

## 间接互惠与合作演化的若干问题研究进展

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**摘要** 2005 年 *Science* 杂志指出“合作行为如何进化”是 21 世纪最关键的 25 个科学问题之一。间接互惠如何促进合作演化的研究已吸引了包括经济学家、社会学家和演化生物学家等众多学者的关注。这是由于：人类社会道德的形成、社会化分工、语言的出现、人类大脑的进化等都和间接互惠密不可分；随着经济全球化和网络时代的到来，依赖声誉和信誉的陌生个体间的交易日益频繁，局部信息条件下个体的信任被利用的“道德风险”逐渐增大。本文所关注的间接互惠是以声誉为核心的“下游互惠”，具体而言，个体通过帮助他人建立自己在群体中的好声誉，从而期待未来获得他人的帮助。可见，声誉是“下游互惠”发挥作用的关键。声誉的建立引发了两方面的研究：1) 如何评价个体声誉的好与坏，焦点是何种声誉评估准则能够促进合作的演化；2) 个体的声誉如何在群体中快速、准确、广泛地传播，使得陌生个体间能够获得彼此的声誉信息，其中八卦这种声誉传播方式成为间接互惠的研究热点之一。基于声誉的间接互惠研究前景广阔，未来可能的研究方向主要有复杂网络上的间接互惠、声誉传播系统的鲁棒性、声誉共享系统的建立和间接互惠在 P2P 网络中的应用。

**关键词** 演化博弈论，间接互惠，声誉评估准则，八卦，P2P 网络

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## Development of Several Studies on Indirect Reciprocity and the Evolution of Cooperation

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**Abstract** ‘How does cooperation evolve’ has been considered as one of the most important scientific problems in the 21st century since 2005. The study about indirect reciprocity has attracted increasing attention from researchers such as economists, sociologists, and evolutionary biologists. There are mainly two reasons for this: Indirect reciprocity is closely related to the formation of human morality, socialized labor division, emergence of language, human brain evolution, and many other social developments; the deal among strangers, which mainly depends on reputation and credit, becomes more and more frequent with the economic globalization and the Internet era coming, thus the ‘moral risk’ of individual trust being exploited is increasing under local information conditions. In this paper, we focus on ‘downstream reciprocity’ which belongs to a form of indirect reciprocity and is based on reputation, specifically, individuals can obtain good reputation by helping others and then look forward to getting others’ help in future. Obviously, reputation is the key factor for ‘downstream reciprocity’ to work. The establishment of reputation has motivated two studies: How do we define good reputation and bad reputation? Such studies aim to answer which reputation evaluation criterion can promote the evolution of cooperation; how does individual reputation information spread among strangers quickly, accurately, and widely so that individuals can know each other’s reputation? Here, gossip, as one way of reputation dispersal, becomes one hot research topic. Indirect reciprocity based on reputation is a promising study, and the possible future research topics are indirect reciprocity in complex networks, robustness of reputation dispersal system, establishment of reputation sharing system, and application of indirect reciprocity in the P2P network.

**Key words** Evolutionary game theory, indirect reciprocity, reputation evaluation criterion, gossip, P2P network

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达尔文的进化论认为“物竞天择、适者生存”，说明竞争在进化中起核心的作用<sup>[1]</sup>。依据这一理论，在“弱肉强食”的生存斗争中，适应性强的个体胜出，适应性差的个体被淘汰。从而在激烈的生存斗争中，每个个体均会从自身利益出发，变得利己自私、

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唯利是图。然而,从细菌群落到蜂群蚁群,从狼群狮群围捕猎物到群居的大猩猩,再到复杂而有序的人类社会,合作行为无处不在<sup>[1-4]</sup>。显然,帮助对手会降低自身的适应度,从而削弱自身的竞争优势,合作的存在看似并不合理。面对广泛存在的合作行为,达尔文本人也深感困惑,在其著作中相应的解释只是一笔带过<sup>[5]</sup>。

合作行为广泛存在,同时在很多领域中又十分匮乏。研究促进合作涌现的机制有以下三点益处:1) 有助于解释众多产生原因未知的现象,例如,细胞的癌变<sup>[6]</sup>、语言的产生<sup>[7]</sup>和集群行为<sup>[8]</sup>;2) 有助于解决我们面临的全球性问题,例如,“公地悲剧”<sup>[9]</sup>、环境恶化<sup>[10]</sup>和资源枯竭<sup>[11]</sup>;3) 有助于破解互联网时代在虚拟世界中我们遇到的新问题,例如,网络欺诈<sup>[12]</sup>等违法犯罪行为。由此可见,研究促进合作演化的机制对人类发展有着重大的现实意义和时代紧迫感。

