Status hierarchy and group cooperation: A generalized model of Mark (2018)

Hsuan-Wei Lee¹, Yen-Ping Chang¹, and Yen-Sheng Chiang*¹

¹Institute of Sociology, Academia Sinica, Taiwan

Abstract

Can status hierarchy facilitate the emergence of group cooperation? In an evolutionary model, Mark (2018) provided a positive answer to the theoretical inquiry. Despite the contribution, we critiqued that there are not only mathematical errors in Mark’s model, but also limitations in applying it to other hierarchical structures. We present a more generalized model by introducing a novel hierarchy measure to interpolate the cooperativeness of group members in any hierarchy structure of interest. We derive the conditions under which cooperation can emerge and verify our analytical predictions by agent-based computer simulation. In general, our evolutionary model provides stronger evidence than Mark’s original model with respect to how status behavior can facilitate the emergence of social cooperation.

1 INTRODUCTION

Group cooperation and status inequality have each received longstanding attention in sociology. While they are usually discussed in independent lines of research (Kollock 1998; Correll and Ridgeway 2006; Fehr and Gintis 2007; Sauder et al. 2012), scholars have recently started investigating both topics in an integrated view (Simpson and Willer 2015). For instance, some contend that status hierarchy benefits the emergence of group cooperation (Hechter 1987; Whitmeyer 2007; Willer 2009; Mark 2018), thus linking two issues into one. Take the leader-follower status for example. Ample evidence from experimental work has shown that people behave more cooperatively in groups with leaders than without (Luo et al. 2007; Olken 2010; Hamman et al. 2011; Grossman and Baldassarri 2012; Bolsen et al. 2014), and it is argued that leaders motivate cooperation among followers by imposing influences and, specifically, sanctions on group members. Yet, compared to the fruitful experimental demonstrations of the phenomenon, the theoretical explanation for it–

*Corresponding author. Email: chiangys@gate.sinica.edu.tw
that is, the mechanism through which status hierarchy induces group cooperation—remains relatively untouched.

Tackling the gap in the literature, we believe evolutionary game theory (EVG) may contribute to the advance of theory here. EVG is a tool that not only biologists (Nowak 2006) but also social scientists (Bendor and Swistak 2001; Bergstrom 2002) rely on in formalizing their explanations of the emergence of human behavior and social institution. One of the aims of EVG is to identify the conditions under which the behavior of interest—represented by a strategy in a game—comes into being and remains stable when competing against alternative behaviors in certain social contexts. The emergence of the target behavior is measured by its evolutionary fitness, in the sense that the more benefits accrued to the behavior, the more likely it would be adopted by actors or by more actors. As far as cooperation is concerned, scientists have indeed used the EVG framework to pin down an array of mechanisms by which the free-riding problem can be mitigated in social cooperation dilemmas (Nowak 2006). We hence wonder whether EVG can shed new light on how status hierarchy facilitates group cooperation as well.

Guiding our investigation, the paper of (Mark 2018) provides a pioneering and refreshing answer to the question. In his model, conditional cooperators—called status cooperators—engage in the pursuit of leadership. Status cooperators cooperate if one and only one of them takes the leader position; they defect otherwise if no leader is chosen. In contrast, defectors never pursue the leader role, nor do they cooperate in the group. Using EVG, Mark then demonstrates that, even though defectors seem to be the advantaged in fitness by free-riding on the efforts of cooperators, it is possible for status cooperators to outperform defectors as long as one of the cooperators becomes the leader to mobilize their fellow cooperators to cooperate. Finally, (Mark 2018) reports that cooperation is more likely to emerge (against defection) when group size is smaller than larger, and when group formation is more assortative than more random.

Despite its merits and insights, we, however, notice that Mark’s EVG model has some fallacies and shortcomings worth elaborating on. Most importantly, the assumption that cooperation would only be activated when exactly one (conditional) cooperator takes the leader position is overly strict. As late sociologist Roger Gould argued, “It is evident that most social hierarchies lie between the two extremes of complete equality and winner-take-all inequality.” (Gould 2002 p. 1149), Mark’s oversimplified model fails to cover other hierarchical structures that could well exist in groups. On the other hand, his assumption is also seemingly responsible for leading into mathematical errors in his paper, which we detail these below. Here, we contend that the restricted assumption, coupled with the mathematical errors, have made Mark’s model underestimate the likelihood that cooperation can emerge in groups with status hierarchy. In this paper, we present this finding in a modified EVG model with Mark’s errors being corrected and assumptions being relaxed.
In addition, our model offers two advantages over existing work, one theoretical and the other methodological. First, we introduce into our model a continuous measure of status hierarchy, in order to capture more hierarchy structures that Mark excluded. The measure allows us to extrapolate the current work to the extent that group members would cooperate at any given level of “hierarchicalness” of interest. In other words, we present a more generalized framework of which Mark’s original model is a special case. Second, unlike Mark’s (2018) sole reliance on analytical solutions, we derived and verified our EVG model not only analytically by mathematics but also numerically by computer simulations; the simulation code is in an open repository for readers’ access.

2 SOCIAL HIERARCHY AND COOPERATION: AN EVOLUTIONARY ACCOUNT

2.1 Status hierarchy

Status inequality is not only ubiquitous in human societies, but also prevalent in the societies of many species of social animals (Chase, 1985; Sapolsky, 2005; Sauder et al., 2012). Biologists argue that social hierarchy, particularly the dominance type, is a result of constant competitions for valuable resources such as food and mating opportunities (Hobson, 2019). For humans, social hierarchy and status inequality are argued to be a cause of social and health problems (Hemingway et al., 1997; Burns et al., 2014). Given the negative consequences of inequality, it is thus puzzling why social hierarchy remains prevalent in human societies.

At least two reasons have been proposed to address this question. First, scholars argue that, even though humans are fairly fairness-minded, perfect equality is never their ultimate aim and people do desire some if not only hierarchy (Starmans et al., 2017). Supporting this idea, evidence suggests that people would accept a certain degree of inequality in exchange for other types of personal benefits (Kuziemko et al., 2014). Research has also shown that once status a hierarchy is formed, people not only tend to live with it but also, sometimes, strive to protect the status quo (Xie et al., 2017). Given that status competition is a zero-sum game, it is then sensible to believe that people may prefer the status quo to take the risk of being demoted on the social ladder. The inertia of status mobility hence explains in part why hierarchy persists.

Secondly, scholars argue that social hierarchy can in fact be beneficial to social coordination and cooperation. For instance, evolutionary psychologists attribute the emergence of leadership and, therefore, the leader-follower disparity among animals and humans to its potential function of exerting social influences in but not limited to risky situations and of coordinating collective efforts in critical group challenges such as hunting for food and
fighting with rivals (Van Vugt, 2006). In support of the argument, experimental studies have shown that people tend to behave more cooperatively with leaders than not (Luo et al., 2007; Olken, 2010; Hamman et al., 2011; Grossman and Baldassarri, 2012; Bolsen et al., 2014). At the same time, it is found that cooperative actors are more likely to receive status approval and be elected as leaders (Willer, 2009). Because of these collective functions, social hierarchies may persist in human societies.

2.2 Mark’s (2018) model: its contribution and problems

In his model, Mark (2018) examines one specific hierarchical structure in how likely cooperation would emerge over an evolutionary game given the structure. The model features two types of actors: status cooperators (SC) and defectors (D). SCs pursue the leader position, whereas the Ds do not. The determination of leadership is made by a process of intent signaling: Every SC signals whether she is interested in being the leader with the probability $\frac{1}{n}$, where $n$ is the group size, and the hierarchy is settled when exactly one SC shows the interest and, therefore, becomes the leader. The process repeats if more SCs express the interest, until a leader is chosen or none signals the intent to lead.

Despite its originality, Mark’s model is however inflexible and, indeed, erroneous. On the one hand, Mark made a mistake when calculating the probability for the single-leader structure to emerge from the leadership signaling process. On the other hand, this single-leader hierarchy is restricted in terms of representing the various hierarchical structures we witness in the real world.

Here, let us start with the first, calculation issue. In Mark’s original model, there are four events happening in one iteration of the game: (1) the determination of the group; (2) preplay communication for leader selection; (3) cooperators’ decisions of whether to contribute to the group; (4) the determination of next generation of status cooperators and defectors based on the payoffs of the current generation. Specifically, Mark states that, in the phase of preplay signaling and formation of a status hierarchy, in each round of signaling, a status cooperator signals (high) intend to lead the group with probability $\frac{1}{n}$ and low/no intend with probability $\frac{n-1}{n}$, while a defector always signals low. The signaling repeats for rounds until a clear status hierarchy is reached, i.e., when there is no player at the top, leader level, or when there is exactly one player at the level. Once the status hierarchy is obvious (i.e., with 0 or 1 player at the top level), the cooperators continue to decide whether to contribute to the group. In Mark’s own words, “Each of the status cooperators in a group signals one or more times until either a status hierarchy is apparent (i.e., exactly one member of the group signaling high and all others signaling low) or a collective lack of confidence and leadership is indicated (i.e., each member of the group signaling low on the first round of signaling).” Following this setting, it is then reasonable to assume that when there are more than 1 player at the top level, the group continues on
preplay signaling, and the signaling process concludes when there is 0 or 1 player at the top level.

