Evolution of social diversity under the distributed prisoner's dilemma

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Abstract

Cooperation is pervasive in social communities, in which frequently some individuals play different roles than others. Recent empirical studies have shown that real social networks are characterized by both a significant average connectivity and a marked heterogeneity – a scenario for which the emergence and prevalence of cooperative behavior is hard to explain theoretically. Here we show how adaptive networks can generate such diversity in social contexts and create sufficient conditions for cooperation to prevail, whenever the social dilemma perceived by each individual is contingent on his/her social context. Cooperative behavior emerges as a result of the positive assortment of strategies and the symmetry breaking of the game. We further show that cooperation can prevail by evolving realistic heterogeneous networks with high average connectivity as the result of a simple topological dynamics and myopic individual self-interest.

1 Introduction

Cooperation and diversity are two ubiquitous properties of human societies. While explaining the emergence of cooperation is a subject of intense research, the influence of social diversity in the outcome of pro-social behavior remains elusive. Many studies on the emergence of cooperation make use of Evolutionary Game Theory (**EGT**) (Smith, 1982, Hofbauer and Sigmund, 1998) in which a population is traditionally assumed to be infinite and well-mixed. Under such setting individuals are commonly assumed to interact through a Prisoner's Dilemma (**PD**) of cooperation, the harshest and also the most studied social dilemma. For the **PD**, **EGT** predicts the success of the selfish (Smith and Szathmáry, 1997, Sigmund, 2010), in contrast with empirical evidence. To tackle this problem several mechanisms were proposed that allow the survival of cooperation under the **PD**, and many important results were obtained over the years (Nowak and May, 1992, Nowak et al., 2004, Nowak, 2006, Darwin, 1874, Traulsen and Nowak, 2006, Santos and Pacheco, 2005, Santos and Pacheco, 2006, Szabo and Fath, 2007, Poncela et al., 2007, Tanimoto, 2007, Zimmermann et al., 2004, Hanaki et al., 2007, Skyrms and Pemantle, 2000, Pacheco et al., 2008, Poncela et al., 2008, Santos et al., 2006b, Ebel and Bornholdt, 2002).

Social diversity, as evidenced empirically (Dorogovtsev and Mendes, 2003, Albert and Barabási, 2002, Onnela et al., 2007), is one of those mechanisms. Social diversity may be introduced in the context of **EGT** by means, e.g., of heterogeneous networks, which lead to an increase in the levels of cooperation (Santos et al., 2008, Gómez-Gardeñes et al., 2007, Masuda, 2007, Pacheco et al., 2009). However, this enhancement is only significant for networks with a low average number of social ties per individual (around 8), which contradicts recent empirical data and studies of real social networks, that reveal values as high as 140 (Dorogovtsev and Mendes, 2003, Barabási and Albert, 1999, Watts, 2003, Amaral et al., 2000, Albert and Barabási, 2002, Watts, 2004). In this manuscript we demonstrate how the delicate interplay between the evolutionary dynamics of cooperation and social diversity provides an answer to this apparent paradox.

Diversity does not resume to social ties. Often the amount each individual contributes to a specific event may depend on the social context they are actually embedded in (Perc and Szolnoki, 2008, Santos et al., 2008). Take for instance a charity event. Some celebrities are usually invited to participate. Their appearance is given maximal audience, and they are shown contributing a large amount of money. With their media coverage, impressive to many, promoters hope to induce a large number of (much smaller) contributions from anonymous (non-celebrities, the overwhelming majority) charity participants, who feel compelled to contribute given the fact that their role model (the celebrity) contributed. Such a disparate portfolio of contributions suggests that people tend to imitate the act of giving but not the amount given.

Many other examples from real life could be provided along similar lines (trivia, fads, stock markets, Humanitarian causes even the salvation of our planet). These situations provide examples of public goods games (**PGG**) (Hardin, 1968), sometimes correlated with reputation building, social norms and moral principles (Nowak and Sigmund, 1998, Ohtsuki and Iwasa, 2004, Nowak and Sigmund, 2005, Pacheco et al., 2006a, Hauert et al., 2007).