如何研究合作行为的演化?这是一个热点问题,2005年 *Science* 杂志就指出“合作行为如何进化”是21世纪最关键的25个科学问题之一<sup>[13]</sup>。演化博弈论(Evolutionary game theory)为研究合作的演化提供一个有力的数学框架。Smith等首次将 von Neumann 开创的博弈论观点(大脑在利益冲突时做出理性决定)扩展为根据自然选择而得出决定<sup>[14]</sup>,这标志着演化博弈论的开创。近年来,国内外越来越多的学者利用此理论研究促进合作涌现的机制<sup>[15-37]</sup>。其中最著名的是哈佛大学的 Nowak 教授,他对“综合进化论”(这一理论将突变、选择和进化的基本概念整合到一个数学框架中)的思想进行了扩展,将囚徒困境放到演化的群体中进行研究。Nowak 首次总结了促进合作涌现的5大机制<sup>[38]</sup>:亲缘选择(Kin selection)、直接互惠(Direct selection)、间接互惠(Indirect selection)、网络互惠(Network reciprocity)和群组选择(Group selection)。亲缘选择意味着,与谁的血缘关系越近,就越倾向与之合作;直接互惠意味着,今天我帮助你,明天你会帮助我;间接互惠意味着,今天我帮助你,明天会有他人帮助我;网络互惠意味着,个体仅仅与邻居进行博弈,合作者团簇最终胜出背叛者团簇;群组选择意味着,竞争既发生在个体之间,也发生在群组之间。除了这5大机制,最近的综述还归纳出另外5种促进合作演化的机制<sup>[39]</sup>:绿胡子选择(Green beard selection)、强互惠性(Strong reciprocity)、有成本的示好(Costly signaling)、集合选择(Set selection)和选择性参与(Optional participation)。绿胡子选择意味着,相似性越高的个体之间越容易发生合作;强互惠性意味着,个体愿意牺牲自身利益惩罚背叛行为;有成本的示好意味着,个体愿意承担成本吸引其他个体的关注;集合选择意味着,个体仅

仅与相同集合的个体进行交互;选择性参与意味着,个体有权利拒绝与特定个体进行博弈。

## 1 关于间接互惠的概述

### 1.1 研究间接互惠的意义

间接互惠是促进合作涌现的重要机制之一。相对于直接互惠,间接互惠不再要求相同的个体间重复相遇,同时利他个体能够从第三方获得收益,这可以很好地解释陌生个体间的合作行为<sup>[40-46]</sup>。大量的非亲缘、非直接的间接互惠行为在人类社会和动物世界中广泛存在。特别地,人类社会中语言的出现<sup>[7,47]</sup>、道德规范的形成<sup>[38]</sup>、社会的分工<sup>[39]</sup>以及人类大脑的发育<sup>[47]</sup>都与间接互惠密不可分。在经济全球化和进入网络时代的背景下,电子商务大大增加了陌生个体间交易的频率,陌生个体间的一次性交互逐步取代传统的相识个体间的重复交互<sup>[37,48-52]</sup>。此时的交易主要依赖于声望和信任,从而局部信息条件下个体信任被利用的“道德风险”不断增大<sup>[45]</sup>。因此,针对间接互惠如何促进合作涌现的研究吸引了演化生物学家、经济学家和社会科学家等学者的极大兴趣。

### 1.2 间接互惠的分类和研究方法

间接互惠包括“上游互惠”(Upstream reciprocity)、“下游互惠”(Downstream reciprocity)和“广义互惠”(Generalized reciprocity)三种形式<sup>[45,53-57]</sup>。如图1所示,“上游互惠”指的是, *B* 得到 *A* 的帮助后受到激励,继而帮助 *C*;“下游互惠”指的是, *C* 观察到 *A* 曾经帮助了 *B*, 因此帮助 *A*, 这是一种建立在声望基础上的间接互惠;“广义互惠”指的是, *D* 观察到 *A* 帮助 *B*, 于是 *D* 帮助 *C*。“上游互惠”并不能单独促进合作的涌现,只有与直接互惠或者网络互惠相结合才能促进合作的涌现<sup>[56-57]</sup>。“下游互惠”和“广义互惠”均可单独促进合作的涌现,不过前者是研究间接互惠的主流方向,而关于后者的相关研究还甚少。目前,针对间接互惠的研究方法主要有理论分析、蒙特卡罗仿真(Monte Carlo simulation)和实验验证(包括实验室实验、实地实验和在线实验)。