However, when we investigated Mark's computations--for example, equations (4a) and (4b), which appear fairly early in his paper--it seemed that he was working on a different setting of the game. Specifically, there is a term in equation (4a), \(1 - \left(\frac{n-1}{n}\right)^{k+1}\), that is supposed to represent the probability that the status hierarchy becomes apparent in the process and makes the status cooperators willing to contribute to the group later, i.e., there is "exactly" 1 player emerging from the top level when the selection concludes. Nevertheless, what is shown in the equation--the above term--is the probability that there is "at least" 1 player who signals the interest in being the leader in the first round of signaling (in a group of \(k + 1\) status cooperators). In other words, the equation implies whenever there are more than 1, say, 2, 3, \(\cdots\), \(k + 1\) players expressing an interest in leadership in the first round, the whole selection will end eventually with exactly 1 player being the leader at the top, thus equating the probability of the former scenario to that of the latter. This calculation, apparently, fails to consider the situation in which there is more than 1 player showing an intention to lead in the first round so the signaling repeats, yet in a later round, the selection concludes with no player being at the top level. Critically, we believe this type of failure of achieving a status hierarchy is allowed in the model, based on Mark's description of it. Together, then, we hold that Mark's paper is at least missing key information if not being built upon a wrong one, from an early stage of his formulation of the model. Such a flaw, unfortunately, should have propagated through the work and affected later computations.

Consequently, we recover the above process of structure formation in the present research following Mark's text: "[W]hen the status hierarchies are not apparent, the structure formation iteration continues, and the process stops when there is 0 or 1 player at the top level." We treat the process as a Bernoulli trial that stops when 0 or 1 player is at the top level. Given there are \(k\) status cooperators in a group of size \(n\), for each iteration, the probability for 0 player to be at the top level is then \(p_0(k) := \left(\frac{n-1}{n}\right)^k\) and the probability for exactly 1 player to be at the top is \(p_1(k) := \binom{k}{1} \left(\frac{1}{n}\right)\left(\frac{n-1}{n}\right)^{k-1}\). Based on the properties of geometric distributions, the expected number of failed and ignored iterations can in turn be derived as

\[
E_f := \frac{1}{p_0(k) + p_1(k)} - 1.
\]

Moreover, it can be shown that the probability that the structure formation process ends with 0 or 1 player at the top level depends on their relative probabilities, as

\[
P_0(k) := \frac{p_0(k)}{p_0(k) + p_1(k)}
\]
for no player at the top level at the last iteration, and as
\[ P_1(k) := \frac{p_1(k)}{p_0(k) + p_1(k)} \]
for 1 player at the top at the last iteration.

Put simply, since the whole process is a Bernoulli trial that only stops when the outcome is a “success,” one can imagine the process of structure formation as rolling a die with faces \{0, 1, 2, 3, 4, 5\}, with “successes” being defined as \{0, 1\} and all other results being “failures.” Each trial, or “roll,” is identical and independent, and one will keep rolling until 0 or 1 shows. As such, the present instance of rolling a 6-face die is analogous to the signaling process in a group of \( k = 5 \) status cooperators: The process will conclude until exactly 0 or 1 group member is at the top level. The probabilities of getting a 0 and a 1 from this die in a round are then \( p_0(5) \) and \( p_1(5) \) respectively, and the probabilities that the signaling process ends with no individual and one individual at the top level are \( P_0(5) \) and \( P_1(5) \) respectively.

To further illustrate these signaling rules, we constructed an agent-based model of the leader selection process of Mark’s game, and then tested Mark’s and our formal predictions against the agent-based simulation. Specifically, we fixed the group size at \( n = 10 \), varied the number of status cooperators \( k \) in the group from 0 to 10, and performed 100,000 trials of the simulation that stopped when there was exactly 0 or 1 individual at the top level in a trial. In Figure 1 (a), we show the average simulated results of the probability of ending the structure formation with 1 individual at the top level, as well as Mark’s and our predictions of the same probability. To reiterate, Mark’s predictions are obtained as
\[ 1 - \left( \frac{n-1}{n} \right)^k, \]
whereas our predictions are calculated as
\[ P_1 := \frac{p_1(k)}{p_0(k) + p_1(k)}. \]

As shown in the figure, our predictions nicely correspond with the results of simulation across all levels of \( k \). Mark’s predictions of the probability of ending the structure formation with 1 individual at the top, by contrast, become over-estimated as \( k \) increases (because, as stated above, his calculation mistakenly counts in “late-emerging failures” of forming a hierarchy). In addition, we plot in Figure 1 (b) the average simulated results of the number of abandoned rounds of signaling wherein group members fail to establish a clear group structure (i.e., with 0 or only 1 cooperator being at the top level). Note that this number also grows as \( k \) increases, as does the probability of eventually agreeing upon one an only
Figure 1: Comparison of Mark’s prediction and our prediction with simulations in the signaling process. Here we fix the group size \( n = 10 \) and vary the number of status cooperators \( k \) in the group. Each dot (gray star) is an average of 100,000 agent-based trials. (a) The probability of the group to reach a status hierarchy, i.e., with one leader at the top level, versus the number of status cooperators in the group. (b) The average number of abandoned rounds of signaling wherein group members fail to establish a clear group structure, \( E_f \), versus the number of status cooperators in the group.

leader. This indicates that there may be an implicit cost of group structure formation that is not seen in Mark’s paper and is ironically associated with a group’s potential to cooperate: The more potential cooperators in the group, the more rounds needed for the group to settle on a (clear) structure.

2.3 Our approach: a more generalized model incorporating hierarchy measurement

Focusing on the astray phase of group structure formation that seemingly plagues Mark’s model, in the current paper, we propose a different approach to incorporating status hierarchy into the EVG of cooperation. That is, instead of considering merely the single-leader hierarchy and abandoning all others, we relax this assumption and extrapolate the model to take into account different levels of hierarchicalness of a structure. Or, we interpolate the cooperativeness of group members by allowing the probability of cooperation taking a probability between 0 and 1. Specifically, if the signaling process generates multiple leaders in a round, rather than dropping the round and starting all over as Mark’s model would, we estimate the hierarchicalness of this—following his terminology—unapparent structure, and then estimate the downstream effects of this structure on cooperation among group members. Importantly, this is not only to recover Mark’s calculation, but also to give the
investigation extra flexibility and realism to, for example, analyze the above found implicit cost of structure formation. Moreover, organizational hierarchy is known to take diverse forms in the real world, well beyond the either-or, one-or-no-leader situation studied by Mark. In the business domain, for instance, it is common to have multiple managers sitting in the executive committee of a company, each of whom is ranked equally in the managerial hierarchy. In professional sports, it is not uncommon either to see multiple elite players in the same team to increase the team’s versatility and competitiveness. In fact, some management scholars have gone so far to postulate that having multiple, rather equal sitting leaders may help promote work performance (Dust and Ziegert, 2016). Overall, then, it seems crucial for us to include the continuous spectrum of structural hierarchicalness in between the two extreme ends of the signal- and the no-leader case.

From here, consequently, the issue that follows is how to gauge the hierarchicalness of structures in which a leader selection produces multiple leaders. Specifically, if the single-leader system is the most unequivocal hierarchical—as suggested by Mark—and hence should be assigned the highest hierarchicalness, what would be the hierarchicalness of a less apparent structure, say, those with two leaders? To address the question, below, we visit the literature of measuring hierarchicalness of organizations, in search of a measure that would meet this current need.

The first approach of measuring hierarchicalness ranks individuals by their dominance, following the idea that those who have a better winning rate and a larger winning differential over others in contests—or simply, stronger dominance—are expected to be ranked higher on the ladder. Traced back to the Bradley-Terry model (Bradley and Terry, 1952), this family of methods has been modified to measure the dominance hierarchy in various organizations such as sports competitions (Massey, 1997; Colley, 2002) and peer relations between teenagers (Martin, 1998; Levi Martin, 2009).

Further, an alternative way to measure social hierarchy is rooted in the social-network literature and more or less built upon the same idea of dominance. From a network perspective, the dominance relation between a pair of actors can be represented by a directed edge stemming from actor $i$ to $j$, showing that $i$ dominates $j$ along a dimension of interest such as aggression, attraction or prestige (Cheng et al., 2013), in a diagraph. If the two actors are equal in status, their relationship can be represented by an undirected edge otherwise. Together, this network diagraph approach thus allows researchers to use social network toolkit to measure the hierarchicalness of a group. For instance, Krackhardt proposed to measure the hierarchicalness of a group by the number of directed edges out of the total number of edges, directed or undirected, in the network (Krackhardt, 1994). In ethology, researchers have also used the prevalence of cyclic subgraphs, wherein actor $i$ dominates $j$, who then dominates $k$, who in turn dominates $i$ (Shizuka and McDonald, 2012), to gauge hierarchicalness. That is, if this kind of cycle is prevalent in a group, then the group is said to be less hierarchical than are the groups wherein $k$ does not dominate.
and is always fixed at the bottom. Finally, Mones et al. developed a hierarchicalness index by tracing the reachability of actors in the digraph of dominance relations (Mones et al., 2012). When a group is highly hierarchical, such as having a tree-like structure, the top actor—called the root node—can reach all other nodes-actors (indirectly) in the network, whereas the bottom node—the branches—cannot reach any other nodes and those in between the top and the bottom can only reach those who are below themselves. In contrast, in the least hierarchical structure—a cycle—everyone can reach everyone else in time. The distribution of the reachability of nodes can consequently reveal the hierarchicalness of the group of the nodes.