The simplest **PGG** involves two individuals that are given a chance to either Cooperate (**C**) - contribute a cost c to a common pool - or Defect (**D**), by contributing nothing. The overall amount collected is then multiplied by an investment factor F and equally shared between both individuals. Hence the payoff of an individual i ($i = 1,2$) using strategy s_i ($s_i = 0$ if **D**, 1 if **C**) is $P_i = Fc(s_1 + s_2)/2 - cs_i$. The following payoff matrix summarizes all possible outcomes:

$$\begin{array}{cc} & \begin{array}{cc} C & D \end{array} \\ \begin{array}{c} C \\ D \end{array} & \begin{pmatrix} (F-1)c & Fc/2 - c \\ Fc/2 & 0 \end{pmatrix} \end{array} \qquad \textbf{(1)}$$

For $F \le 1$ there is no real investment and **D**s dominate unconditionally, i.e., it is better not to contribute. For $F = 2$ no strategy is favored in well-mixed populations; yet, for $F > 2$, it is better to play **C** despite the fact that, in a mixed pair, a **D** collects a higher payoff than a **C**. For $1 < F < 2$ the game falls into the payoff ranking characteristic of the one-shot Prisoner's Dilemma (**PD**).

With the payoff from (1), any **C** contributes the same **cost per** game, providing the corresponding benefit to the partner. However, there is no reason to assume that everybody contributes the same amount (as argued before). In fact, it is easy to rewrite this formulation taking into account not only diversity of contributions, but also an intuitive coupling between game dynamics and social diversity: The first (second) individual contributes a cost c_1 (c_2) if playing **C** and nothing otherwise. Hence, player i ($i = 1,2$) now gets the following payoff from this game:

$$P_i = F(c_1 s_1 + c_2 s_2)/2 - c_i s_i \qquad \textbf{(2)}$$

Unlike (1), equation (2) indicates that, whenever $c_1 \neq c_2$, there is a symmetry breaking of the game. This, as we show below, can be spawned by a induced diversity of social ties: different cooperating individuals will provide different contributions to the same game depending on their social context. Following (Pacheco et al., 2009) we refer to the game in which **C**s contribute a fixed, common cost per game as Conventional Prisoner's Dilemma (**CPD**), as opposed to the game in which Cs contribute a fixed cost per individual (see below) which we call the Distributed Prisoner's Dilemma (**DPD**).

In section 2 we investigate the emergence of cooperation under the **CPD** and **DPD** paradigms for a finite, fixed, underlying social network. Social diversity may be present in what concerns both social ties and does with respect to contributions of individuals. A question naturally arises: which paradigm has a larger impact on the emergence of cooperation? In section 3 we let diversity evolve, investigating its interplay with the emergence of cooperation. Finally, we offer one conclusion in section 4.

2 Context dependent investments and symmetry breaking of the Prisoner's Dilemma

Let us consider a population of N individuals distributed along the nodes of a complex network of the same size; we define k as the number of neighbors of an individual (node degree). The individual's neighborhood defines their local network of interactions. Here we explore two classes of networks: homogeneous and heterogeneous. While the former exhibit a single-peaked degree distribution, meaning that diversity of connectivity is absent, the latter are characterized by a broad distribution of the node's degree, representing a socially diverse population.

The outcome of all interactions in which an individual participates dictates their social success. This, in turn, drives the social dynamics of ***C***s and ***D***s: individuals will tend to imitate the strategies of the most successful neighbors. For the **CPD** studies we assume $c = 1$, while for the **DPD** the cost each node i pays in each game depends on their degree $c_i = k_i^{-1}$. Hence, in the **DPD** we assume that individuals share their limited resources among the set of interactions they maintain (in the sense that a teacher, for instance, has limited time to share with his students), in contrast with the "unlimited resources scenario" that is implicitly assumed under the **CPD**. This diversity of contributions translates into an obvious diversity on the benefits collected (equation 2). In real world situations, people may discriminate their partners regarding each contribution. Hence, the **CPD** and **DPD** are expected to provide extreme limiting situations.