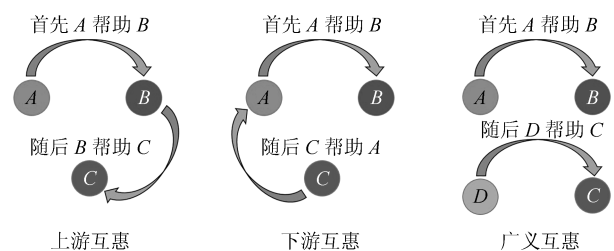


图1 间接互惠的三种形式

Fig. 1 Three kinds of indirect reciprocity

接下来的文章从以下三方面归纳总结关于“下游互惠”的研究: 经典的博弈模型、声望评估准则与行为准则和基于八卦的声望信息传播.

## 2 经典的博弈模型

在演化博弈论框架下研究间接互惠, 需要将个体之间发生的交互行为抽象为博弈模型. 目前, 常被用来研究间接互惠的博弈模型包括捐助博弈 (Donation game)<sup>[43-44, 58-72]</sup>、信任博弈 (Trust game)<sup>[73-75]</sup>、独裁者博弈 (Dictator game)<sup>[76-82]</sup> 和公共品博弈 (Public goods game)<sup>[83-88]</sup>.

1) 捐助博弈, 如图 2(a) 所示. 一方为捐助者 A, 另一方为接受者 B: 如果 A 给予 B 捐助, 则 A 付出成本  $c$  且 B 得到收益  $b$  ( $b > c$ ); 如果 A 不给予 B 捐助, 则双方均未获得收益且没有损失.

2) 信任博弈, 如图 2(b) 所示. 一方为投资者 A, 另一方为响应者 B: A 将部分资金  $c$  (总额为  $R$ ,  $0 \leq c \leq R$ ) 给予 B, 从而 B 获得收益  $r \times c$  ( $r > 1$ ); 随后, B 决定将其获得的部分收益  $a$  ( $0 \leq a \leq r \times c$ ) 返还给 A. 最后, A 获得收益  $R - c + a$ , B 获得收益  $r \times c - a$ .

3) 独裁者博弈, 如图 2(c) 所示. 一方为独裁者 A, 另一方为接受者 B: A 将部分资金  $c$  (总额为  $R$ ,  $0 \leq c \leq R$ ) 分给 B. 无论 A 给了 B 多少, B 只能接受, 没有拒绝的权利, 从而 B 得到收益  $c$ , 而 A 获得其余收益  $R - c$ .

4) 公共品博弈, 如图 2(d) 所示. 博弈的成员同时向公共资源池进行投资, 投资总额乘以增益系数  $r$  ( $1 < r < \text{博弈人数}$ ) 后平均分配给所有博弈成员, 每个成员的收益为所获得的回报减去自身的投资额.

## 3 声望评估准则与行为准则

### 3.1 常见的声望评估准则及其相关研究

声望是间接互惠发挥作用的核心, 然而声望的建立首先面临的问题是如何评价个体声望的好与坏, 即如何构建声望评估准则. 目前, 被广泛研究的评估准则包括“一阶评估”、“二阶评估”和“三阶评估”<sup>[43-44, 59-71, 85-101]</sup>, 如表 1 所示.

“一阶评估”在评价个体声望时仅考虑捐助者行为 (是否给予帮助). 经典的“一阶评估”是“形象分数”: 当捐助者帮助接受者时, 捐助者的形象分数增加一分; 当捐助者拒绝帮助接受者时, 捐助者的形象分数减少一分. 1998 年, Nowak 等首次利用“形象分数”构建了刻画间接互惠的数学模型, 如图 3 所示. 他们认识到间接互惠在促进合作演化方面的巨大作用<sup>[43]</sup>: 当玩家的声望由多值“形象分数”确定时, 蒙特卡罗仿真表明合作行为在群体中以较高频率涌现. 之后, 这个结论被行为实验证实<sup>[63]</sup>. 与此同时, Nowak 等理论分析了二值“形象分数”<sup>[43-44]</sup>. 稍后的理论研究表明很多因素导致合作行为在采取二值“形象分数”的群体中消失<sup>[64-66, 96]</sup>. 这种现象是由于此准则固有的困境: 拒

