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Strong ties promote the evolution of cooperation in dynamic networks☆

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ABSTRACT

Research on the evolution of cooperation in networked populations has assumed that ties are simply present or absent. Here we bring relational sociological insights about the strength of ties to bear on the problem of cooperation in dynamic networks. We argue that the value of ties affects their strength, which in turn promotes cooperation. We evaluate this argument with two studies. First, results from an agent-based model are consistent with the logic of our argument and are robust across a variety of initial conditions. Second, results from a controlled laboratory experiment with human participants support the key predictions. Across both studies we demonstrate that tie strength, operationalized as relationship duration, mediates the impact of tie value on cooperation.

Cooperation in nature is something of a paradox as cooperators may be exploited by defectors, or those who take advantage of others' cooperative behaviors. One emerging line of research addresses the conditions under which structured or networked populations promote cooperation (Fehl et al., 2011; Hanaki et al., 2007; Rand et al., 2011). In particular, dynamic networks allow cooperators to shed relationships to those who do not reciprocate their benevolent acts (Santos et al., 2006; Wang et al., 2012), which enables cooperators to maintain many ties and form clusters characterized by high levels of cooperation (Bravo et al., 2012). Mutual cooperation, in turn, increases the fitness of those cooperators, making cooperation a more viable strategy in dynamic networks than in unstructured populations.

Thus far the literature on the evolution of cooperation has assumed that relations are equally weighted (e.g., Rand et al., 2011; Wang et al., 2012). Here we aim to bring in sociological insights about the strength of ties to the problem of cooperation in dynamic networks. We argue that as tie value increases, so should the stability of relationships and thus their duration. Duration is a key dimension of tie strength (Granovetter, 1973) and one of the best indicators of it (Marsden and Campbell, 2012). In turn, these more durable, stronger ties promote cooperation. We elaborate this argument below and evaluate it using agent-based models. We then test it using data from a controlled laboratory study. The results from both studies support our argument. The agent-based model shows that tie value is positively related to cooperation. Likewise, as expected, our laboratory experiment shows that tie strength, as operationalized by relationship duration, mediates the effect of tie value on cooperation. At the same time, we find low levels of cooperation in dynamic networks in which tie value and strength do not vary between relations. Below we review the relevant literature leading up to our argument.

1. When do networks promote cooperation?

A recent review (Rand and Nowak, 2013) pointed to five theoretical bases of cooperation, *structured populations* being the most relevant for sociologists.[1] Structure can result from geography (e.g., Hauert and Doebeli, 2004) or social networks. Here we focus on networks and describe the conditions under which they enable cooperation to persist. Specifically, our work addresses cooperation in *dynamic networks*, where ties can be altered (added or deleted) over time.

Two processes have been shown to promote cooperation in dynamic networks. First, simulation work suggests that as networks grow, preferential attachment to cooperators results in

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[1] The others, less relevant to our aims, include *direct*- and *indirect*-reciprocity, *multi-level selection*, and *kin selection* (Rand and Nowak, 2013).

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networks with scale-free degree distributions, with cooperators having a disproportionate share of connections to others (Santos and Pacheco, 2005). In line with this work, Bravo et al. (2012) found that cooperative agents establish more relations than defectors or free-riders, which increases the overall fitness of cooperators. Likewise, Eguíluz et al. (2005) found that "leaders" emerge within regions of large simulated networks and these leaders are cooperative agents with many ties and high payoffs. Each of these studies demonstrate that in dynamic networks, cooperators are likely to have more ties, and hence more opportunities to accumulate resources, than defectors.

The second process that facilitates cooperation in dynamic networks has been demonstrated in both simulations and experiments with human subjects across a variety of network conditions. While cooperation in static networks generally requires that clusters of cooperators be imposed exogenously (Assenza et al., 2008), research on dynamic networks reveals how clusters of cooperators emerge endogenously, as cooperators maintain ties to each other while severing ties to non-cooperators (Fu et al., 2008; Poncela et al., 2008; Wang et al., 2012; Fehl et al., 2011; Rezaei and Kirley, 2012).[2]

Importantly, multiple experiments with human subjects (Rand et al., 2011; Shirado et al., 2013) have found that the rate of relation changes or tie swaps in dynamic networks affects aggregate levels of cooperation. If actors can only alter relations infrequently, it is difficult to shed ties to non-cooperators. Non-cooperators then take advantage of the fact that their partners are stuck with them. As a consequence, defection dominates cooperation. At the other extreme, research shows that, if relations are updated too frequently, non-cooperators quickly reattach to cooperators which, again, favors defection.[3] Thus, as typically studied, network dynamics exhibit a "Goldilocks" effect (Shirado et al., 2013) where moderate levels of relation changes yield optimal levels of cooperation.[4]

2. Tie strength and cooperation

The research reviewed in the prior section has significantly advanced our understanding of how networks shape cooperation, but we can substantially extend and sharpen our understanding of the role of networks in the evolution of cooperation by investigating variation in the value and strength of social relations. The value of social relations derives from an array of sources, including the benefits that accrue to the actors from the relation (Molm and Cook, 1995), the existence of alternative relations (Emerson, 1962), the status value of association with a contact (Berger et al., 1972), or the emotional "buzz" actors attribute to the relation (Collins, 2004; Lawler, 2001; Molm, 2008). Regardless of the "source" or type of value, more valued relations will tend to generate stronger ties, since actors will be more motivated to spend time in the relation and, most relevant to our arguments, more motivated to maintain them.

