

# **A NetLogo Model for the Study of the Evolution of Cooperation in Social Networks**

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## **Abstract**

Cooperation has played a key role in the evolution of various species, from single-celled organisms without any cognitive capacity whatsoever, to diverse species of birds and fish, from non-human primates such as chimpanzees and capuchin monkeys to humans, where the role of cooperation may have been most evolutionarily significant. Arriving at a coherent understanding of how cooperation can evolve in the face of self-regarding agents remains one of the most formidable challenges to those that study the management of conflict. At the same time, the study of network theory, complex systems, and nonlinear dynamics has pervaded all of science. Indeed, E. O. Wilson, who once characterized the evolution of cooperation as one of the greatest challenges for modern biology, more recently made a more emphatic appeal for research on complex systems. And yet, remarkably little work has been done that investigates the evolution of cooperation using network theory and the tools of complex systems analysis. Our work seeks to make contributions at the intersection of these two important areas of study.

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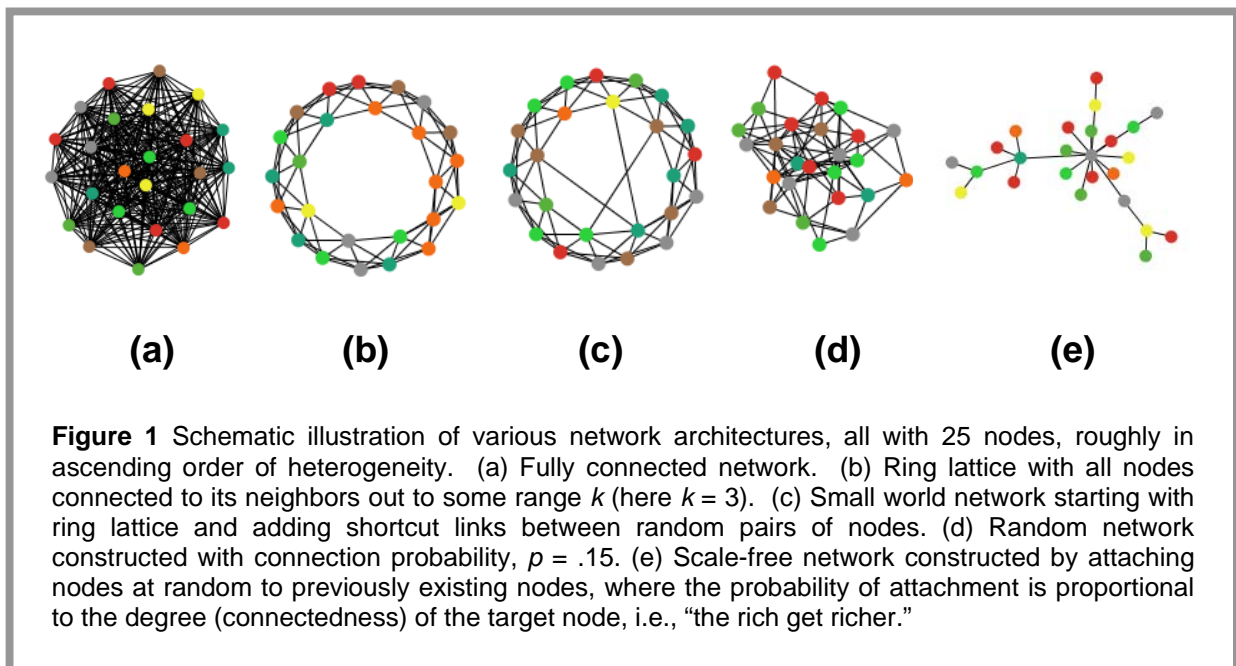
**Key Words:** Cooperation; Reciprocity; Social Networks; Heterogeneity; NetLogo

# A NetLogo Model for the Study of the Evolution of Cooperation in Social Networks

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Cooperation has played a key role in the evolution of various species, from single-celled organisms without any cognitive capacity whatsoever, to diverse species of birds and fish, from non-human primates such as chimpanzees and capuchin monkeys to humans, where the role of cooperation may have been most evolutionarily significant (Hammerstein, 2003). And yet arriving at a coherent understanding of how cooperation can evolve in the face of self-regarding agents remains one of the most formidable challenges to those that study the management of conflict.

At the same time, the study of network theory, complex systems, and nonlinear dynamics has pervaded all of science. We personally feel the consequences of the power of networks, (Strogatz, 2001) as in 1996 when two faulty power lines in Oregon brought about wide-spread blackouts in 11 US states and two Canadian provinces, in 2000 when the Love Bug worm spread through the Internet causing billions of dollars of damage worldwide, and in 2001 when 19 terrorists who were part of the al-Qaeda network hijacked four commercial passenger jet airliners and used them to bring down the twin towers of the World Trade Center and seriously damage the Pentagon, killing nearly three thousand people. Indeed, E. O. Wilson, who once characterized the evolution of cooperation as one of the greatest challenges for modern biology (Wilson, 2000), more recently made a more emphatic appeal for research on complex systems. “The greatest challenge today, not just in cell biology and ecology, but in all of science, is the accurate and complete description of complex systems. Scientists have broken down many kinds of systems. They think they know most of the elements and forces. The next task is to reassemble them, at least in mathematical models that capture the key properties of the entire ensembles.” (Wilson, 1998, p. 85).