Drawing from the literature, in this paper, we introduce the hierarchicalness measure developed by Mones et al. (2012) into Mark’s model (2018). We adopt the tenet of Mark’s work that “the status hierarchy is the key to how status behavior promotes social order” (line 4-5, p. 1607). We then expand this idea by the hierarchicalness measure, so that the single-leader hierarchy in Mark’s model becomes a special case of a more general model. Specifically, we follow Mark’s argument that “when status behaviors combine to create a status hierarchy, they help the members of a group overcome a social dilemma. When status behaviors do not create a status hierarchy, they do not promote cooperation” (line 5-8, p. 1607). Accordingly, we use the chosen hierarchicalness measure to answer: If the single- and the no-leader structure represent the most and the least hierarchical structure respectively and they render total and zero cooperation among status cooperators respectively, what would be the level of cooperation in a group whose hierarchicalness is in between these two types of extremes and is measured by the index of (Mones et al., 2012)? We detail our argument below.

3 THE MODEL

The section is organized as follows. First, we introduce the hierarchicalness measure of (Mones et al., 2012). We then incorporate it into (Mark, 2018) EVG to form a more general relationship between status hierarchy and group cooperation. Along the way, we highlight the differences between Mark’s and our work, in the conditions under which cooperation could emerge. Specifically, for ease of presentation, we follow (Mark, 2018) presentation to first discuss the case of random mixing, then move on to that of assortative mixing.

3.1 Hierarchy score and the contributing probability $H_n(x)$

As mentioned, there are four phases in one iteration in Mark’s original evolutionary game: (1) the determination of the group; (2) preplay communication among group members;
(3) cooperators’ decisions to contribute to the group or not; (4) the determination of the
next generation of status cooperators and defectors based on their payoffs from the current
generation. For the aim of the current paper, here, we generalize this model by allowing
multi-leader structures to pass phase (2) and, therefore, forcing cooperators to make their
decisions to contribute in such “unapparent” structures in phase (3). Phases (1) and (4)
are unchanged and, consequently, are not discussed in detail below; we focus on phases (2)
and (3).

As in Mark’s model, there are two levels of hierarchy in our model, the top and the bottom,
to be formed from preplay communication. In the process, every status cooperator similarly
signals their willingness to be the leader with probability $\frac{1}{n}$ and, hence, a lack of such
intention with probability $\frac{n-1}{n}$. If there is no player expressing the interest in taking the
leader role at the top level, it is assumed that all status cooperators will not contribute
to the group in the next phase of the game, as will the defectors at the bottom level.
From here, however, Mark posits that status cooperators will only contribute if there is
one and only leader emerging. If there are more, he requires the hierarchy formation to
start over until only one or no leader shows up. To break from this assumption, we thus
loosen the model design by incorporating the possibility that leadership is often shared
by many in the real world (Selznick, 2011; Case and Maner, 2014; Eslen-Ziya and Erhart,
2015). Practically, if there are multiple players signaling high versus low/no intention to
lead the group, instead of abandoning the round of leader selection, we retain the surfacing
multi-leader structure and allow status cooperators to still contribute, though this time,
with a likelihood. By so designing the game, then, not only is our model capable of
studying more forms of hierarchy as we set out to achieve; there will be no issue of the
hidden costs of failure for group members to agree upon a clear hierarchy (as is the case
in Mark’s work), because all hierarchical statures are now considered a success and the
costs of leader selection become a natural part of the game. Finally, it might be worth
noting that the two extreme situations which Mark examines—that is, in which either one
or zero leader is established—are taken into account in our model as two special cases out
of all permitted hierarchical structures. Indeed, because Mark requires that all status
cooperators cooperate when there is one leader and none of them cooperate when there is
no leader, he sets up the boundaries of the cooperation probability of our model. That is,
when the group is the most hierarchical, with one above all, all will follow and contribute
with the highest cooperation probability of 1. By contrast, when the group is the least
hierarchical, with all on the same flat level, none will contribute, or, will do so with the
lowest cooperation probability of 0. Together, the two scenarios become the upper and the
lower limit of our model, implying that all other less apparent hierarchical structures that
we sought to include should sit in between these two extremes of cooperation probability
equal 0 or 1.

Following Mark’s theorizing, we then assume that, when there are multiple leaders at
the top level and make the group’s hierarchy obscure, the leaders’ authority will become
attenuated and, therefore, relatively ineffective in terms of motivating cooperation in the group. Importantly, not only is this assumption stems directly from Mark’s reasoning; it has been supported in empirical studies. For instance, it has been documented that members of multi-leader teams simply need more resources, e.g., time, to communicate and to agree upon share goals (Rice, 2006). This then increases the risk of failing to achieve consensus in which group members, especially subordinates, can work on together and cooperate with one another. Further, even if leaders can enclose distinct domains of leadership by, say, different specialties, allowing them to pursue independent objectives at the same time—much as what we model—runs on the possibility that they would get into each other’s way, competing for common resources such as material and human resources (Friedrich et al., 2009). On the other hand, though organizing leaders into a larger system may help them coordinate and therefore temper the problem (Dust and Ziegert, 2016), it implicitly violates the idea of multi-leadership that we sought to investigate, as now the leaders are also followers under something or someone greater. In terms of mathematics, this means a reduction of the dimensionality of group leadership hidden behind a superficial constant number of leaders in the group. Consequently, we hold and indeed postulate that the clarity of hierarchicalness of a group can serve as a proxy to the likelihood that status cooperators can coordinate and collaborate: The more clearly hierarchical a group, the more its members will cooperate. Now, to stay close with Mark’s work that the current paper is built upon, we similarly assume that there are only two layers, the top and the bottom, as in Mark’s model, and we reiterate that our hierarchicalness measure needs to be higher when there are relatively fewer leaders at the top level and it needs to be lower when there are more leaders, so that the contribution willingness of status cooperators can be derived as a proportion to hierarchicalness bounded between 0 and 1.

Accordingly, we adopted the measure of hierarchicalness developed by (Mones et al., 2012), as it bears the mathematical properties we were looking for. However, note that this measure is defined for any arbitrary complete network and is hence more flexible than needed in the current case. As such, we restricted the measure for our model, i.e., a system with two layers of players, as follows. Given an unweighted directed graph \( G = (V,E) \) containing a vertex set \( V \) with \( n = |V| \) number of vertices and an edge set \( E \) with \( M = |E| \) number of edges, the local reaching centrality \( c_R(i) \) of node \( i \) was defined as the ratio of the number of reachable nodes of \( i \) through its out-edges, to the total number of nodes that a node could potentially reach (assuming no self-loop). That is,

\[
c_R(i) = \frac{|S_i|}{n - 1},
\]

where \( S_i = \{j \in V | 0 < d_{out}(i,j) < \infty\} \) is the set of nodes that have nonzero but finite out-distances from node \( i \). And the general reaching centrality \( GRC(G) \) of graph \( G \) is the normalized sum of all nodes’ local reaching centrality by the maximum local reaching
centrality:

\[ GRC(G) = \frac{1}{n-1} \sum_{i \in V} \left[ c_{R}^{\text{max}} - c_R(i) \right], \]  

(1)

where \( c_{R}^{\text{max}} \) denotes the largest local reaching centrality in the network. In other words, when \( GRC = 1 \) and the structure is the most hierarchical, the graph would have only one node—the leader—with nonzero local reaching centrality to all others when others have no out-edge at all. The structure, therefore, represents the (apparent) hierarchy in Mark’s model with the highest possible hierarchical score.

Here, to keep generalizing the GRC to two-level groups of nodes, we considered that the players at the top level, however many, have control over others at the bottom and, therefore, each at top has an out-edge toward every other at the bottom. The structure studied in the present research thus became networks, and we defined the hierarchicalness \( H_n(x) \) of this kind of two-level cooperation structures with group size \( n \) and \( x \) players at the top level using the GRC of network \( G \). That is,

\[
H_n(x) = \begin{cases} 
\frac{(n-x) \cdot \frac{n-x}{n-1}}{n-1} = \left( \frac{n-x}{n-1} \right)^2 & \text{if } 0 < x \leq n \\
0 & \text{if } x = 0.
\end{cases}
\]  

(2)

Notice here that, when \( 0 < x \leq n \), eq. (2) applies eq. (1) to a two-level network with \( x \) players at the top level. In this case, \( c_{R}^{\text{max}} = \frac{n-x}{n-1} \) since players at the top show maximum reachability to \( n-x \) nodes at the bottom, who do not have this reachability. Moreover, when \( x = 0 \) and everyone is at the bottom level, we set \( H_n(0) = 0 \) to represent the lack of leadership in the group. Readers may consult Figure 2 for an illustration of all group structures and their corresponding \( H \) values that a group with size \( n = 5 \) can have. Specifically, in the two extreme cases in the figure where there is no player at the top (subplot (a)) or every node is at the top (subplot (f)), \( H = 0 \). These two cases demonstrate that, when every node is equal in status, there is no hierarchy/hierarchicalness in the network. In addition, notice that when \( x = 1 \), the \( H \) value becomes 1, the highest among all scenarios. This thus represents the clear hierarchical structure formed in Mark’s EVG. Finally and critically, except for the special case of \( x = 0 \), for which we stipulated its \( H = 0 \), \( H_n(x) \) is a decreasing function of \( x \), as required by our conceptual analysis above. Put differently, this decreasing trend suffices that the more leaders at the top level \( (x) \), the less apparent hierarchical the commanding system \( (H) \). Readers may also refer to Figure 3 which shows the \( H_n(x) \) functions with different cases of \( n \) and \( x \). For these cases, \( x \) is defined to be less or equal to the group size \( n \), and it can be seen that, again, \( H_n(x) \) always takes the value between 0 and 1.