Our conception of tie strength also follows prior work. For instance, Granovetter's (1973: 1361) seminal work defined tie strength as a "combination of the amount of time, the emotional intensity, the intimacy (mutual confiding), and the reciprocal services which characterize the tie." This definition has given rise to many operationalizations of tie strength, including relationship duration (Atterton, 2007; Baer, 2010; Wegener, 1991), frequency of contact (Holbrook and Kulik, 2001; Jones et al., 2013; Louch, 2000), type of relation (Wegener, 1991), subjective closeness (Baer, 2010), and the amount of support received from the tie (Holbrook and Kulik, 2001). Marsden and Campbell (1984, 2012) noted that closeness and relationship duration, especially outside of families, are good indicators of tie strength. (Most kinship ties are not dynamic, making duration a poor indicator of the strength of ties between family members.) As detailed more fully below, we use duration as an indicator of tie strength for two main reasons: (*i*) it is straightforward to objectively measure in our empirical studies, and (*ii*) it would be impossible to implement psychological closeness in our agent-based model without introducing unnecessary additional assumptions.

Although tie strength has been used to explain employment (Bian, 1997; Granovetter, 1974, 1985; Lin and Dumin, 1986; Montgomery, 1992, 1994), information flows (Onnela et al., 2007), social support (Wellman and Wortley, 1990), and a host of other outcomes, no prior work has addressed the impact of tie strength on network dynamics and cooperation. That said, a few recent findings are suggestive. Harrison et al. (2011) found that individuals were willing to incur greater costs to benefit more strongly tied alters. Specifically, using innovative experimental methods, they found that individuals agreed to experience greater physical discomfort for the benefit of alters to whom they were more closely tied. They argued that close ties were likened to kin by the participants, and kinship is another key mechanism that promotes cooperation and self-sacrifice (e.g., Nowak, 2006). While the study by Harrison and colleagues illustrates that individuals are more likely to cooperate with strong ties, it is silent on how tie strength impacts network dynamics and the emergence and robustness of cooperation. In other work, Macy and Skvoretz (1998) used a genetic computational model to show that trust and cooperation may evolve in neighborhoods and spread through weak ties. In this context, however, tie strength was not an explicit focus, but was instead used generically to denote ties to "strangers" (i.e., nodes with whom ego had not interacted).[5]

Why specifically should tie strength matter for cooperation in dynamic networks? Relationship duration is one key dimension of tie strength (Granovetter, 1973; Marsden and Campbell, 2012). Relations that endure allow for the development of trust and commitment within the dyad (Kollock, 1994; Yamagishi et al., 1998; DiMaggio and Louch, 1998). Moreover, relations that persist over time in dynamic networks tend to be between more cooperative actors, whereas relations connecting cooperators to defectors, or defectors to one another, are more likely to be severed, because trust and commitment have been violated by at least one party.

[2] This result closely parallels earlier studies that, although not framed as investigations of network structure, demonstrated how the ability to enter or exit relations favors more cooperative strategies (Orbell and Dawes, 1993; Yamagishi and Hayashi, 1996; Boone and Macy, 1999).

[3] Note, however, that this result occurs only because, in these prior studies, actors seeking to form new ties are randomly connected to another actor in the *entire* pool of available actors, including those to whom they have previously shed ties. This is, of course, an unrealistic simplifying assumption. In the studies introduced below, we allow actors to form new ties only among the pool of actors to whom they have not previously been connected.

[4] Specifically, Shirado and colleagues reported maximum levels of cooperation when 70% of the dyads were selected for tie updates. While this percentage might seem high, it is important to note that previously severed relations could be added in subsequent rounds of the experiment. Wang et al. (2012) used a different approach, but also found that increasing the number of tie updates promotes cooperation. Importantly, when participants were asked to form new ties with others, they were provided with their decisions to cooperate or defect on the previous 5 rounds. It is therefore unclear whether increased levels of cooperation result from network dynamics or reputation effects, which also promote cooperation (Nowak and Sigmund, 1998). The tie updating strategy we employ in the studies outlined below is more in line with the Wang et al. (2012) method, though we are careful to avoid conflating dynamic network effects with reputation effects.

[5] In contrast to our focus, other work on tie strength and cooperation (Flache and Macy, 1996; see also Horne, 2001; Kitts, 2006) addresses how dyadic ties between individuals in a group impact contributions to collective actions.