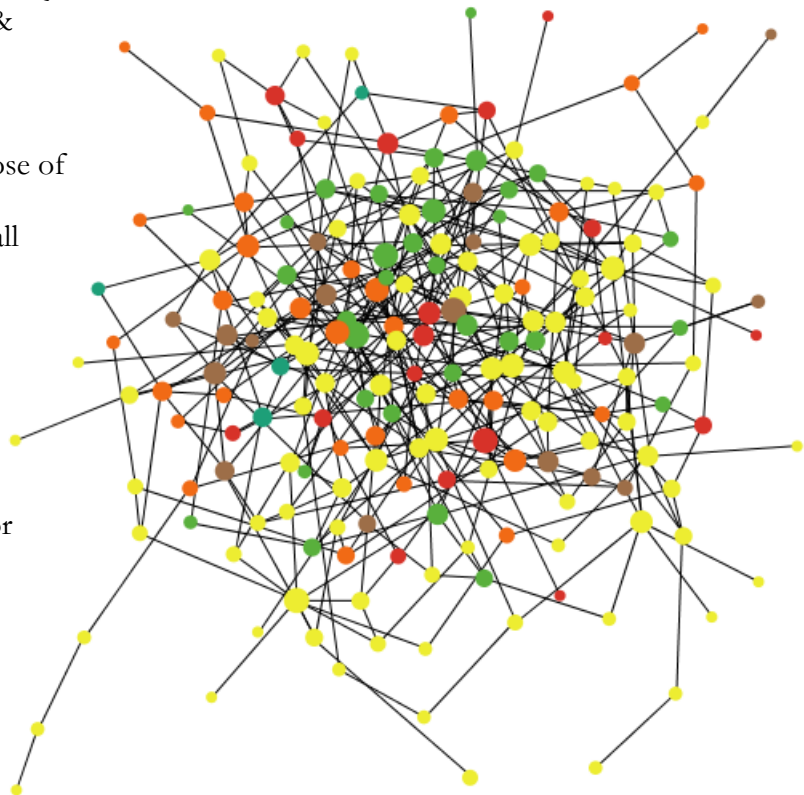
And yet, remarkably little work has been done that investigates the evolution of cooperation using network theory and the tools of complex systems analysis. Our work seeks to make contributions at the intersection of these two important areas of study.

### The Predictions of Evolutionary Game Theory

Scholars from fields as diverse as anthropology, biology, sociology, ecology, economics, management, psychology, political science, law, mathematics and physics frequently rely on evolutionary game theory as a common mathematical framework for investigations into the evolution of cooperation (Santos, Rodriguez & Pacheco, 2005; Maynard-Smith, 1982; Gintis, 2000). Quite often, the prisoners' dilemma (PD) (Axelrod & Hamilton, 1981) is employed as a model of cooperation between individuals in circumstances where individual interests conflict with those of the group. Axelrod's original simulations (Axelrod, 1984) posed all agents against all others (and thus corresponded to mean field approximations) without the evolutionary dynamics that would have made his results more universally applicable. In fact, it was subsequently shown that in well-mixed populations, replicator dynamics result in domination by defectors (Gintis, 2000), as is predicted by the Nash equilibrium in the game.

Correlated association (Skyrms, 1996), where agents have a higher probability of interacting with similar agents, offers more hope for the survival of cooperation. One way in which this association is possible is when the games take place in spatially structured populations that limit the possibilities of interaction (Nowak & May, 1992).

Structured populations have been investigated on rings and regular lattices as well as more complex network architectures (Figure 1), however, most of the work that has considered the effects of these network dynamics has been limited to simple, single-round PD games where agents employ one of only two strategies – cooperation or defection (Nowak & May, 1992; Nowak, Bonhoeffer & May, 1994; Pakdaman & Mestivier, 2001; Vainstein & Arenzon, 2001; Holme, Trusina, Kim &



**Figure 2 Reciprocity Emerging.** Random network of 200 agents constructed with connection probability,  $p = .01$ . Agents are sized proportional to degree. After 5 generations of 10 PD games with deterministic imitation, reciprocating strategies (yellow agents) are emerging towards population dominance.

Minnhagen, 2003; Pacheco & Santos, 2005; Duran & Mulet, 2005; Santos & Pacheco, 2005). As one-shot games, there is no chance of two agents facing each other again, no need for memory of previous interactions, and no opportunity for reciprocity.