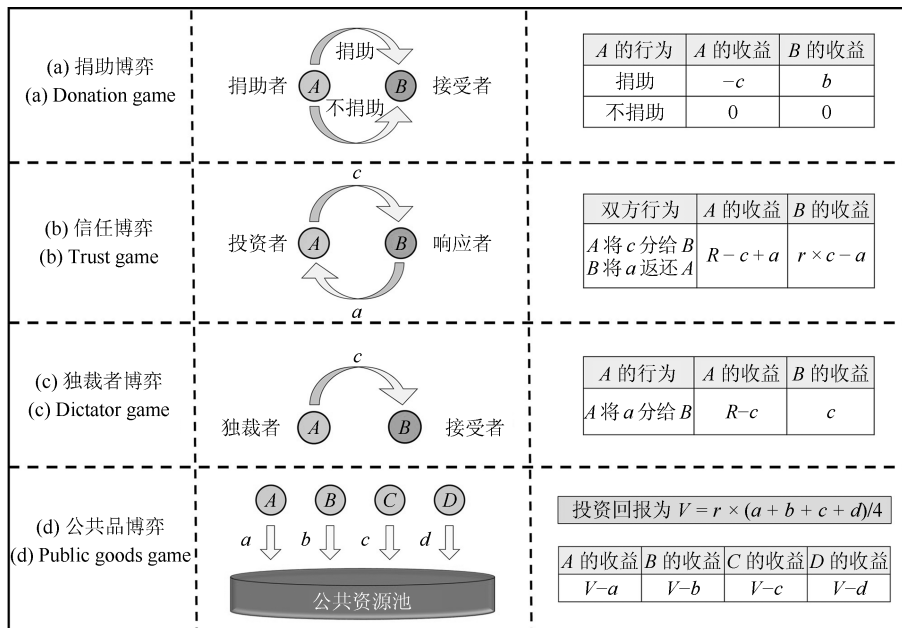


图 2 博弈模型及收益矩阵

Fig. 2 Games and their payoff matrices

表 1 声望评估准则  
Table 1 Reputation evaluation criterion

声望评估准则	定义	数量(种)	典型的例子
“一阶评估”	考虑捐助者行为	$2^2 = 4$	“形象分数”
“二阶评估”	同时考虑捐助者行为和接受者声望	$(2^2)^2 = 16$	“温和准则”、“严苛准则”
“三阶评估”	同时考虑捐助者行为和声望及接受者声望	$((2^2)^2)^2 = 256$	

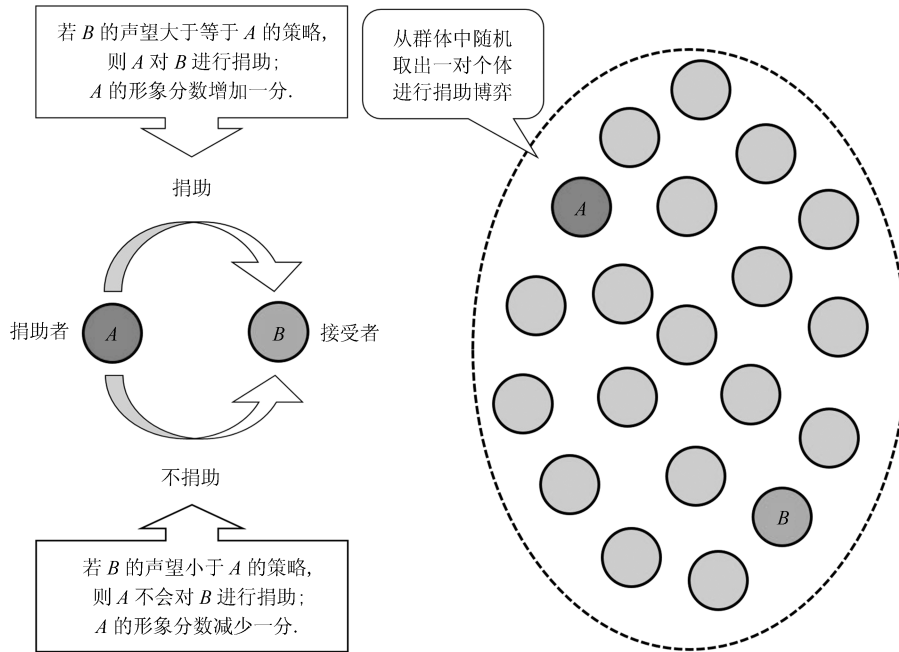


图 3 经典的间接互惠模型  
Fig. 3 Representative model about indirect reciprocity

绝帮助形象差的玩家, 虽然惩罚了他们, 但同时也令自身形象变差<sup>[67, 97-98]</sup>. 显然, 仅考虑捐助者行为的二值“形象分数”会造成不公正的声望评价. 最近, 理论工作揭示了多人博弈<sup>[68, 99]</sup>、三值“形象分数”(好、中性、坏)<sup>[69]</sup>或特定“一阶评估”(观察者根据捐赠者在以往多次行动中的表现确定其名声)<sup>[70, 100]</sup>可以克服这个困境, 促进合作行为的涌现.