We start with 50% of **C**s and 50% of **D**s randomly distributed in the population. At each time step an individual (A) selected at random from the population is given the chance to imitate the strategy of a randomly selected neighbor (B) with a probability p given by the Fermi probability distribution:

$$p = \left[1 + e^{-\beta(f_B - f_A)}\right]^{-1} \tag{3}$$

where f_A and f_B represent the fitness of A and B respectively, and β the intensity of selection, which regulates the stochasticity of the system (similarly to an inverse temperature in statistical physics): $\beta \to \infty$ leads to the so-called (deterministic) imitation dynamics often used to model cultural evolution, whereas $\beta \to 0$ leads to neutral drift (maximal stochasticity) (Verdasca et al., 2005, Traulsen et al., 2006a, Traulsen et al., 2006b). Here we consider $\beta = 1.0$.

The population evolves for 10^6 time-steps (or until an absorbing state is reached, if in less time), and we assess the sustainability of cooperation by noting the number of Cooperators present in that state. We average this process for 10^4 realizations.

Figure 1 shows the final fraction of cooperators for three different network topologies: Ring Regular **(REG)** (Szabo and Fath, 2007, Watts and Strogatz, 1998); Exponential **(EXP)** (Newman, 2003) and Scale-Free **(SF)** networks (Barabási and Albert, 1999). The first (**REG**) represents homogeneous networks, while the others (**EXP** and **SF**) exhibit increasing degree of heterogeneity, respectively; they are both built using the Barabási and Albert (**BA**) (Barabási and Albert, 1999) model, with a random and linear preferential attachment rule, respectively.

Each one of these structures accounts for a different level of social diversity. Here we study how cooperation is sustained on these structures across the entire range of the enhancement factor ($1 < F < 2$) and thus assess the impact of social diversity resulting from the heterogeneity of the underlying network on both the **CPD** and **DPD**.

Figure 1A shows the outcome of evolution under the **CPD** where diversity is exclusively associated to the network (social ties). The existence of a minority of highly connected (social) individuals in **SF** networks (line and filled circles) allows the population to preserve high cooperative standards, while on homogeneous networks (line and empty diamonds), **D**s dominate for the entire range of parameters, as a result of the pairwise comparison rule adopted (Szabó and Tőke, 1998). Thus, diversity paves the way for the emergence of cooperation. Highly connected individuals (i.e. hubs) work as catalyzers of cooperators, as their large number of interactions allows them to accumulate a high fitness (Santos et al., 2008). This, in turn, leads them to act as role models for a large number of social partners. To the extent that hubs are **C**s, they influence a vast majority of the population to follow their behavior. Clearly, this feature has stronger impact on **SF** networks than on **EXP** networks, the difference between these two types stemming from the presence or absence of the preferential attachment mechanism, respectively.