### The Evolution of Social Structure

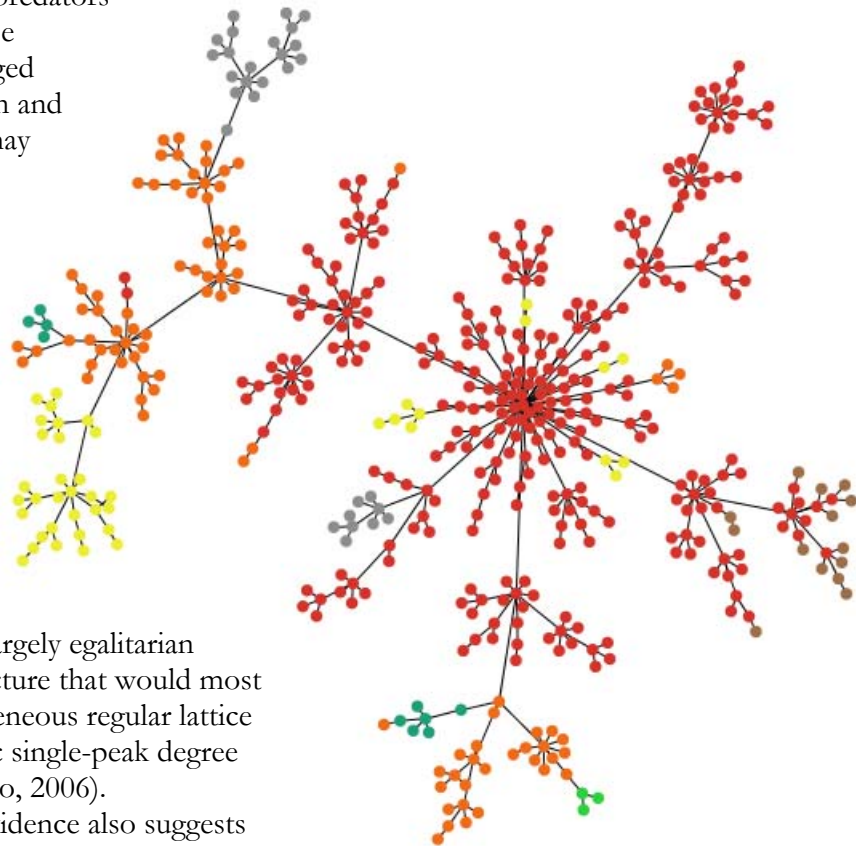
Modern living affords present day humans a bounty of benefits that reduce morbidity and mortality, offer comforts that would seem astonishing to most of our ancestors, and all but eliminate the threats of most predators

(Buss, 2000). Along with these benefits, however, have emerged discrepancies between modern and ancestral environments that may present us with a variety of unanticipated ills. Humans evolved in small groups, consisting of approximately 150 individuals (Dunbar, 1993) largely made up of extended kin networks.

There is mounting evidence that social networks in this environment of evolutionary adaptedness (EEA) (Bowlby, 1969) were largely egalitarian (Kanazawa, 2001) with a structure that would most closely approximate a homogeneous regular lattice (Figure 1) with a characteristic single-peak degree distribution (Santos & Pacheco, 2006).

On the other hand, evidence also suggests that many natural, social, and technological networks analyzed today are more heterogeneous exhibiting multi-peaked degree distributions (Santos & Pacheco, 2006; Barabasi & Albert, 1999; Amaral, Scala,

Barthelemy & Stanley, 2000; Albert & Barabasi, 2002; Dorogotsev & Mendes, 2003). Much of social structure is determined to conform to either small world networks (Watts & Strogatz, 1998; Figure 1) or scale-free networks (Barabasi & Albert, 1999; Figures 1 & 3). It appears that the characteristic social structure of humans has changed significantly in the 10,000 years since the Pleistocene epoch (the EEA). And given that the human brain, and its associated psychological mechanisms adapted to the EEA, has not changed much during the same time frame, it may be that cooperation and conflict behaviors in the current environment are maladaptive (Kanazawa, 2001).



**Figure 3 A Modern Network.** Scale-free network of 500 agents. After 5 generations of 10 PD games with deterministic imitation, niches of various strategies, including reciprocators (yellow agents), survive in equilibrium, but defectors (red agents) dominate from the most highly connected hub.

## Reciprocity in Social Networks

In this work, we demonstrate a NetLogo (Wilensky, 1999) model developed to expand upon the investigations of network dynamics in the simple PD game by studying the repeated game with memory, giving rise to the possibility of reciprocity. Fully connected networks (Figure 1a) provide the baseline case in which the dominance of defection characteristic of mean field simulations is not surprising. Ring lattices (Figure 1b) provide prototypical homogeneous spatial structure. Small world networks (Figure 1c) and scale-free networks (Figures 1e & 3) provide variants of heterogeneous spatial structure. Random networks (Figures 1d & 2) provide controllable, intermediate levels of heterogeneity.

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