“二阶评估”也能弥补二值“形象分数”固有的缺陷: 在评价个体声望时, 不仅考虑捐助者的行为(是否给予捐助), 还要考虑接受者的声望(好、坏). 典型的“二阶评估”包括“温和准则”和“严苛准则”, 如表 2 所示. 二者唯一的不同点在于, 前者认为拒绝帮助坏人会为捐助者带来好的声望, 而后者认为此行为会为捐助者带来坏的声望. 学者在“二阶评估”中引入惩罚策略(不仅给被惩罚者带来损失, 而且惩罚者也要承担少量损失), 发现对背叛者置之不理比惩罚背叛者更有利于合作的涌现<sup>[71]</sup>.

在“二阶评估”基础上, 额外考虑捐赠者的声望, 这种评估准则被称为“三阶评估”<sup>[91-92]</sup>. 例如, 名声

差的人通过帮助好名声之人“收买”好名声. 学者考察所有可能的“三阶评估”, 假设群体最多拥有两种策略, 发现了 8 种评估准则可以令合作行为具有演化稳定性<sup>[93]</sup>. 这 8 种准则如表 3 所示, 具有一些共性: 与好人合作(捐助)其名声为好, 而背叛好人(不捐助)则为坏, 同时好人背叛坏人不会损坏名声. 值得一提的是, 它们均不属于“一阶评估”, 而其中两种属于“二阶评估”, 分别为“温和准则”和“严苛准则”. 学者在群体共存多种策略的假设下对这两种准则进行研究<sup>[94]</sup>. 上述研究均假设群体共享相同评估准则, 而比较的是不同行为准则的竞争. 鉴于认知差异会导致个体对于如何评估声望的理解不同, 学者也考虑了评估准则因人而异的情形<sup>[95, 101]</sup>.

表 2 典型的“二阶评估”  
Table 2 Representative “second-order evaluation”

	捐助者行为/接受者声望			
	捐助/好	捐助/坏	不捐助/好	不捐助/坏
“温和准则”	好	坏	坏	好
“严苛准则”	好	坏	坏	坏

表3 8种促进合作演化的声望评估准则

Table 3 Eight reputation evaluation criteria which favor the evolution of cooperation

	捐助者声望/接受者声望			
	好/好	好/坏	坏/好	坏/坏
捐助者捐助	好	未知	好	未知
捐助者不捐助	坏	好	坏	未知

### 3.2 常见的行为准则及其相关研究

关于间接互惠的早期研究假设个体仅帮助声望好的个体, 或者个体仅帮助形象分数高于某一阈值的个体<sup>[43-44, 64-68, 96-99]</sup>. 这些最简单的行为准则(行为准则是能否捐助的依据)要求个体仅根据对手的声望决定是否给予捐助. 稍后, 略微复杂的行为准则, 例如个体决定是否捐助时需要同时考虑自身和对手的声望, 受到关注<sup>[69-71, 89-90, 94-95, 100-101]</sup>. 上述研究主要关注哪种声望评估准则更有利于合作的演化. 最近, 学者们对较为复杂的行为准则如何影响合作涌现进行了探索<sup>[72, 87, 102]</sup>. 一些学者考察个体在决定是否捐助时对接受者的声望有一定的容忍范围(当接受者的声望在这个范围内则进行捐助), 通过仿真发现, 一定的声望容忍度有助于合作的涌现<sup>[87, 102]</sup>. 还有一些研究提出了一种基于向量的行为准则(捐助者将自身声望与接受者声望进行比较, 当至少满足三种条件中的两种时则进行捐助, 这三种条件包括声望近似、声望高于自己和声望低于自己), 通过仿真发现, “捐赠者会为与自己声望近似或者高于自己声望的接受者进行捐助”这种策略在较小的成本收益比下能够成为占优策略, 同时促进合作的演化<sup>[72]</sup>.

## 4 基于八卦的声望信息传播

直接观察和八卦(个体之间通过交流, 共享彼此的声望信息)是声望信息传播的两种方式<sup>[45, 103-104]</sup>, 如图4所示. 当群体规模较小时, 个体可以通过直接交互或者直接观察获得对方一手的声望信息. 然而随着群体规模的扩大, 直接观察到所有个体行为变得不大可能, 必须通过与第三方交流来分享和传播二手的声望信息<sup>[104-105]</sup>. 可见在较大的群体中, 八卦常常是声望信息传播的主要方式.