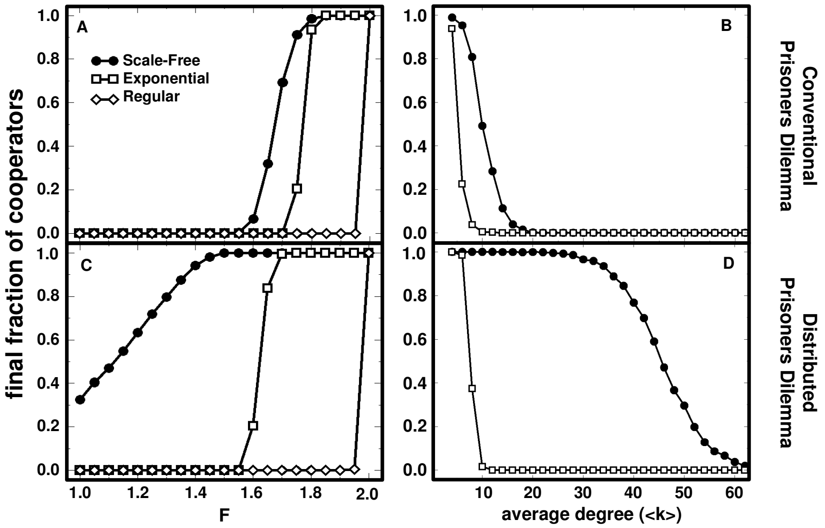

Figure 1: Final fraction of Cooperators as a function of i) the enhancement factor F (panels A and C) and ii) the average degree for the **EXP** and **SF** networks with $F = 1.8$ (panels B and D). **Panel A:** Under **CPD** Cooperation is able to dominate on SF networks (filled circles), unlike what happens on **REG** structures (empty diamonds). On exponential networks, intermediate levels of cooperation emerge, as a result of the heterogeneity of such topologies (empty squares). **Panel C:** Under **DPD** the advantage of **Cs** is dramatically enhanced when the same cost is evenly shared among each neighbor. As expected, abandoning the well-mixed regime leads to a break-up of neutrality for F = 2. **Panels B and D:** Cooperation is able to dominate on sparse networks. Yet only under **DPD**, combined with the high levels of heterogeneity attained on Scale-Free networks, one observes the robustness of cooperative behavior in highly connected populations. The results were obtained for networks of 10^3 nodes and variable average degree (k = 4 in panels A and C) starting with 50% of **Cs** randomly distributed in the population**.**

The results for the **DPD** in **Figure 1C** are essentially the same for homogeneous networks, as it amounts to a rescaling in the intensity of selection. However, with increasing heterogeneity of the underlying network of social ties, the presence of a further level of diversity in the amount contributed per individual to each game creates a remarkable boost in the final fraction of **C**s for the entire range of F. A comparison between contributive paradigms (**Figures 1A** and **1C**) shows that **EXP** networks exhibit a moderate gain which is almost irrelevant when compared with the spectacular boost achieved in cooperation on **SF** networks: hubs become extremely influential under the **DPD**.

The analysis of **Figure 1** shows that heterogeneous networks generally boost the levels of cooperation. When combined with the **DPD**, we observe even higher levels of cooperative behavior.

In order to probe deeper into the mechanism(s) underlying the prevalence of cooperators in the **DPD**, we start by defining the finite population analog $G(x)$ of the gradient of selection under the replicator dynamics $x(1-x)(f_c - f_d)$ (Hofbauer and Sigmund, 1998): $G(x) = T^+(x) - T^-(x)$, where $T^+(x)(T^-(x))$ is the average frequency of transitions increasing (decreasing) the number of **C**s for each random configuration with xN **C**s, valid for any population size and structure. G becomes positive whenever cooperation is favored by evolution and negative otherwise. Whenever $G = 0$, selection becomes neutral and evolution proceeds mainly by random drift. Naturally, G will depend implicitly on the population structure, on the fraction x of **C**s and also on how **C**s are distributed in the network.

As was mentioned above, at start, each individual in the population is assigned a strategy (**C** or **D**) randomly, with equal probability, such that correlations between individuals with the same strategy are not present. As the population evolves such correlations are expected to increase as **C**s breed **C**s and **D**s breed **D**s (Santos and Pacheco, 2006, Santos et al., 2006a). Hence, one expects that a possible outcome of evolution will be the assortment of strategies where each **C** (**D**) has, at least, one **C** (**D**) in his neighborhood. This assorted distribution of **C**s and **D**s can be computed from all numerical simulations we did. For that reason we will always compare the results of random strategy configurations against $G(x)$ of assorted strategy configurations (Figure 2).

In **Figure 2** we plot $G(x)$ as a function of the fraction of cooperators for two different values of F and both contributive schemes (**CPD** and **DPD**). **Figure 2 A** and **2 B** indicate that, in the case of **CPD**, introducing diversity in roles and positions of the social network effectively leads to a coordination game, characterized (in an infinite well-mixed population) by a critical fraction x^* above which **C**s are always advantageous ($G < 0$ for $x < x^*$ and $G > 0$ for $x > x^*$). This result provides a powerful qualitative rationale for many results obtained previously on heterogeneous networks under strong selection (Santos and Pacheco, 2005, Santos et al., 2006b, Santos et al., 2008) in which degree heterogeneity is shown to induce cooperative behavior, inasmuch as the initial fraction of **C**s is high enough (sufficient to overcome the coordination threshold). Moreover **Figure 2C** shows that changing the contributive schemes from **CPD** to **DPD** in **SF** population structures acts to effectively change the **PD** into a scenario in which **C**s dominate irrespectively of the fraction of **C**s $(x^* \sim 0)$, a scenario known as the Harmony Game. In **EXP** networks, diversity is enough to promote coordination, but not cooperation dominance throughout (Harmony Game).

