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Hsuan-Wei Lee

Institute of Sociology, Academia Sinica

Yen-Ping Chang

National Tsing Hua University

Yen-Sheng Chiang (✉ chiangys@gate.sinica.edu.tw)

Institute of Sociology, Academia Sinica

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Can status inequality organize cooperation in multi-leader systems? An evolutionary theory

Hsuan-Wei Lee¹, Yen-Ping Chang^{1,2}, and Yen-Sheng Chiang^{*1}

¹Institute of Sociology, Academia Sinica, Taiwan

²Department of Educational Psychology and Counseling, National Tsing Hua University, Taiwan

Abstract

Status hierarchies often emerge in small collective task groups. In these groups, clearly defined hierarchies facilitate and stabilize structured cooperative interactions among group members, supporting their evolutionary function in the real world. What the existing research in this field has failed to consider, however, is that cooperation matters in these hierarchies with clear status inequality, as well as in other more realistic, multiple-leader groups with less clear hierarchies. Multi-leadership is ubiquitous but, by definition, flattens status inequality and may, in turn, jeopardize its capacity to sustain cooperation. Leveraging the relationship between multi-leadership and cooperation, our evolutionary game model reveals that hierarchies, in general, promote cooperation in groups with multiple leaders, but these hierarchies only do that up to a point, after which multi-leadership backfires. Accordingly, the model provides not only a theoretical account for how multi-leadership coexists with cooperation but also the conditions under which the coexistence would break.

1 Introduction

Interpersonal cooperation and domination are two prominent characteristics of human societies. On the one hand, in both natural and social sciences, understanding how cooperation emerges has become an important topic that draws attention from multiple disciplines, including biology¹, economics², psychology³, and sociology⁴, among others. A plethora of mechanisms has been proposed to explain how cooperation can be favored over free riding in collective action problems¹. These mechanisms have been formulated and tested using different methods, ranging from evolutionary modeling⁵ to laboratory and field experiments⁶.

^{*}Corresponding author. Email: chiangys@gate.sinica.edu.tw

On the other hand, social hierarchy is equally important for understanding how social interaction is organized and how economic resources are distributed in social groups. This status inequality is not only ubiquitous in human societies, but also prevalent in societies of many species of social animals^{7–9}. Biologists argue that having leaders and social hierarchy could increase the fitness of a group or its chances of survival, by facilitating the allocation of resources, resistance against enemies, regulation of reproduction, and division of labor. Dominance hierarchies and collective behaviors are widely found in ants¹⁰, elephants¹¹, baboons¹², condors¹³, and so on. However, for humans, it is also suggested that social hierarchy and status inequality are causes of social and health problems^{14,15}. Such negative consequences lead to the question: why does status inequality persist?

Against this backdrop of the mixed impacts of hierarchy for humans, at least two reasons have been proposed to address why social hierarchy persists. First, scholars argue that, even though humans are mostly fairness-minded, perfect equality is never their ultimate goal; people do desire some, if not overly steep, hierarchy¹⁶. Supporting this idea, evidence suggests that people would accept a certain degree of inequality in exchange for other types of personal benefits¹⁷. Research has also shown that, once a status hierarchy is formed, people not only tend to live with it but also sometimes strive to justify and protect the status quo¹⁸. Secondly, and most relevantly to the focus of our paper, scholars propose that social hierarchy can be more than the lesser evil, and can actually benefit people by facilitating social coordination and cooperation. For instance, evolutionary psychologists attribute the emergence of leadership and, therefore, the leader-follower status disparity among animals and humans to the social influence exerted by the disparity, especially (but not only) in context of risky situations and critical group-wide challenges, such as hunting for food and fighting with rival tribes¹⁹. In support of the argument, experimental studies have shown that people tend to behave more cooperatively with leaders than without them^{20–24}. Furthermore, research shows that cooperative actors are more likely to receive status approval and be elected to leadership positions as a reward, than non-cooperative members of the group²⁵. That is, there seems to be a mutual reinforcement and dependency between status hierarchy and cooperation. It may be because of these collective functions that social hierarchy persists in human societies.