Given its useful mathematical properties, we subsequently used \( H_n(x) \) as the proxy to and defined it as the probability that a status cooperator would contribute to the group. By so doing, as explained above, we make Mark’s model a special case of ours, setting the most
and the least hierarchical extreme scenarios of our model. Specifically, given a group of size $n$ and $x$ players at the top level, let $H_n(x)$ also be the probability of a status cooperator to contribute in any group structure emerging from the prepay communication. As such, if there is only one player signaling their interest in higher status and, thus, rise to the top, all status cooperators will contribute, that is, with a probability $H_n(1) = 1$, as in Mark’s model. On the other hand, if there is no player at the top level, all status cooperators will not contribute, that is, with a probability $H_n(0) = 0$, again as in Mark’s model. Together, these two special cases then cover the cases Mark discusses. Beyond these, importantly, the group structure in our model can also have any number of leaders, so long as it does not exceed the total number of players in the group. With the current definition of $H_n(x)$, we were consequently able to delineate the cooperation process wherein there is any arbitrary (but logical) number of players in the leader role.
Figure 3: Values of $H_n(x)$, for $n = 0, 1, \cdots 10$. 
3.2 Random mixing

As mentioned, we followed the overall settings of Mark’s original game and only modified
the process of preplay communication and the corresponding contribution of status cooper-
ators (SC in Mark’s paper, now we use C). The determination of groups and the population
dynamics remained the same along with the evolution. Therefore, our changes to Mark’s
model should have merely affected its expected payoffs for the status cooperator \( W(C) \)
and the defector \( W(D) \) within one iteration. Everything in-between iterations would hold.
As such, below, we focus on \( W(C) \) and \( W(D) \) first, and then analyze the corresponding
changes in predicted cooperation as a result of changed expected payoffs.

To examine the changes in \( W(C) \) and \( W(D) \), we start from a small group of size \( n \), assuming
an unbiased random mixing among cooperators and defectors. When \( n = 2 \), the expressions
of the expected payoffs for the status cooperators and defectors are shown in formula (3)
and (4), respectively. With the probability for our protagonist, the status cooperator, to
meet another cooperator being \( f_c \) and to meet a defector being \( 1 - f_c \), in equation (3), the
first and the second line are the expected payoff for a status cooperator meeting another
coooperator and a defector, respectively. Particularly, there are three terms in the first line
of equation (3); they in turn represent the situations where the focal cooperator meets
another cooperator while there are 2, 0, or 1 player at the top level. As a result, when all
players (i.e., 2) or no player is leaders, no status cooperator contributes, and each of them
takes \( c \) back. By contrast, when there is 1 and only leader in the group—the special case of
\( H_n(1) \)—every status cooperator contributes equally and receives \( b \) equally. Moreover, the
two terms of the second line, in turn, represent the case wherein the status cooperator
meets a defector, does not go to the top level themself, and hence not contribute, and
the case wherein the cooperator goes to the top and contributes. Notice that in the latter
scenario, the contribution \( b \) will be shared by the two players in the group since the defector
does not contribute.

\[
W(C) = f_c \cdot \left\{ \begin{array}{l}
(2) \left( \frac{1}{2} \right)^2 \left( \frac{2-1}{2} \right)^0 \cdot c + (2) \left( \frac{1}{2} \right)^0 \left( \frac{2-1}{2} \right)^2 \cdot c + (2) \left( \frac{1}{2} \right)^2 \left( \frac{2-1}{2} \right)^1 \cdot b \\
+ (1 - f_c) \cdot \left\{ \begin{array}{l}
(0) \left( \frac{1}{2} \right)^0 \left( \frac{2-1}{2} \right)^1 \cdot c + (1) \left( \frac{1}{2} \right)^1 \left( \frac{2-1}{2} \right)^1 \cdot b \end{array} \right. \\
\end{array} \right. 
\]
(3)

Turning to the expected payoff for the defector, here we express it in equation (4) in that,
whether the defector meets a status cooperator or another defector, he always keeps his
cost \( c \)—the first term in the equation. Therefore we only need to focus on whether they can
get additional shares of \( b \). In the current case of \( n = 2 \), the defector would only obtain
the benefit \( b \) when meeting a cooperator who goes to the top level (therefore contributes).
This is the second term in the line.
\[ W(D) = c + f_c \cdot \left\{ \frac{1}{0} \left( \frac{1}{3} \right)^0 \left( \frac{2}{3} \right)^0 \cdot \frac{b}{3} \right\} \] 

Now, generalizing the equations, the hierarchy function \( H_n(x) \) joins in for the payoffs for a larger group size \( n \). Notice that \( x = 1 \) is always a special case. The status hierarchy is apparent and all cooperators contribute. The other special case is that all status cooperators are at the same level, either at the top or the bottom. In this case, no cooperator contributes. Accordingly, below are the expected payoffs for the cooperator and the defector when \( n = 3 \), in equation (5) and (6), respectively.

\[ W(C) = f_c^2 \cdot \left\{ \left( \frac{3}{3} \right)^3 \left( \frac{1}{3} \right)^3 \left( \frac{3}{3} - 1 \right)^0 \cdot c + \left( \frac{3}{0} \right)^0 \left( \frac{3}{3} - 1 \right)^0 \cdot c + \left( \frac{3}{1} \right)^1 \left( \frac{3}{3} - 1 \right)^2 \cdot b \right\} + \left( \frac{2}{2} \right)^2 \left( H(2) \right)^0 \cdot \left( 1 - H(2) \right)^0 \cdot \frac{b}{3} \]

\[ + \left( \frac{2}{1} \right)^1 \left( H(2) \right)^1 \cdot \left( 1 - H(2) \right)^1 \cdot \frac{b}{3} + \left( \frac{2}{1} \right)^1 \left( H(2) \right)^1 \cdot \left( 1 - H(2) \right)^0 \cdot \frac{2b}{3} \]

\[ + \left( \frac{1}{0} \right)^1 \left( H(2) \right)^1 \cdot \left( 1 - H(2) \right)^0 \cdot \frac{b}{3} \]

\[ \] 

\[ W(D) = c + f_c^2 \cdot \left\{ \left( \frac{2}{1} \right)^1 \left( \frac{1}{3} \right)^1 \left( \frac{3}{3} - 1 \right)^1 \cdot \frac{b}{3} + \left( \frac{2}{2} \right)^0 \left( \frac{3}{3} - 1 \right)^0 \right\} \]

\[ \] 

\[ \cdot \left[ \left( \frac{2}{1} \right)^1 \left( H(2) \right)^1 \cdot \left( 1 - H(2) \right)^1 \cdot \frac{b}{3} + \left( \frac{2}{2} \right)^0 \left( H(2) \right)^0 \cdot \frac{2b}{3} \right] \}

\[ \] 

\[ + 2f_c(1 - f_c) \cdot \left\{ \left( \frac{1}{1} \right)^1 \left( \frac{3}{3} - 1 \right)^0 \cdot \frac{b}{3} \right\} \]

The first three lines in equation (5) represent the situation in which a status cooperator meets two other status cooperators, lines 4 to 6 represent the situation in which the cooperator meets one cooperator and one defector, and the last line represents the situation in
which all others are defectors. Here, we focus on the first three lines as the rest is obtained following the same calculation. That is, the three terms in the first line are the special cases: In order, all cooperators become leaders, none of them does, and exactly one among them goes to the top level. Further, lines 2 and 3 together show the case where two status cooperators go to the top level yet one does not, i.e., $x = 2$. Here, one needs to consider two different scenarios: If the focal cooperation does not contribute, they can keep $c$ and obtain extra portions of $b$ depending on the number of players who contribute. In other words, though a cooperator to start, this player acts as a defector in the end, given the probability $1 - H_3(2)$ “not” to follow the lead. This probability is always 0 in Mark’s model because of $1 - H_3(1) = 0$, but does not have to be so in ours. Consequently, the focal player can take $\frac{k}{3}$ shares of $b$ if there are $k$ cooperators who end up contributing. For example, the last term in line 3 expresses the scenario that one status cooperator contributes and the other two do not, therefore the protagonist obtains $\frac{k}{3}$ and the rest of the equation was derived following the same rationale.

On the other hand, equation (6) is the expected payoff for the defector when $n = 3$. Note that, again, a defector can always take back $c$. They then obtains additional fractions of $b$ if they meets two cooperators—with probability $f_c^2$ (the first two lines)—or one status cooperator—with probability $2f_c(1 - f_c)$ (the last line). Specifically, the first term inside the part following $f_c^2$ represents that exactly one status cooperator becomes the leader, so both status cooperators contribute. Line 2 represents the scenario where both status cooperators become leaders, and therefore, each of them has a probability $H_3(2)$ to contribute. In this case, the first term of line 2 expresses that one cooperator contributes and the other does not, and the second term shows both of them do. As a result, the focal defector obtains $\frac{b}{3}$ and $\frac{2b}{3}$ of benefits, respectively. The last line then follows the same rationale as in the prior analysis.

