors) for different values of the temptation to defect T ($W = 5$, $\beta = 0.005$, $N = 10^3$, $z = 30$). The inset provides the level of cooperation for values of T between 1 and 2.5. The values of λ of all individuals are uniformly distributed in $[0, 1]$ at the start of each evolution, as indicated by the black solid line. Overall, cooperators end up much more loyal to their partners than defectors. Natural selection only renders loyal cooperators disadvantageous when the tension of the game is high ($1.8 \leq T \leq 2.1$). Defectors, on the other hand, loose almost every commitment to their partners for any tension of the game.

This latter result is a consequence of heterogeneity created by rewiring defectors. As we start from well-mixed communities of limited connectivity, rewiring of links creates a heterogeneous environment, which always favors cooperators [18]. Thus even when cooperators are more loyal than defectors, they prosper at the expense of the defectors greed. Overall, our results clearly show that swift decisions concerning partner choice provide a proactive force toward the evolution of cooperation, *independent of the strategy*.

Given this effect of loyalty (or the absence of it) on the outcome of the **PD** game, we now analyze the effects of evolving this feature as well. To this end, every time an individual changes his strategy by adopting that of a neighbor, he also changes his loyalty to that of his neighbour. In Figure 3, we show the evolution of loyalty of both cooperators and defectors. We start each evolution by assigning every individual a loyalty value λ selected from a uniform distribution. We analyze the distribution of λ at the end of the evolutionary process when the population reaches fixation (i.e., all individuals adopt the same game strategy). The lines in Figure 3 correspond to the cumulative distribution $C(\lambda)$ ($C(\lambda_0)$ being defined as the fraction of individuals with $\lambda \geq \lambda_0$) of cooperators (in gray) and defectors (in black non-solid lines). The initial distributions lead to the black diagonal line in Figure 3; the final distributions are shown with different shapes for different values of the temptation to defect T of the **PD** game. Each of them is obtained by averaging the results of 1000 independent simulations for each value of T. From the results discussed previously one would expect that swift action will always be preferred to

loyalty. This is, however, not true in general. In the range of T values for which cooperation prevails ($T < 1.8$, see the inset of Figure 3), the distribution of λ of all individuals hardly changes. They rapidly become satisfied with all their links, thereby quickly removing any incentive to become more willing to change. For higher values of T, a transition occurs from cooperator dominance to defector dominance, as also indicated in the inset of Figure 3. As competition between cooperators and defectors becomes fierce, it pays to respond swiftly to adverse ties. Consequently, evolution leads to an arms race for swiftness between cooperators and defectors, as evidenced by the decrease in the cumulative distribution in Figure 3. For even larger values of T (> 2.1), defectors dominate the results and evolutionary competition fades away. As a result, the incentive to become more willing to change reduces, a feature which is indeed reflected in the behaviour of $C(\lambda)$ in Figure 3. Once all individuals ultimately become defectors there are no fitness differences anymore and hence no selection pressure to further changes. Nonetheless, the fundamental differences between cooperators and defectors still have an impact in the overall evolutionary dynamics. When cooperators dominate, many social ties rely on mutual satisfaction, and hence there is no incentive to change. On the contrary, even when dominant, defectors are never able to find a partner with whom mutual satisfaction occurs, as a defector with local information only will always strive to find a cooperator to exploit, whereas a cooperator will strive to escape exploitation. Consequently, under cooperator dominance we reach a stable and slowly changing network of ties. In the opposite limit, a quasi-static network is never reached; instead, a stationary one emerges, exhibiting an intrinsic degree of heterogeneity that decreases with increasing number of defectors.

V. DISCUSSION

The present results demonstrate how any selective pressure for disloyalty remains absent when cooperation flourishes. This finding corresponds nicely to experimental evidence indicating that people have a tendency to keep interacting with the same partner, even when attractive alternatives are available [40]. When cooperators are no longer dominant, on the other hand, individuals show an increased willingness to sever adverse social ties. The struggle for survival between cooperators and defectors leads to an arms race for swiftness in adjusting ties, based purely on a self-regarding judgment. Since defectors are never able to establish any tie under mutual agreement, they are overall swifter than cooperators. Ironically, defectors' constant search for new partners to exploit leads to heterogeneous networks that improve the survivability of cooperators compared to homogeneous populations.

From a broader perspective, our work may provide some important insights on the consequences of the fundamental changes taking place in modern networks of exchange and cooperation, where partnership preferences surpassed the limitations imposed by kin-like or geographical constraints. Self-regarding individuals engage nowadays in increasingly

diverse, short-lived and geographically uncorrelated social ties. In this context, social structures such as groups, political parties and other social agglomerates that rely on persistent social ties, usually related to an idea of loyalty which is associated with some form of survival advantage [41], are evanescent. Our results even indicate that the persistence of social ties can bring along an evolutionary disadvantage, both from an individual and a group perspective. Once the ability to freely reshape partnerships arose — most likely originating from the human organization into increasingly larger communities (with associated increasing return benefits [42]) — those individuals that acquired the aptness to respond quickly to unwanted interactions obtained an evolutionary edge over those that remained stuck to the same social contacts whatever the cost. It is reassuring to know that this change in paradigm does not restrain people to cooperate. On the contrary, it may for instance be linked to the rapid emergence of online social communities — such as the ones involved in wikis or open source projects — that are mostly based on cooperative efforts while devoid of norm enforcement mechanisms [43], and ultimately provide an escape hatch from the global challenges of cooperation we also face today [44–46].

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