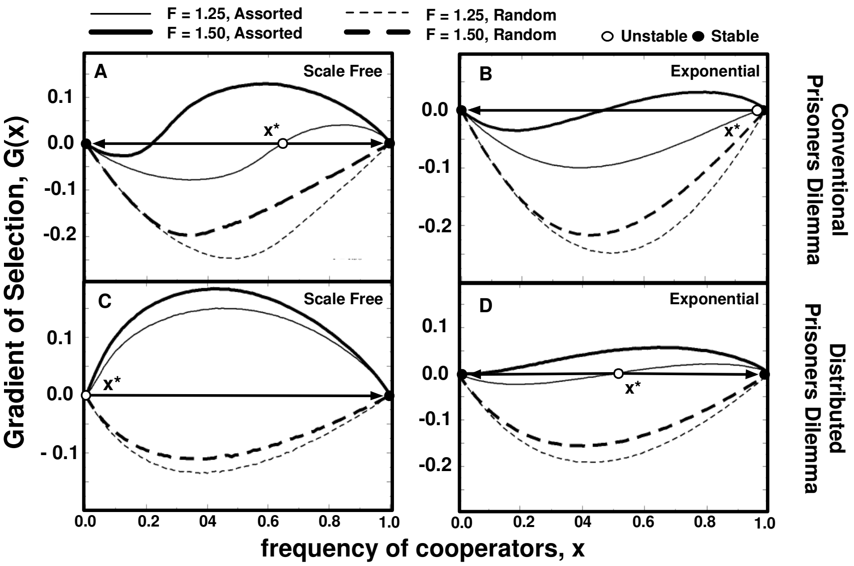

Figure 2. Gradient of Selection $G(x)$ for $F = 1.25$ (thin lines) and $F = 1.50$ (thick lines) for random (dashed lines) and assorted (solid lines) distributions of strategies for both types of heterogeneous networks (**EXP** and **SF**). Under the **CPD** paradigm (panels A and B) and with the appropriate value of F, heterogeneous networks lead to the appearance of an unstable fixed point x^* (open circles) characteristic of a coordination game. Under **DPD** (panels C and D), the change in the effective game is even more marked and in the case of SF networks the game transformation occurs between a $G(x)$ always negative (prisoner's dilemma) to a scenario where it is positive for most values of x, akin to a Harmony game, where cooperators dominate unconditionally. In both panels the networks employed had 10^3 nodes and an average degree $z = 4$, and $\beta = 10.0$.

3 Evolving Diversity

Figures 1B and **1D** show the robustness of the results discussed so far for networks with increasing $<k>$. However, under the **CPD** the levels of cooperation drop to zero for a relatively low average degree $(<k>\sim 20)$ and although with the **DPD** we can increase the chances of cooperation for values of $<k>$ as high as 60, we are still far below the maximum empiric value of 140 mentioned in the introduction.

To tackle this problem we introduce a simple topological evolution rule (Santos et al., 2008, Van Segbroeck et al., 2009, Santos et al., 2006a) which lets individuals adjust their social ties . When combined with strategy evolution, such an adaptive rule will enable network diversity to evolve as well.