Finally, the expected payoffs for a status cooperator and a defector in a general case of arbitrary $n$ are identified in equations (7) and (8), respectively. To construct the equations, we aggregated the payoff that a focal player obtains based on three quantities: (i) the number of status cooperators in the group, (ii) the number of status cooperators who become leaders, and (iii) the number of status cooperators who end up contributing to the group. Together, the expected payoff of the player can be expressed with a triple summation of the three quantities, denoted with dummy variables $i$, $j$, and $k$, corresponding to the quantities of (i), (ii), and (iii). Here, it might be worth noting that (ii) depends on (i) and (iii) depends on them both. Consequently, the first two lines of equation (7) describe the scenarios in which the focal status cooperator does not contribute and takes back $c$, whereas the last two lines describe the scenarios in which they take portions of $b$ depending on quantities (i), (ii), and (iii). On the other hand, equation (8) indicates that the defector always keeps $c$ with extra shares of $b$ similarly depending on (i), (ii), and (iii).
Validating the general equations (7) and (8), we further built an agent-based simulation (see Appendix for the code) of our EVG. As shown in Figure 4, we compared the analytical and the simulated predictions of the internal equilibrium—i.e., the cost-to-benefit ratio $c/b$ that makes $W(C) = W(D)$—of groups with different sizes $n$ and fractions of status cooperators $f_c$. A dot in the figure is an average of 100,000 simulations of a given pair of $n$ and $f_c$, and the lines are the analytical predictions of their same-color dots. As can be seen, the equations that based the predicted lines—equations (7) and (8)—yielded nearly perfect matches with the simulations, bolstering the validity of our formal model. In addition, note that above a line, the cost becomes higher and $W(D) > W(C)$. Therefore status cooperators will decrease in number in the next iteration of the population dynamics. By contrast, below a line, the cost is lower and $W(D) < W(C)$. Therefore cooperators will increase in the next iteration.

Having established the model, subsequently, we studied the cost-to-benefit range wherein status cooperation is a stable evolutionary strategy in social dilemmas. To determine the range, we searched for the upper and the lower bound for cooperation to remain stable, following the reasoning in Mark’s paper. Specifically, our multi-leader model would not change the lower bound that Mark obtained, because only one status cooperator would be placed in a group without any other cooperator. This made the lower bound of the
Figure 4: Comparison of simulations and analytics for different group size $n$.

cost-to-benefit ratio $\frac{1}{n}$ as in Mark’s work. Put different, if the ratio is smaller than $\frac{1}{n}$, then $b$ becomes too large relative to $c$ to keep the game a dilemma: Contribution will always outperform defection by design.

Moreover, to investigate the upper bound of the cost-to-benefit range that makes cooperation a stable strategy in a social dilemma—that is, the conditions under which that $f_c = 1$ is stable—we again followed the approach taken by Mark. That is, we considered a population of status cooperators and then replace one of them with a defector. If these cooperators’ expected payoff in the original homogeneous group is larger than that for the invading defector, it is said that cooperation is an evolutionarily stronger and hence stable strategy against defection. Conversely, if it is expected that payoffs accrue faster for the invading defector than for the group of cooperators, the former will eventually take over the group. Mathematically, the conceptual analysis means to first compute a status cooperator’s payoff under $f_c = 1$. If it is larger than a defector’s payoff under $f_c = \frac{n-1}{n}$, then cooperation
is stable. Accordingly, we plugged these condition in equations (7) and (8) to find the boundary of $c/b$.

As shown in Figure 5, although sharing the same lower bound, Mark’s and our model do not have the same upper bound. Without his neat analytical form

$$\frac{n^{n-1}}{n^n - (n-1)^n},$$

our upper bound of $c/b$–derived numerically using equations (7) and (8)–is higher than Mark’s and, indeed, much higher. Therefore, the region of the cost-to-benefit ratio in which status cooperation is a stable strategy in social dilemmas in our model is much wider than that in Mark’s. Consequently and ironically, that we corrected and lowered Mark’s over-estimation of the probability for an apparent hierarchy to form to maneuver group members into cooperation and that we reduced the effectiveness of cooperation among group members in an unapparent hierarchy, together, made cooperation seen more but not less stable than predicted by Mark. Lastly, we examined the region of $c/b$ in larger groups, because it can be derived analytically that the upper bound of Mark’s model will approach 0 and, therefore, eliminate the region as $n$ goes to infinity. As shown in Figure 6 we found that the upper bound of our model also seemingly approaches 0 as $n$ goes to infinity, though as above, the region seems wider than that of Mark’s.
Cooperation is a stable strategy in social dilemmas. Our model and Mark’s model have the same lower bound. The upper bound in our model (shown in red dots and lines) is larger than in Mark’s (shown in black dots and lines).
Cooperation is a stable strategy in social dilemmas

Figure 6: Cooperation is a stable strategy in social dilemmas for large $n$. Our model and Mark’s model have the same lower bound. The upper bound in our model (shown in red dots and lines) is larger than in Mark’s (shown in black dots and lines).
3.3 Assortative mixing

Similar to Mark’s work, in this section, we explore how our multi-leader model behaves with assortative mixing. In Mark’s original paper, he reports that a status cooperator may be able to reversely invade a population of defectors with the help of enough assortativity, because assortative mixing unequally protects and, therefore, favors cooperative strategies. Following this analysis, we then adopted the assortative mixing rules developed in Mark’s paper, that is, selection of the first individual of a group is unbiased and random yet the successive members in the group are biasedly selected depending on the assortativity parameter $\tau$. To construct this analysis in our model, the only change to make lay in the rate of meeting a cooperator $f_c$. We thus developed the expected payoffs for a status cooperator and a defector in a multiple leader model with assortative mixing in equations (9) and (10) as follows.
\[ W(C) = \left\{ \left\{ \left( \frac{1}{n} \right) \left[ \tau + (1 - \tau)f_c \right]^{n-1} + \left( \frac{n-1}{n} \right) f_c \left[ \tau + (1 - \tau)f_c \right]^{n-2} \right\} \left( \frac{n}{n} \right) \left( \frac{1}{n} \right)^n \left( \frac{n-1}{n} \right)^0 \right. \]
\[ + \left. \sum_{i=0}^{n-1} \left\{ \left( \frac{i+1}{n} \right) \left[ \frac{1}{i+1} \right] \left( \frac{n-1}{i} \right) \left[ \tau + (1 - \tau)f_c \right]^i [(1 - \tau)(1 - f_c)]^{n-i-1} \right. \right. \]
\[ + \left. \left( \frac{i}{i+1} \right) f_c \left( \frac{n-1}{i} \right) \left[ \tau + (1 - \tau)f_c \right]^{i-1} [(1 - \tau)(1 - f_c)]^{n-i-1} \right. \right. \]
\[ + \left. \left( \frac{n-i-1}{n} \right) (1 - f_c) \left( \frac{n-1}{i} \right) [(1 - \tau)f_c]^{i-1} [(1 - \tau)(1 - f_c)]^{n-i-2} \right\} \]
\[
W(D) = c + \left\{ \sum_{i=0}^{n-1} \left( \frac{i}{n} \right) \left\{ f_c \binom{n-1}{i} \left[ \tau + (1-\tau)f_c \right]^{i-1} \left[ (1-\tau)(1-f_c) \right]^{n-i-1} \right\} 
\right. \\
+ \left( \frac{n-i}{n} \right) \left\{ \left( \frac{1}{n-i} \right) \binom{n-1}{i} \left[ (1-\tau)f_c \right]^i \left[ \tau + (1-\tau)(1-f_c) \right]^{n-i-1} \right\} \\
+ \left( \frac{n-i-1}{n-i} \right) (1-f_c) \binom{n-1}{i} \left[ (1-\tau)f_c \right]^i \left[ \tau + (1-\tau)(1-f_c) \right]^{n-i-2} \right\} \\
\cdot \left\{ \frac{i}{n} \binom{n-1}{i} \left[ 1-\binom{i}{n} \right] \left( \frac{1}{n} \right)^{i-1} \sum_{j=2}^{i} \binom{i}{j} \left( \frac{1}{n} \right)^j \binom{n-1}{i-j} \left[ (1-\tau)f_c \right]^{i-j} \right\} \\
\cdot \left[ \sum_{k=1}^{i} \left( \frac{k}{k+1} \right) \binom{n-1}{i} \left( H_n(j) \right)^k \left( 1-H_n(j) \right)^{i-k} \left( \frac{kb}{n} \right) \right] \right\} \\
\text{(10)}
\]

Equations (9) and (10) may look daunting, yet are merely incremental from the general random-mixing equations (7) and (8). As mentioned, only terms related to the fraction of status cooperators \( f_c \) should be modified, and fortunately there are only two such terms. Specifically, \( (f_c)^{n-1} \) in the first term of the first line of equation (7) is substituted with

\[
\left( \frac{1}{n} \right) \left[ \tau + (1-\tau)f_c \right]^{n-1} + \left( \frac{n-1}{n} \right) f_c \left[ \tau + (1-\tau)f_c \right]^{n-2}
\]

in equation (9). The \( \frac{1}{n} \) term here is the probability for a focal player to be chosen as the first member and then \( n-1 \) others to be chosen as status cooperators. On the other hand, the \( \frac{n-1}{n} \) is the probability for another status cooperator to be the first member and \( n-1 \) others including the focal player to be cooperators.