### 4.1 关于八卦的解析研究和仿真研究

一些学者通过解析和仿真的方式对于八卦如何影响合作的涌现进行研究. 此时的模型通常假设观察者以一定的概率 $q$ 了解玩家的声望(通过概率的形式简单模拟了声望的局部传播). 针对“形象分数”, Nowak 等给出了简单的数学关系: 当 $q$ 高于成

本收益比 $c/b$ 时, 合作可以涌现<sup>[43-44]</sup>. 在“二阶评估”下, 类似的条件在两个调查中获得<sup>[106-107]</sup>, 这两个调查最大区别在于, 当观察者未看到交互过程时, 捐赠者的名声保持不变或者设定为未知. 若将交互划分为公开和私下两种(观察者一直看到公开交互而以概率 $q$ 看到私下交互), 类似的条件仍然满足<sup>[108]</sup>. 上述研究均假设 $q$ 为常数, 针对 $q$ 随时间推移而增大的情形(观察者越来越可能了解其余个体的声望), 也有学者进行了理论分析<sup>[109]</sup>.

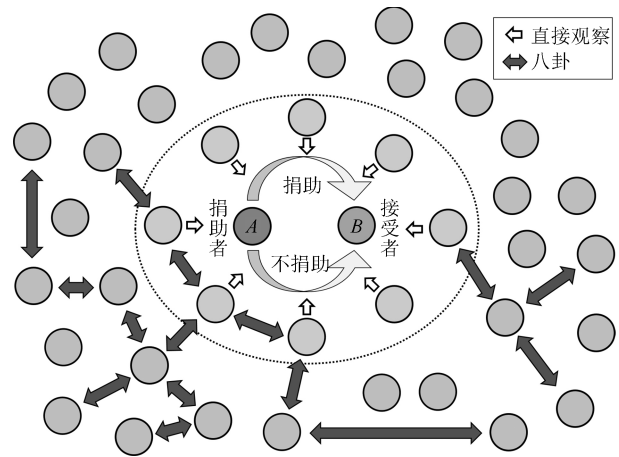


图4 声望信息传播的两种方式

Fig. 4 Two ways of reputation dispersal

八卦在传播声望信息过程中可能受到噪声的干扰和谎言的入侵, 导致不公正的声望评价. 噪声一方面来源于不完整的观察给出不公正的声望, 另一方面来源于在声望传播过程中无意地误导他人; 而谎言则是故意传播虚假的声望信息而对他人进行误导. 一项研究在声望传播中引入欺骗策略(传播虚假声望信息), 发现这种策略在没有其他机制的情形下导致群体合作演化的失败<sup>[110]</sup>. 另两项研究表明: 当群体中没有虚假信息传播时, 八卦数量的增加有助于促进合作的演化; 而存在噪声干扰和谎言所导致的不公正评价时, 中等数量的八卦最有利于促进合作的演化<sup>[111-112]</sup>. 这两项研究是基于累加的八卦信息进行决策, 而最近的研究发现基于最新的八卦信息作出决策更能促进合作的演化<sup>[113]</sup>. 上述关于八卦的模型均没有加入声望传播所需的成本(例如时间的消耗). 当考虑这种成本时, 结果表明间接互惠不再促进合作的演化<sup>[114]</sup>.

### 4.2 关于八卦的实验研究

另一部分学者通过行为实验的方法对八卦进行研究, 主要发现如下. 即使个体能够通过直接交互或者直接观察获取他人的一手声望信息, 实验发现个体也会倾向于基于八卦信息做出判断<sup>[115-117]</sup>. 八卦所传播的声望信息有助于个体甄别合作对象从而

避免被欺骗,并有效提高群体的合作水平<sup>[88,103,118]</sup>.当八卦将个体的声望传播到未来会与其发生交互的个体时,八卦可以促使个体更加关注自身声望并促进慷慨行为的产生<sup>[82,119-121]</sup>.八卦按照传播主题可以被划分为传播好名声和传播坏名声两种,传播好名声的八卦更能够促进合作的涌现<sup>[115]</sup>.社会网络结构允许个体可以在不同时间从多个来源获取彼此的声望信息,这有助于减少信息传播中可能出现的误差<sup>[122-123]</sup>。“道德威慑”通过拆穿谎言后的惩罚机制维护八卦的可信性,从而促进合作的涌现<sup>[124]</sup>.当声望被视为可以买卖的物品时,由于人类具有认知和辨别能力以及欺骗者为了购买声望会付出一定的收益而降低适应度,因此,虚假的声望对合作水平的影响并不明显<sup>[125-126]</sup>.