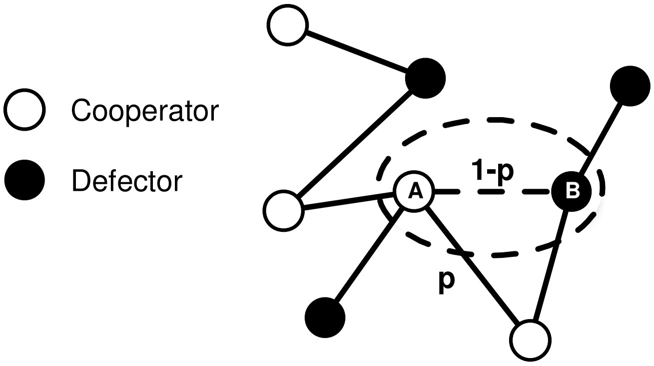

Figure 3. Readjusting social ties. Cooperators and Defectors interact along the links of a network. A (B) is dissatisfied (satisfied) since B (A) is Defector (Cooperator). Consequently A wants to change the link whereas B does not. The success of the rewiring depends on the fitness values f_A and f_B of A and B, respectively. With probability *p* (given by equation 3) A redirects the link to a random neighbor of B. Otherwise, with probability 1 - *p*, A stays linked to B. Other possibilities may occur depending on the strategies of the chosen individuals (see Section 3).

In this new model, individuals acquire the ability to decide which links they want to keep, irrespective of their strategies: given an edge connecting individuals A and B, we say that A (B) is satisfied with that edge if B (A) is a **C**, being dissatisfied otherwise. This tool offers a means to study the emergence of diversity under two distinct schemes of individual contributions.

To study the co-evolutionary interplay between the two processes (strategy and network evolution), we define $W = \tau_e / \tau_a$, the ratio between the characteristic time scales for the two processes: τ_e for the strategy evolution and τ_a for the structural adaptation. Whenever $W = 0$ no network adaptation takes place and we recover the results for static networks. For $W > 0$, we have co-evolution of both strategy and rewiring dynamics. We assume without loss of generality $\tau_e = 1.0$.

At each time step and with probability $(1+W)^{-1}$ we choose a strategy update event, as described in the previous section. Otherwise we choose a structure update event (illustrated in Fig. 3), that happens as follows: an individual (A) is selected at random from the population to evaluate the link with one of his neighbors (B) also randomly chosen. The evaluation is performed according to equation 3. Depending on their respective strategies: **1)** If A and B are both satisfied (they are both **C**s) nothing happens; **2)** If A (B) is a **C** and B (A) is a **D** then, with probability p, A (B) redirects the link to a random neighbor of B (A). **3)** If A and B are both dissatisfied (they are both **D**s) then the rewiring takes place such that the link keeps attached to A with probability p and attached to B with probability $1 - p$. During the rewiring process no links are destroyed or created, so that the average connectivity of the network, $<k>= N^{-1}\sum_{i=1}^{N} k_i$, remains constant.

As in section 2, we start with a population composed of 50% of Cooperators and 50% of Defectors randomly distributed on an homogeneous random graph (**HRND**), also known as random regular graph, which constitutes the random limit of the homogeneous small world networks defined in (Watts, 2003).

Figure 4 shows the fraction of **C**s at the end of evolution for different values of W. On homogeneous populations, with no network adaptive dynamics ($W = 0.0$), cooperation bears almost no chance under both **CPD** and **DPD** – this is because the average connectivity $<k>$ is 30. Yet, when we give a chance for individuals to change their social ties, we start to observe major changes. As **C**s (**D**s) seek for **C**s to cooperate (exploit), **C**s tend to acquire a higher number of links when compared with **D**s. This self-organization of diversity (network heterogeneity) benefits the emergence of cooperators, in particular because **C**s promote their positioning in highly connected nodes.

These dynamics are responsible for the emergence of diversity at the level of the social ties, by changing the degree from individual to individual. However, in the **DPD** paradigm these dynamics are responsible for one additional change, as the game perceived by each individual also evolves as their degree changes. Clearly, under the **DPD** , the diversity of resource allocation by cooperators in each game, spawned by network diversity, further favors the emergence of cooperation.

As shown before (Pacheco et al., 2009), under **DPD** the condition for a highly connected ***C*** to become advantageous becomes less stringent the larger their connectivity. On the contrary, under **CPD** the cost of cooperation plays a major role in the overall fitness of a cooperative hub. The larger their connectivity, the higher the cost of cooperation and hence the harder it will be for a cooperative hub to become advantageous with respect to a successful ***D*** in their neighborhood. Consequently, under **DPD** cooperation is much easier to emerge and benefits from the additional break of symmetry of the game induced by evolution of the social structure.