Further, in the first and the third line of equation (7), the term

\[
\sum_{i=0}^{n-1} \binom{n-1}{i} (f_c)^i (1-f_c)^{n-1-i}
\]

is substituted with

\[
\sum_{i=0}^{n-1} \left( \frac{i+1}{n} \right) \left\{ \left( \frac{1}{i+1} \right) \binom{n-1}{i} \left[ \tau + (1-\tau)f_c \right]^{i-1} \left[ (1-\tau)(1-f_c) \right]^{n-i-1} \right\} \\
+ \left( \frac{i}{i+1} \right) f_c \binom{n-1}{i} \left[ \tau + (1-\tau)f_c \right]^{i-1} \left[ (1-\tau)(1-f_c) \right]^{n-i-1} \right\} \\
+ \left( \frac{n-i-1}{n} \right) (1-f_c) \binom{n-1}{i} \left[ (1-\tau)f_c \right]^i \left[ \tau + (1-\tau)(1-f_c) \right]^{n-i-2}.
\]

25
Here, the first two lines of the expression represent the scenario wherein the first member of a group is a status cooperator. The term with $\frac{1}{i+1}$ is the probability for the focal cooperator to be the first member and $i$ others to be chosen as status cooperators; the term with $\frac{i}{n}$ is the probability for another status cooperator to be the first member and $n-1$ others including the focal player to be cooperators. Lastly, the third line of the expression describes the case in which the first member of a group is a defector and they meet $i+1$ status cooperators including the focal player.

With aforementioned modifications, equation (9) was then obtained. Importantly, when $\tau = 0$, i.e., under random mixing, this equation (9) reduces to equation (7) as expected. Similarly, equation (10) was obtained by changing the terms related to $f_c$ in equation (8). The term in first line of (8)

$$\sum_{i=0}^{n-1} \binom{n-1}{i} (f_c)^i (1-f_c)^{n-1-i}$$

is substituted with

$$\sum_{i=0}^{n-1} \left( \frac{i}{n} \right) \left\{ f_c \left( \frac{n-1}{i} \right) \left[ \tau + (1-\tau)f_c \right]^{i-1} \left[ (1-\tau)(1-f_c) \right]^{n-i-1} \right\}$$

$$+ \left( \frac{n-i}{n} \right) \left\{ \left( \frac{1}{n-i} \right) \left( \frac{n-1}{i} \right) \left[ (1-\tau)f_c \right]^{i-1} \left[ \tau + (1-\tau)(1-f_c) \right]^{n-i-1} \right\}$$

$$+ \left( \frac{n-i-1}{n-i} \right) (1-f_c) \left( \frac{n-1}{i} \right) \left[ (1-\tau)f_c \right]^{i} \left[ \tau + (1-\tau)(1-f_c) \right]^{n-i-2} \right\} \right.$$

The first line of the expression shows the scenario wherein the first member of a group is a cooperator and they meets $i-1$ other status cooperators, and the second and third lines express the scenario in which the first member of a group is a defector. The term with $\frac{i}{n}$ is the probability for the defector to be the first member with $i$ others being status cooperators, and the term with $\frac{n-i-1}{n-i}$ is the probability for another defector to be the first member with $i$ other in the group being cooperators. Following these changes, equation (10) was subsequently formed. Again, when $\tau = 0$, this equation (10) reduces to equation (8).

As before, to validate equations (9) and (10), we built an agent-based simulation of our extended multi-leader model, now with assortative mixing (see Appendix for the code). Following the same simulation procedure, as shown in Figure 7, we compared the analytics and the simulations of assortatively mixed groups, in their cost-to-benefit ratio $c/b$ against the fraction of status cooperators $f_c$ given internal equilibrium. Different from the prior random-mixing analysis, here we fixed group size $n = 10$ and instead color-coded $\tau$. The results indicate that equations (9) and (10) yield nearly perfect matches with the simulations. In addition, there is an internal equilibrium between cooperation and defection.
falls at higher cost-to-benefit ratios as \( \tau \) increases, supporting that assortativity protects cooperation against defection. However, unlike smaller group sizes, which also shield cooperation (see Figure 5), assortativity’s ability to heightens the equilibrium \( c/b \) decays with \( f_c \). By contrast, small group sizes do so almost uniformly across different levels of \( f_c \).

Figure 7: Comparison of simulations and analytics of the lines \( W(C) = W(D) \) with different mixing ratio \( \tau \).

Now, given that our analytical equations match the agent-based simulations, we used the equations to investigate the behavior of our model. As can be seen in figure 8, the predictions derived using equations (9) and (10) for different group sizes confirm that increasing the assortative level promotes cooperation across group sizes, and this effect of assortativity decreases as \( f_c \) increases. Interestingly, however, the decay seems more pronounced in larger groups than in smaller ones. When the group is small, for example, of only 3 people, \( \tau \) seems to pull up the equilibrium \( c/b \) almost equally when \( f_c = 0 \) and when \( f_c = 1 \). By contrast, when the group is large, say, of 10, \( \tau \) matters more when \( f_c = 0 \) than when \( f_c = 1 \).

Lastly, we investigated the effects of assortative mixing on the range of cost-to-benefit
ation $c/b$ for cooperation to be a stable strategy in social dilemmas. The result is shown in Figure 9. Again, the lower bound of the social dilemma is the same as for randomly mixed groups, independent of $\tau$. For the upper bounds, we added the cases of different assortative levels $\tau$. Here, the upper bound is the same as the one we obtained in the random-mixing case when $\tau = 0$. When $\tau$ increases, the upper bound also increases. One can therefore see the effect of assortative mixing on promoting cooperative behavior again, although the effect might not seem substantial in size.

4 General Discussion

Using evolutionary game theory, Mark (2018) provided a pioneering evolutionary account for how group cooperation may benefit from status hierarchy. Despite the contribution, we found a mathematical error in Marks’ calculation, specifically, in his probability of the formation of a clear group status hierarchy wherein there is one and only leader in the group. With both analytical and numerical examination, we show that the error creates more pronounced overestimation of the target probability when there are more status cooperators in the group. Given that the error occurs in the leadership-signaling process where Mark chose to ignore the cases in which the signaling generates multiple leaders, we subsequently present a solution to the problem by gauging the hierarchicalness of these multiple-leader cases and then estimating the level of cooperation mobilized by the leader-“s.” We show that, when these multiple-leader scenarios are taken into account and properly handled, the emergence of cooperation against the invasion of defection in fact seems stronger than predicted by Mark’s original calculation. In other words, our work not only generalizes Mark’s model over the continuous spectrum of hierarchicalness, but also conveys an optimistic message regarding how group cooperation may go hands-in-hand with status hierarchy. Indeed, to verify the analytical results of our proposed model, we developed an agent-based model, ran computer simulation using the model over tens of thousands of random replications, and demonstrate that the results of simulation well match those of our calculation. Since we have publicized the simulation code (programmed in MATLAB) in an open repository in support of full scientific transparency and sharing, the agent-based model as well as its analytical counterpart further open the door for future follow-up attempts to replicate and to extend our current findings.

4.1 Empirical basis of the current model

Despite of being a theoretical and computational paper, the present research is motivated and supported by empirical evidence and experiences. First, it is trivial to say that people do live in a world with multi-leader organizations; they often if not always collaborate with one another in such environments. This fact, besides the questionable calculation
of Mark’s paper, serves as the reason that we conducted the current investigation. And we do find cooperation possible and conditionally stable when there are more than one leader in a group in the model, as it is in the real world. Notably, our model shows that, though still possible, the more individuals competing for leadership in a group, the less stable cooperation is a behavioral strategy against defection. This is in line with the many scientific studies reporting that, say, the marginal benefit of having star investors on an investment team not only decreases when the number of such individuals increases. With the rising challenge of finding consensus among high-status group members, having talented investors on the team eventually backfires and reduces team profits [Groysberg et al., 2011]. That is, the group members would in fact be better off if not working together. Anecdotally, many might also remember the surprising bumpy start of the Miami Heat of their 2010-11 NBA season when LeBron “King” James first joined with two other all-stars on the team, Dwyane Wade and Chris Bosh. Without having played together enough, the “Big Three” seemed to lead the team independently as three individuals as opposed to working as one unit, resulting in many lost games. Indeed, commentators regularly attribute the Heat’s successes in winning the championship in the following years to the three’s finally finding a way to, literally, play at different positions in one and only united system, again implying that the more “independent” leaders, the less cooperation may achieve.

In addition to predicting what people experience in everyday life, our model relies on assumptions in line with everyday experiences too Particularly, we assume that the more group members, the less they would want to be the leader. This follows from the established bystander effect in social psychology such as that shown in Darley and Latané’s [Darley and Latané, 1968] research. In this classic series of experiments, Darley and Latané demonstrate that study participants were less likely to speak up and report potential emergencies—fire in the laboratory for example—when there were more participants in the lab. In other words, even if presumably everyone wanted to get out of the fire, when the group was large, few would emerge to lead the rest. By contrast, it was found easy for a person to lead themselves and simply leave the room. Moreover, we build our major contribution to the literature—that cooperation is possible not only in single—but also in multi-leader hierarchy—on the premise that the more leaders in the group, the less likely the rest would follow. The design is in accordance with the long-standing Competing Values Framework of leadership, which states that the leadership of an organization often has competing goals. The goals can be of a single leader and need to be reconciled within themself, or of different leaders and need to reconcile among themselves. Either way, if the goals cannot be integrated within or between leaders, the resources of the organization would be divided into the goals and thereof used less effective for all goals. For instance, it is reported that in a politically polarized country—the U.S. in this study—people tend to be less cooperative with those who follow a different political ideology even on non-political daily economic issues [McConnell et al., 2018]. As a potential result, human resources in general in the country would be
arranged along the party line and, as in our model, inefficiently organized to achieve the common good for all. From here, consequently, not only does our theorizing stem from empirically bolstered bases; another way to conceptualize our work is to think of high-status agents in our model not as leaders, but as leaderships. Instead of treating them as individual persons who may or may not hold contradictory opinions, we define the agents as paradoxical opinions that the group has to juggle and allocate resourceful cooperation between, thus opening the implications of the current paper for information processing and integration within groups and even within individuals’ minds.