## 5 总结

合作行为在很多领域中十分匮乏,因此,研究促进合作演化的机制对人类发展有着重大的现实意义和时代紧迫感.2005年*Science*杂志就指出“合作行为如何进化”是21世纪最关键的25个科学问题之一.在演化博弈论的框架下,研究人员已提出一些促进合作演化的机制,其中间接互惠是促进合作演化的最重要机制之一,并已吸引了演化生物学家、经济学家和社会学家等学者的极大兴趣.它包括“上游互惠”、“下游互惠”和“广义互惠”三种方式:“上游互惠”并不能单独促进合作的涌现,只有与直接互惠或者网络互惠相结合才能促进合作的涌现;“下游互惠”和“广义互惠”均可单独促进合作的涌现,不过前者是研究间接互惠的主流方向,而关于后者的相关研究还甚少.本文关注的是以声望为核心的“下游互惠”,具体而言,个体通过帮助他人建立自己在群体中的好声望,从而期待未来获得他人的帮助.

本文从三个方面对关于“下游互惠”的研究进行总结.首先,回顾了演化博弈论框架下研究间接互惠的博弈模型:捐助博弈、信任博弈、独裁者博弈和公共品博弈.其次,回顾了被广泛研究的三类声望评估准则:“一阶评估”、“二阶评估”和“三阶评估”.相关研究假设采用比较简单的行为准则,而聚焦于哪种声望评估准则能够促进合作的演化.同时回顾了关于较为复杂的行为准则如何促进合作演化的一些研究.再次,回顾了利用解析方法和仿真方法对八卦如何促进合作演化进行的研究.解析研究一般假设个体以一定的概率获得彼此的声望信息,这个概率通常为常值,个别研究假设其可随时间变化.仿真研究假设更加复杂的模型,例如八卦不再如实传递信息,而是融入了噪声和谎言.同时也回顾了利用行为实验对八卦进行的研究,内容十分宽泛.

## 6 未来展望

基于声望的间接互惠具有广阔的研究前景,其未来可能的研究方向有复杂网络上的间接互惠、声望传播系统的鲁棒性、声望共享系统的建立和间接互惠在P2P网络中的应用.

### 6.1 复杂网络上的间接互惠

目前,大部分理论研究均是在混合均匀群体中获得的<sup>[127-129]</sup>.然而,绝大多数现实社会中的群体并非混合均匀的,个体之间的交互和声望传播都是利用复杂网络实现的.在演化博弈论框架下,未涉及间接互惠的静态复杂网络和动态复杂网络已被广泛研究<sup>[130-142]</sup>,而只有较少研究关注复杂网络上的间接互惠<sup>[143-147]</sup>.文献[143]发现在社会网络中,根据声望选择交互伙伴这种行为有助于促进合作的演化.文献[144-145]假设小世界网络和无标度网络等复杂网络可以重构(断边重连),发现声望共享“联盟”的存在有助于促进群体合作.文献[146-147]假设直接互惠和间接互惠同时存在于网络上,发现间接互惠有助于刻画现实社会的无标度网络的形成.

虽然科研人员已经对于复杂网络上的间接互惠进行了一些初步的探索,但是还有很多问题需要进一步研究.例如,上述研究均认为声望是通过观察获得的公共信息(即声望全局可知),然而在现实社会中,声望多数情况下是通过八卦进行传播的,由此可见,静态或动态复杂网络上八卦这种声望传播方式如何影响合作的演化是一个值得深入研究的方向.

### 6.2 声望传播系统的鲁棒性

八卦是大规模群体中声望传播的主要方式,它在传播声望信息过程中可能受到噪声的干扰和谎言的入侵,从而导致不公正的声望评价.噪声一方面来源于不完整的观察给出不公正的声望,另一方面来源于在声望传播过程中无意地误导他人;而谎言则是故意传播虚假的声望信息而对他人进行误导.一项研究在声望传播中引入欺骗策略(传播虚假声望信息),发现这种策略在没有其他机制的情形下导致群体合作演化的失败<sup>[110]</sup>.另两项研究表明:当群体中没有虚假信息传播时,八卦数量的增加有助于促进合作的演化;而存在噪声干扰和谎言所导致的不公正评价时,中等数量的八卦最有利于促进合作的演化<sup>[111-112]</sup>.这两项研究是基于累加的八卦信息进行决策,而最近的研究发现基于最新的八卦信息作出决策更能促进合作的演化<sup>[113]</sup>.