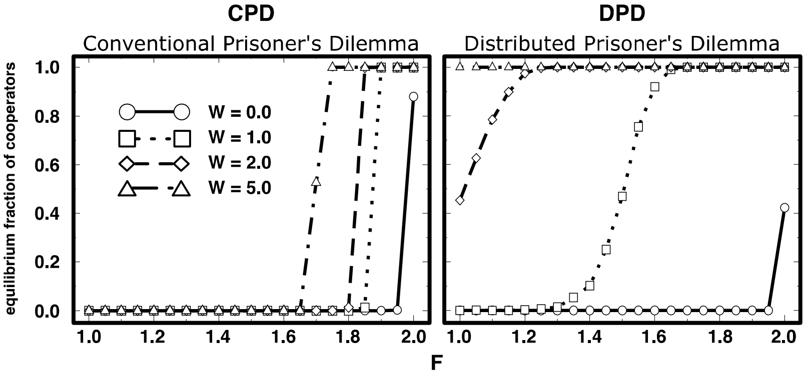

Figure 4. Co-evolution of strategies and topology for different time scales. Equilibrium fraction of Cooperators as a function of the enhancement factor F starting with a **HRND** graph of k = 30 and β = 1.0. **Left panel:** Under **CPD** it is difficult for cooperation to emerge unless we allow a fast adaptation of the network structure. As ***W*** increases, so does the rate of link rewiring and the viability of cooperation. **Right panel:** Under **DPD**, in addition to the adaptive assortment of Cs, cooperation benefits from the break of symmetry associated with the nature of the dilemma and emerging heterogeneity of the network.

This becomes clearer when one compares the results on both panels of **Figure 4** and recalls the results of **Figure 1**. Although for the **CPD** with W = 5.0 the curve resembles the one obtained for W = 0.0 and an underlying **EXP** network, when one looks at the **DPD** the result bears no resemblance and cooperation thrives for the entire range of the enhancement factor. This indicates the emergence of different structures for the different paradigms. Nevertheless, for a sufficient large W, we get full cooperation for both paradigms.

While for small values of W **C**s do not survive long enough, as W approaches a critical value W_{crit} they steadily acquire the evolutionary edge necessary to eradicate all **Ds** from the population. W_{crit} increases monotonically with <k>, which is a consequence of a larger number of links in need of rewiring.