4.2 Implications

In addition to correcting the equations of Mark’s model and then proving the right predictions, one important contribution of the current paper is that we go one step further to show that cooperation can be a stable strategy even if the leadership in a group is shared by many and thus attenuated. This multi-leader hierarchy was not allowed in Mark’s analysis, and thus makes our work not only quantitatively different from Mark’s in modeling the same phenomenon of cooperation under “apparent” structures, but also qualitatively different in incorporating more, “unapparent” hierarchical structures into the investigation. For theory, we hold that this advance well increases the realism of our model compared to Mark’s, as organizational leadership is often shared than monopolized in the wild. Even if it is held by only one person in some cases—say, of presidential power—the process of forming such clear consensus is commonly costly and, indeed, painful. Just think about how a politician funnels through the countless public debates and votes to survive their party nomination to first become the candidate, and then more debates and votes to finally win the one presidential seat. All these hurdles exist exactly because there can only be one president. Ignoring the costs resulting from this kind of challenge in the leader selection processes, especially in single-leader structures such as those in Mark’s model, consequently, seriously compromises the applicability of the model. Putting the hidden costs back in sight as in our model, on the other hand, serves as a significant step closer to formal modeling the negotiation of leadership in groups and—in the present paper—its influences on cooperation among group members. Finally and importantly, we demonstrate that cooperation can emerge from multi-leader models as well, even if the leader’s authority is divided among multiple individuals, just as in the real world; people regularly if not always work with one another for the common good, under the direction not merely of one, but also of many (Dust and Ziegert, 2016). The validity of our analysis is therefore bolstered by daily observations; its future generalizability is then laid out.

As for generalizability, nevertheless, we would like to point out one implication from the present work that we believe still needs future scrutiny: that cooperation under hierarchy may be more stable than predicted by Mark’s original model. On the one hand, it is encouraging to see cooperation thrive. This is what we hope for humanity and what scientifically
aligns with everyday experiences—people do cooperate from time to time in a multi-leader world. On the other hand, we are uncertain about jumping to the conclusion that cooperation may emerge more easily in a universe where leadership can be divided into groups—that is, our model—than when it cannot be—Mark’s model. The reason is we ourselves find that cooperation is more stable and stronger against defection when the hierarchy is clearer with fewer leaders at the top sharing the authority. This is tested analytically as well as numerically and is indeed in line with Mark’s theorizing. As such, following his erroneous calculation by which all structures beginning with multiple leaders ended up having exactly one leader, all multi-leader, less-cooperation-supporting hierarchies in our model would be treated as single-leader and, therefore, fully-cooperation-supporting in Mark’s model. Consequently, Mark’s original prediction should have rendered cooperation more but not less stable than are our mathematical as well as agent-based prediction, which accords among themselves. Here, we are reluctant to chase the discrepancy down the rabbit hole; it is not the aim of the current work. We are however welcome future endeavors on the general issue of the effect of attenuated leadership on cooperation, hoping our model and computer code fully publicized help with the investigation.

4.3 Limitations and future directions

Multiple directions can be considered to extend our current work. First, both our and Mark’s models have merely considered the 2-level hierarchy (with only the top and the bottom level) but clearly, social hierarchy in real life takes various other forms. Intuitively, for instance, the most hierarchical structure is the linear system, wherein the top actor outranks the second, who in turn outranks the third, and so on and so forth until the bottom position; this system can easily have more than two levels. Further, however, prevalent linear systems are in the dominance structure of social animals (Shizuka and McDonald, 2012), they still do not characterize all human status structures. For one, in many contests such as those of sports, while high-ranked contestants by definition win more in a tournament, they may still lose to low-ranked others from time to time. In ethology, researchers have also found cases (e.g., gorillas) where dominance relations in the group are non-transitive in the sense that actor A dominates B and B dominates C, but C somehow turns back to dominate A, thus forming a cycle structure in the group. Together, future work may continue to the literature by investigating the extent to which these diverse hierarchical structures ameliorate or deteriorate the evolution of group cooperation and, importantly, how the structures affect cooperation.

In terms of the mechanisms through which hierarchy may benefit cooperation, we see two lines of research that may shed light on this investigation. First, besides examining the within-group competition between status cooperators and defectors, the level of analysis can be shifted up to the group level to focus on how, for instance, the cultural contexts
embedding groups with different levels of emphasis on status egalitarianism influence cooperation within groups. Social norms are arguably one of the strongest propellants for the evolution of group cooperation ([Herrmann et al., 2008]). Combining the cultural evolution models ([Henrich et al., 2012]), future modeling efforts can, therefore, examine the effects of larger social norms on both status hierarchy and group cooperation. This line of investigation will extend our current work to the co-evolution of social hierarchy, group cooperation, and culture.

Further, one may dig deeper down into individual persons’ minds to study the psychology that associates being in a hierarchical situation at the moment with the decision to or not to act cooperatively. In the management and the organizational psychology literature, scholars have shown that, although at the moment subordinates may follow orders and cooperate with one another regardless, the motivating reasons that they follow orders still have a significant impact on whether the cooperation would persist in the future. For instance, if one contributes to their group, feeling autonomous in doing so, cooperation may be more likely to continue than it may when one feels forced ([Maner and Case, 2016]). Even if similarly willing, those who approach the decision from an exchange-orientated perspective have been further found to be motivated to contribute more easily yet, in the meanwhile, be demotivated more easily as well and “pull out” more quickly in future, than are those approach the decision of cooperation from a communal-orientated perspective ([Thompson and DeHarppor, 1998]).

Here, especially pertinent to our present research on leader hierarchy is the evidence that followers’ psychology often reflects the psychology of their leaders. For example, the exchange orientation of subordinates can be caused by the transactional leadership of their supervisors. By contrast, subordinates’ communal orientation can result from their supervisors’ transformational leadership ([Wang et al., 2005]). Together in the terminology of EVG, it is hence the case that the psychology underlying cooperation behavior influences the strength of this behavioral strategy for shielding itself from the invasion of defection and, therefore, its stability over the long run. When combined with the model proposed in the current paper, this direction for future work may then broaden the scope of leader “psychology” types in the formal modeling of cooperation in hierarchical organizations.

Finally, corresponding to the great theoretical variety of hierarchy is the large literature on the methodology of measuring hierarchicalness. While one can always try a different measure to make their model perform better, not all of the alternatives would work equally well. For instance, as does Mark’s model, our model does not take into account information about individuals differentials in the social hierarchy. This makes the first kind of hierarchicalness measure discussed in section two (i.e., social hierarchy and cooperation) becomes inapplicable. Even if other methods are logically applicable—take the measure by ([Krackhardt, 1994]) for example—while the measure shares a similar idea with the method developed by ([Mones et al., 2012]) and adopted by the present paper, only the latter but
not the former distinguishes the hierarchicalness of a structure—say, one that has one leader and \( n - 1 \) subordinates—from the hierarchicalness of the structure’s reverse form—one that has \( n - 1 \) leaders and one subordinate. In other words, Kackhardt’s method would treat the two structures as equally hierarchical, which is against Mark’s theorizing and clearly counter-intuitive, since the single-leader structure is commonly deemed more hierarchical than the single-subordinate one. In contrast, the measure by \( \text{(Mones et al., 2012)} \) works better in pinpointing this asymmetry between the two example structures, and thus is more suitable for the purpose of our work. Overall, then, future investigations would want to be mindful of both the theory and the methodology, as well as of their fit with each other. Just because our choice of the hierarchicalness measure functions well in our research does not mean it will do the same elsewhere. We encourage researchers to explore their options in the future.
Figure 8: $W(C) = W(D)$ lines in different settings of group size $n$ and assortative level $\tau$. 

34
Cooperation is a stable strategy in social dilemmas with different $\tau$.

Figure 9: Cooperation is a stable strategy in social dilemmas with different assortative level $\tau$. 
5 Appendix

5.1 Revisit of the average payoff of status cooperators and defectors

In this subsection, we revisit Mark’s original model of the average payoff of status cooperators and defectors. Here in the signaling process, if the group reaches a status hierarchy, only one individual could be on the top level. If more than one status cooperators go to the top level, this yields a failed attempt and the group starts its signaling process again. Note that in this setting, it is possible that during the first attempt there are more than one status cooperators at the top level. But since this is a failed attempt, later there could be no status hierarchy, i.e., no individuals at the top level.

Let $f_c$ be the ratio of status cooperators in a group, the formula (4a) and (4b) in Mark’s paper become:

$$W(C) = \sum_{i=0}^{n-1} \binom{n-1}{i}(f_c)^i(1-f_c)^{n-1-i}$$

$$\cdot \left[ \frac{(i+1)(\frac{1}{n})(\frac{n-1}{n})^i}{(1+1)(\frac{1}{n})(\frac{n-1}{n})^i + (\frac{n-1}{n})^{i+1}} \cdot \left( \frac{(i+1)b}{n} \right) + \frac{(n-1)^{i+1}}{(1+1)(\frac{1}{n})(\frac{n-1}{n})^i + (\frac{n-1}{n})^{i+1}} \cdot c \right],$$

and

$$W(D) = c + \sum_{i=0}^{n-1} \binom{n-1}{i}(f_c)^i(1-f_c)^{n-1-i} \cdot \left[ \frac{(i)(\frac{1}{n})(\frac{n-1}{n})^{i-1}}{(1)(\frac{1}{n})(\frac{n-1}{n})^{i-1} + (\frac{n-1}{n})^{i}} \cdot \left( \frac{ib}{n} \right) \right].$$

Figure 10 and 11 are the comparison of simulations, Mark’s formula, and our formula. We build and agent-based model for the phase of preplay signaling and payoff determination. In order to compute expected values of $W(C)$ and $W(D)$, the parameters we choose here are $b = 1$ and $c = 0.2$. Each dot is an average of 100,000 simulations. We can see using Mark’s formula (4a) and (4b), the prediction gets worse when $f_c$ is large. The discrepancy in Mark’s formula and simulations is not getting smaller as we increase the group size $n$. Note that there are still discrepancies for our predictions, but as $n$ increases, the discrepancies become smaller asymptotically.