科研人员已经对于加入噪声和谎言的八卦进行了初步的探索,但已研究的模型还有很多可以改进的地方,相应的结果并不全面.在未来的研究中,我们需要建立更加合适的模型,结合现实生活提出能

够抵抗噪声干扰和谎言入侵的八卦, 令声望传播系统具有鲁棒性, 进而发现能够促进合作演化且强抗干扰的机制.

### 6.3 声望共享系统的建立

以往关于间接互惠的绝大多数研究均没有考虑个体间声望共享所需的成本. 但在实际中, 人们在评价和分享他人声望的过程中需要耗费时间和精力. 例如, 在网络购物平台中, 人们需要花费时间和精力去评价所购买的产品或者服务. 近期的一项研究表明, 当考虑声望共享所需成本时, 间接互惠无法促进合作的涌现<sup>[114]</sup>.

随着经济全球化和网络时代的到来, 陌生个体间的交易日益频繁. 为什么人们会不计成本、不厌其烦地和陌生人分享他人的真实声望呢? 目前的研究还没有给出一个满意的答复. 因此, 我们需要针对考虑声望共享所需成本的模型, 提出能够建立声望共享系统且促进合作涌现的有效机制.

### 6.4 间接互惠在 P2P 网络中的应用

近年来, P2P (Peer to peer) 网络应用广泛, 因此对其研究发展快速. 在 P2P 网络中, 参与者共享自身所拥有的一部分硬件资源 (存储能力、网络连接能力和打印机等), 这些共享资源通过网络提供服务和内容, 能被其他对等节点 (Peer) 直接访问而无需经过中间实体. 在此网络中的参与者既是资源、服务和内容的提供者 (Server), 又是资源、服务和内容的获取者 (Client). 合作是确保所有参与者获得所需服务的关键, 出于恶意和自私的非合作行为往往导致参与者获得较少服务甚至一无所获. 消除非合作行为的有效机制包括信任机制和激励机制. 信任机制指的是根据参与者的交互历史计算他的可信程度<sup>[148-153]</sup>, 例如, eBay 声望系统<sup>[151]</sup>、Beta 声望系统<sup>[152]</sup>、Eigentrust 声望系统<sup>[148]</sup> 和 Powertrust 声望系统<sup>[153]</sup>. 激励机制包括金钱激励和非金钱激励<sup>[154-157]</sup>.

鉴于 P2P 网络中个人利益和集体利益相冲突, 经典博弈理论已被广泛用来研究此类网络<sup>[154, 157-160]</sup>. 不过经典博弈理论假设参与者完全理性且拥有全局信息. 这些假设并不现实, 同时经典博弈理论不能描述参与者策略的动态演化过程及策略在整个系统中的传播过程. 近来, 可以克服上述缺点的演化博弈论被用来研究 P2P 网络<sup>[155, 161-165]</sup>. 文献 [161] 假设 P2P 网络是混合均匀且有无限节点, 并利用复制动力学研究三种激励机制的稳定性. 文献 [162] 同样利用复制动力学发现一种延拓的模仿动力学可以改进整个网络路径选择的效率, 从而避免路径上的过载或长延迟. 文献 [163] 假设 P2P 网络具有有限节点, 分别在混合均匀网络 and 同型结

构网络上研究一种激励机制 (Reciprocation-based incentive mechanism). 文献 [164] 将关于同类激励机制的研究推广到异型结构的 P2P 网络. 文献 [155, 165] 假设 P2P 网络具有有限节点, 利用计算机仿真调查两种信任机制. 上述研究是针对一般性的 P2P 网络, 还有一些研究利用演化博弈论分析特殊的 P2P 网络, 例如基于 P2P 的无线传感网络<sup>[166-169]</sup> 和基于 P2P 的车辆自组织网络<sup>[170]</sup>.

科研人员已利用演化博弈论对 P2P 网络进行了一些探索, 本文主体部分总结了在演化博弈论框架下对于间接互惠的研究成果, 一个自然的想法是将这些研究思路应用到关于 P2P 网络的研究中. 大体思路有以下 4 点:

1) 声望评估准则可视作信任机制. 将“一阶评估”、“二阶评估”或“三阶评估”作为信任机制集合, 寻找能够令 P2P 网络中合作行为稳定的信任机制.

2) 行为准则可视为激励机制. 将已研究过的行为准则构成激励机制集合, 寻找能够令 P2P 网络高效、有序运行的激励机制.

3) 在 P2P 网络的声望传播过程中融入八卦, 研究八卦对于网络稳定性的影响.

4) 可以将深度学习<sup>[171]</sup> 与间接互惠机制结合, 来研究网络控制问题<sup>[172-174]</sup>.

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