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Review

Universal scaling for the dilemma strength in evolutionary games

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Abstract

Why would natural selection favor the prevalence of cooperation within the groups of selfish individuals? A fruitful framework to address this question is evolutionary game theory, the essence of which is captured in the so-called social dilemmas. Such dilemmas have sparked the development of a variety of mathematical approaches to assess the conditions under which cooperation evolves. Furthermore, borrowing from statistical physics and network science, the research of the evolutionary game dynamics has been enriched with phenomena such as pattern formation, equilibrium selection, and self-organization. Numerous advances in understanding the evolution of cooperative behavior over the last few decades have recently been distilled into five reciprocity mechanisms: direct reciprocity, indirect reciprocity, kin selection, group selection, and network reciprocity. However, when social viscosity is introduced into a population via any of the reciprocity mechanisms, the existing scaling parameters for the dilemma strength do not yield a unique answer as to how the evolutionary dynamics should unfold. Motivated by this problem, we review the developments that led to the present state of affairs, highlight the accompanying pitfalls, and propose new universal scaling parameters for the dilemma strength. We prove universality by showing that the conditions for an ESS and the expressions for the internal equilibriums in an infinite, well-mixed population subjected to any of the five reciprocity mechanisms depend only on the new scaling parameters. A similar result is shown to hold for the fixation probability of the different strategies in a finite, well-mixed population. Furthermore, by means of numerical simulations, the same scaling parameters are shown to be effective even if the evolution of cooperation is considered on the spatial networks (with the exception of highly heterogeneous setups). We close the discussion by suggesting promising directions for future research including (i) how to handle the dilemma strength in the context of co-evolution and (ii) where to seek opportunities for applying the game theoretical approach with meaningful impact.

Keywords: Evolutionary games; Cooperation; Dilemma strength; Equilibrium; Reciprocity; Scaling parameters

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1. Introduction

1.1. Advances in the research of cooperation in social dilemmas

The evolution of cooperation is a basic conundrum in biological systems because unselfish, altruistic actions apparently contradict Darwinian selection [1]. Nevertheless, cooperative behavior is ubiquitous among living organisms, from bacterial colonies to animal and human societies [2–6]. Archetypal examples include vampire bats sharing a meal of blood [7], social animals emitting alarm calls to warn of predators in the vicinity [8], fish inspecting predators preferably in pairs [9], and monkeys grooming each other [10], to name a few. It is noticeable that, in all these examples, cooperative entities make a sacrifice – they help others at a cost to themselves. Exploiters, or cheaters, reap the benefits and forgo costs. Starting from the mid 20th century, a wealth of models and mechanisms have been proposed to explain how a cooperative trait can survive and even thrive [6,11–15]. In particular, the mathematical framework of evolutionary game theory has become essential to overcome the benefit disadvantage in the face of exploitation [11,16]. Moreover, evolutionary game theory generates important insights into the evolution of cooperation, many of which have been found applicable across a myriad of scientific disciplines [15,17–20].

With the advent of new analytical methodologies, many contributions have been made to the proposition of reciprocal altruism and its underlying mechanisms. The pioneering research of Dawes [21] found that natural selection favors defection in a well-mixed population playing the prisoner's dilemma game (PD, perhaps the most famous metaphor for the problem of cooperation) [22–26]. However, if everybody defects, the mean population payoff is lower than if everybody cooperates, thus creating a social dilemma. Resorting to a more technical description, PD is characterized by a Nash equilibrium in which all players are defectors, although the population of cooperators is Pareto efficient [27]. Subsequently, more scenarios have been identified that avoid the inevitability of a social downfall embodied in the well-mixed PD. One such scenario is the chicken game (CH) (also the snowdrift game (SD) or the hawk–dove game (HD)) [28,29], in which mutual defection is individually less favorable than a cooperation–defection pair. Accordingly, CH allows for a stable coexistence of cooperators and defectors in a well-mixed population (namely, the number of cooperator–defector pairs increases). The stag hunt game (SH) [30,31], which together with PD and CH comprises the standard trio of the most investigated social dilemmas [32–36], offers even more support for cooperative individuals in the sense that the interest of mutual cooperation exceeds the benefit of exploitation or cheating. Yet, cooperation in SH can also be compromised by the fact that mutual defection is individually more beneficial than being an exploited cooperator. This game, therefore, has two Nash equilibriums in which all players are either cooperators or defectors.

A research field that has been evolving in parallel with evolutionary game theory is network science, which provides a comprehensive framework for understanding the dynamical processes on networks [37]. Early blending of the two theories happened with the investigation of social dilemmas on a square lattice. In their pioneering work, Nowak and May [38] unveiled that considering spatial topology via the nearest neighbor interactions enabled cooperators to survive by forming clusters and thus minimizing exploitation by defectors. Afterwards, the role of a wide variety of spatial structures in evolutionary games was explored [26,39–73]. Remarkably, heterogeneous networks, such as small-world and scale-free networks [33,74–99], strongly support cooperation in the above-mentioned social dilemmas. Recently proposed multilayer architectures also enrich the impact of spatial topology on the evolution of cooperation [100–107]. Moreover, an even larger realm of evolutionary games (e.g. rock-paper-scissors [108–114], public goods [115–125], and ultimatum [126–131] games) is currently being investigated in conjunction with spatially structured populations. These achievements link to the phenomena (e.g. the emergence of phase transitions [132–135], percolation [136–140], pattern formation [109,141–143], and self-organizing behavior [144]) or the analytical methods (e.g. the mean-field method [42,145] and the pair approximation [25,146,147]) of statistical physics.

Aside from the theoretical studies of equilibriums in well-mixed and networked populations, an important generator of progress has been identifying scenarios that can offset the unfavorable outcome of social dilemmas and stimulate the evolution of cooperation. Well-know examples include tit-for-tat or win-stay-lose-shift strategies [148–151], voluntary participation [115,121,152–154], memory [45,65,155,156], age structure [157–159], social diversity and preference [160–165], heterogeneous action [85,166–171], partner selection [172–174], and punishment and reward [175–180]. Furthermore, the mobility of players [181–195], times scales in evolutionary dynamics [36,196], the role of the finite population size [197–200], and the impact of noise and uncertainty [201–205] have also been thoroughly investigated. Lately, the co-evolution schemes [35,80,81,158,206–219], which involve the joint adjustment of individual strategies and network topology (or the updating rules), emerged as another potential promoter of cooperation (refer to [220] for a comprehensive review).