5.2 Simulations and analytic codes

All the codes are available on the author’s GitHub account:

https://github.com/waynelee1217/status_cooperation
Figure 10: Comparison of $W(C)$ by simulating form Mark’s original model using formula (4a) (left, dashed lines) and our formula (right, solid lines).

Figure 11: Comparison of $W(D)$ by simulating form Mark’s original model using formula (4b) (left, dashed lines) and our formula (right, solid lines).
References

Bendor, J. and Swistak, P. (2001). The evolution of norms. *American Journal of Sociology, 106*(6):1493–1545.

Bergstrom, T. C. (2002). Evolution of social behavior: individual and group selection. *Journal of Economic perspectives, 16*(2):67–88.

Bolsen, T., Ferraro, P. J., and Miranda, J. J. (2014). Are voters more likely to contribute to other public goods? evidence from a large-scale randomized policy experiment. *American Journal of Political Science, 58*(1):17–30.

Bradley, R. A. and Terry, M. E. (1952). Rank analysis of incomplete block designs: I. the method of paired comparisons. *Biometrika, 39*(3/4):324–345.

Burns, J. K., Tomita, A., and Kapadia, A. S. (2014). Income inequality and schizophrenia: increased schizophrenia incidence in countries with high levels of income inequality. *International Journal of Social Psychiatry, 60*(2):185–196.

Case, C. R. and Maner, J. K. (2014). Divide and conquer: When and why leaders undermine the cohesive fabric of their group. *Journal of personality and social psychology, 107*(6):1033.

Chase, I. D. (1985). The sequential analysis of aggressive acts during hierarchy formation: an application of the ‘jigsaw puzzle’ approach. *Animal Behaviour, 33*(1):86–100.

Cheng, J. T., Tracy, J. L., Foulsham, T., Kingstone, A., and Henrich, J. (2013). Two ways to the top: Evidence that dominance and prestige are distinct yet viable avenues to social rank and influence. *Journal of personality and social psychology, 104*(1):103.

Colley, W. (2002). Colley's bias free college football ranking method.

Correll, S. J. and Ridgeway, C. L. (2006). Expectation states theory. In *Handbook of social psychology*, pages 29–51. Springer.

Darley, J. M. and Latané, B. (1968). Bystander intervention in emergencies: diffusion of responsibility. *Journal of personality and social psychology, 8*(4p1):377.

Dust, S. B. and Ziegert, J. C. (2016). Multi-leader teams in review: A contingent-configuration perspective of effectiveness. *International Journal of Management Reviews, 18*(4):518–541.

Elsen-Ziya, H. and Erhart, I. (2015). Toward postheroic leadership: A case study of gezi’s collaborating multiple leaders. *Leadership, 11*(4):471–488.
Fehr, E. and Gintis, H. (2007). Human motivation and social cooperation: Experimental and analytical foundations. *Annu. Rev. Sociol.*, 33:43–64.

Friedrich, T. L., Vessey, W. B., Schuelke, M. J., Ruark, G. A., and Mumford, M. D. (2009). A framework for understanding collective leadership: The selective utilization of leader and team expertise within networks. *The Leadership Quarterly*, 20(6):933–958.

Gould, R. V. (2002). The origins of status hierarchies: A formal theory and empirical test. *American journal of sociology*, 107(5):1143–1178.

Grossman, G. and Baldassarri, D. (2012). The impact of elections on cooperation: Evidence from a lab-in-the-field experiment in uganda. *American journal of political science*, 56(4):964–985.

Groysberg, B., Polzer, J. T., and Elfenbein, H. A. (2011). Too many cooks spoil the broth: How high-status individuals decrease group effectiveness. *Organization Science*, 22(3):722–737.

Hamman, J. R., Weber, R. A., and Woon, J. (2011). An experimental investigation of electoral delegation and the provision of public goods. *American Journal of Political Science*, 55(4):738–752.

Hechter, M. (1987). Principles of group solidarity berkeley: California u.

Hemmingway, H., Nicholson, A., Stafford, M., Roberts, R., and Marmot, M. (1997). The impact of socioeconomic status on health functioning as assessed by the sf-36 questionnaire: the whitehall ii study. *American journal of public health*, 87(9):1484–1490.

Henrich, J., Boyd, R., McElreath, R., Gurven, M., Richerson, P. J., Ensminger, J., Alvard, M., Barr, A., Barrett, C., Bolyanatz, A., et al. (2012). Culture does account for variation in game behavior. *Proceedings of the National Academy of Sciences*, 109(2):E32–E33.

Herrmann, B., Thöni, C., and Gächter, S. (2008). Antisocial punishment across societies. *Science*, 319(5868):1362–1367.

Hobson, E. A. (2019). Differences in social information are critical to understanding aggressive behavior in animal dominance hierarchies. *Current Opinion in Psychology*.

Kollock, P. (1998). Social dilemmas: The anatomy of cooperation. *Annual review of sociology*, 24(1):183–214.

Krackhardt, D. (1994). Graph theoretical dimensions of informal organizations, computational organization theory, l. *Computational Organizational Theory, K. Carley, and M. Prietula, Eds. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc*, pages 89–111.
Kuziemko, I., Buell, R. W., Reich, T., and Norton, M. I. (2014). “last-place aversion”: Evidence and redistributive implications. *The Quarterly Journal of Economics*, 129(1):105–149.

Levi Martin, J. (2009). Formation and stabilization of vertical hierarchies among adolescents: Towards a quantitative ethology of dominance among humans. *Social Psychology Quarterly*, 72(3):241–264.

Luo, R., Zhang, L., Huang, J., and Rozelle, S. (2007). Elections, fiscal reform and public goods provision in rural China. *Journal of Comparative Economics*, 35(3):583–611.

Maner, J. K. and Case, C. R. (2016). Dominance and prestige: Dual strategies for navigating social hierarchies. In *Advances in experimental social psychology*, volume 54, pages 129–180. Elsevier.

Mark, N. P. (2018). Status organizes cooperation: An evolutionary theory of status and social order. *American Journal of Sociology*, 123(6):1601–1634.

Martin, J. L. (1998). Structures of power in naturally occurring communities. *Social Networks*, 20(3):197–225.

Massey, K. (1997). Statistical models applied to the rating of sports teams. *Bluefield College*.

McConnell, C., Margalit, Y., Malhotra, N., and Levendusky, M. (2018). The economic consequences of partisanship in a polarized era. *American Journal of Political Science*, 62(1):5–18.

Mones, E., Vicsek, L., and Vicsek, T. (2012). Hierarchy measure for complex networks. *PloS one*, 7(3).

Nowak, M. A. (2006). Five rules for the evolution of cooperation. *Science*, 314(5805):1560–1563.

Olken, B. A. (2010). Direct democracy and local public goods: Evidence from a field experiment in Indonesia. *American Political Science Review*, 104(2):243–267.

Rice, N. (2006). Opportunities lost, possibilities found: Shared leadership and inclusion in an urban high school. *Journal of Disability Policy Studies*, 17(2):88–100.

Sapolsky, R. M. (2005). The influence of social hierarchy on primate health. *Science*, 308(5722):648–652.

Sauder, M., Lynn, F., and Podolny, J. M. (2012). Status: Insights from organizational sociology. *Annual Review of Sociology*, 38:267–283.
Selznick, P. (2011). Leadership in administration: A sociological interpretation. Quid Pro Books.

Shizuka, D. and McDonald, D. B. (2012). A social network perspective on measurements of dominance hierarchies. Animal Behaviour, 83(4):925–934.

Simpson, B. and Willer, R. (2015). Beyond altruism: Sociological foundations of cooperation and prosocial behavior. Annual Review of Sociology, 41:43–63.

Starmans, C., Sheskin, M., and Bloom, P. (2017). Why people prefer unequal societies. Nature Human Behaviour, 1(4):0082.

Thompson, L. and DeHarpport, T. (1998). Relationships, goal incompatibility, and communal orientation in negotiations. Basic and applied social psychology, 20(1):33–44.

Van Vugt, M. (2006). Evolutionary origins of leadership and followership. Personality and Social Psychology Review, 10(4):354–371.

Wang, H., Law, K. S., Hackett, R. D., Wang, D., and Chen, Z. X. (2005). Leader-member exchange as a mediator of the relationship between transformational leadership and followers’ performance and organizational citizenship behavior. Academy of management Journal, 48(3):420–432.

Whitmeyer, J. M. (2007). Prestige from the provision of collective goods. Social forces, 85(4):1765–1786.

Willer, R. (2009). Groups reward individual sacrifice: The status solution to the collective action problem. American Sociological Review, 74(1):23–43.

Xie, W., Ho, B., Meier, S., and Zhou, X. (2017). Rank reversal aversion inhibits redistribution across societies. Nature Human Behaviour, 1(8):1–5.