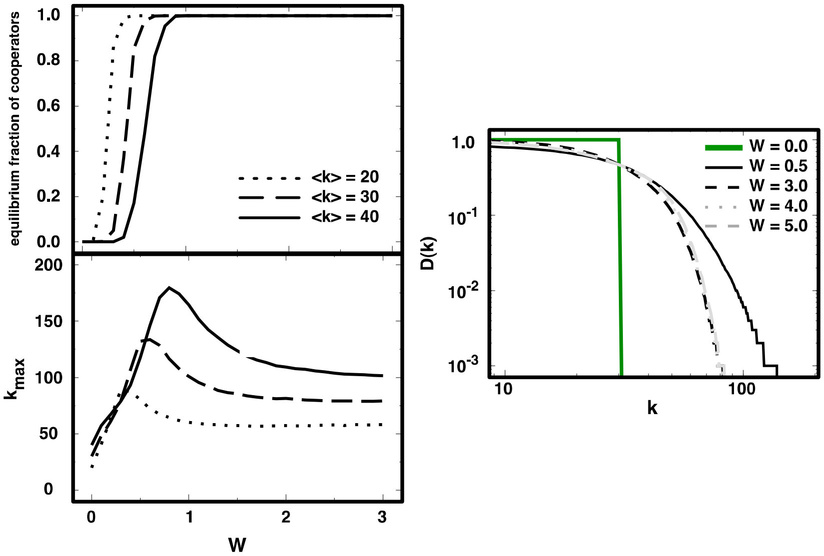

Figure 5. Co-evolution of strategy and topology for different networks. DPD game for $F = 1.8$ and $\beta = 1.0$ starting from homogeneous random **HRND** graphs. **Upper left panel:** Equilibrium fraction of Cooperators as a function of W for different values of k. For each value of k there is a critical value of the time scale W_{crit}, above which Cooperators wipe out Defectors. **Lower left panel:** Maximum value k_{max} of the connectivity in the population as a function of W. Not only W_{crit} increases monotonically with $< k >$, but also k_{max} is maximal at W_{crit}. **Right panel:** Cumulative degree distributions for different values of W. Starting from a **HRND** network with $k_{\max} = < k > = 30$, the distribution widens as long as W $\neq 0$, resulting in both single scale networks ($W = 0.5$, solid brown line) and broad-scale networks ($W > 3$, dotted black and grey lines). W_{crit} also corresponds to the value for which the heterogeneity of the associated network reaches a maximum.

Figure 5 provides evidence of the detailed interplay between strategy and structure, and the properties of the social structure that emerges from it. In contrast with the local assortment of strategies (**C**s breed **C**s and **D**s breed **D**s), which takes place at W = 0.0, structural updating promotes now local assortative interactions between **C**s and disassortative between **D**s.

From the left panels of **Figure 5**, the overall onset of increasing heterogeneity qualitatively follows the wave of cooperation for the corresponding $< k >$. Indeed, the overall heterogeneity of the network reaches a maximum at W_{crit} , above which heterogeneity again decreases to a stationary state. This is clearly shown in the right panel of **Figure 5** for a **DPD** with enhancement factor of $F = 1.8$. The results shown suggest that the adaptive dynamics of social ties accounts for the heterogeneities observed in realistic networks of social ties. Also, similar analytic results were already obtained in a simpler model of link rewiring (Pacheco et al., 2008, Pacheco et al., 2006b).

4 Conclusion

The present study highlights the impact of breaking the symmetry of cooperative contributions on the prototypical two-player game both at the level of the game itself and also at the level of the underlying structure of the population.

On strongly heterogeneous networks, the results of **Figure 1** provide an impressive account of the impact of this diversity of contributions. Our results suggest that whenever the act of cooperation is associated to the act of contributing, irrespective of the amount contributed, cooperation blooms insofar as the structure of the social web is heterogeneous, leading individuals to play diverse roles.

Figures 4 and **5** show, unequivocally, how adaptive social networks can easily transform a defection dominance scenario into a fully cooperative one, meaning that diversity in the game coupled with network diversity induced by adaptation adds up to even more cooperative behavior.

Moreover, this multiplicity of roles and contributions induced by the social structure effectively transforms a local cooperative dilemma into a global coordination game (Skyrms, 2004). Indeed, the assortment of strategies arising from the intricate nature of collective dynamics of cooperation in a complex network leads to a change in the effective game played by the population. For that reason, while at a local scale cooperation can be understood as a prisoner's dilemma, at a global scale individuals are effectively involved in a coordination dilemma (Skyrms, 2004).

Finally, allowing the co-evolution of strategy and structure can lead to realistic heterogeneous networks in which cooperation prevails.

The present study provides a bottom-up answer to the problem of cooperation, showing how complex social topologies can result from simple social dynamical processes, exclusively based on local assumptions.

Overall, diversity seems to emerge as an efficient promoter of cooperation. Here we have discussed a few examples, but, in fact, other forms of diversity have been recently considered, which corroborate this idea. For instance, in (Szolnoki et al., 2008) it is shown how diversity in learning rates can support cooperative behavior. Also, it can be shown that topological heterogeneity together with incipient forms of cognition (Vukov et al., 2011) may hold back the invasion of free riders, once cooperation is achieved: Diversity promotes robustness. Similarly, in

(Santos et al., 2011) it has been shown that the fate of cooperation may be dependent on the diversity of pre-play signals available, illustrating the advantages of a complex signaling system. All these theoretical insights correlate nicely with recent experiments investigating the role of diversity and globalization (Buchan et al., 2009) in human cooperation, offering a positive message concerning the advantages of a tolerant and socially diverse world.

Acknowledgments

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