Compared to the fruitful empirical demonstrations of the phenomenological linkage between hierarchy and cooperation, theoretical explanations for how status hierarchy facilitates the emergence of cooperation have nonetheless remained relatively untouched. Addressing the gap in the literature, here we propose a modified evolutionary game theory model¹, arguing that conditional cooperators—called status cooperators—play an important role in sustaining cooperation in groups. In line with the literature reviewed above, status cooperators engage in a pursuit of leadership, and they cooperate depending on how many of them take the leadership position; they defect if no leader is chosen. In contrast, pure defectors never pursue the leadership role, nor do they cooperate. Modeling this setting as an evolutionary game, we show that, even though defectors seem to be in an advantageous

position, as they always free-ride on the efforts of (conditional) cooperators, it is possible for these status cooperators to outperform defectors in the process of evolution, based on the influence of the cooperative leadership.

To measure different hierarchical structures, we introduce a statistical physics’ hierarchy measure²⁶ to the evolutionary game model. Our model shows that, while the cooperator-to-defector ratio helps with cooperation (as expected), it helps only up to a point and then it backfires. In other words, we identify an ironic effect: having too many cooperators in a group may in fact jeopardize the emergence of cooperation within the group. We further elaborate on the findings by investigating the effect of assortativity of the two types of players in the model. Analogous to the limited benefit of the cooperator-to-defector ratio, we find that the benefit of assortativity comes with a cost too: it helps facilitate cooperation only up to a point, after which it may reverse the effect of the cooperator-to-defector ratio and make it detrimental to the evolution of cooperation. Together, these two counter-intuitive findings imply the existence of an optimal “Goldilocks” solution in the delicate mutual relationship between social hierarchy and the emergence of cooperation. Below, we detail how we modeled the phenomenon and the associated findings.

2 Results

2.1 Hierarchical score and the cooperation probability $H_n(x)$

Given the similarity, we extended the evolutionary games (EVG) proposed by Mark²⁷ to build our model. There are four phases in one iteration of the EVG as suggested by²⁷: (i) the determination of the group—the group size is fixed to be n during the evolution process; (ii) preplay communication among group members to choose at most one leader; (iii) cooperators’ decisions about whether to contribute to the group or not; (iv) the determination of the next generation of status cooperators and defectors based on their payoffs from the current generation.

We generalized this model by allowing multi-leader hierarchies in the preplay phase (ii) and, therefore, forcing cooperators to make decisions on whether to contribute in such “unapparent” hierarchical structures, or a multi-leader game, in phase (iii). In these two phases, all the players have the opportunity to engage in the preplay signaling, and then they participate in a one-shot prisoner’s dilemma in each iteration (as in Mark’s original game). Depending on the hierarchical structure and their own status, each actor has the option of contributing a benefit of magnitude b to a common pool or of keeping a benefit of magnitude c for herself. In (iv), the population dynamics are determined by the linear replicator dynamic (as in Mark’s original game):

$$\begin{aligned}
P(C_{t+1}) &= \frac{P(C_t) \cdot W(C_t)}{P(C_t) \cdot W(C_t) + P(D_t) \cdot W(D_t)}, \\
P(D_{t+1}) &= \frac{P(D_t) \cdot W(D_t)}{P(C_t) \cdot W(C_t) + P(D_t) \cdot W(D_t)},
\end{aligned} \tag{1}$$

where $P(C_t)$ is the proportion of status cooperators at time t , $P(D_t)$ is the proportion of defectors at time t , $W(C)$ is the expected payoff to a status cooperator, and $W(D)$ is the expected payoff to a defector.

Closely following the model in²⁷, our model consisted of two levels of hierarchy to be formed through preplay communication: the leaders at the top and the followers at the bottom. In the process, every status cooperator signals the willingness to be a leader with probability $\frac{1}{n}$ and, hence, a lack of such intention with probability $\frac{n-1}{n}$. If no player ends up expressing an interest in taking the leadership role at the top level, it is assumed that neither any status cooperators nor defectors at the bottom level will contribute to the group in the next phase of the game. Here,²⁷ posits that status cooperators will contribute without hesitation if there is a leader chosen. If there are more leaders, the hierarchy formation will start over until a clear, i.e., no-leader or one-leader, structure shows. We however loosened this model design by incorporating the possibility that leadership is often shared by many in the real world^{28–30}. 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 retained the surfacing multi-leader structure and allowed status cooperators to still contribute, though this time, with a likelihood that represents hesitation. It is worth noting that the two extreme situations in²⁷, in which either one or no leader is established, were taken into account in our model as two special cases out of all permitted hierarchical structures. Our modification, therefore, was to allow the full spectrum between these two extreme structures. Specifically, the two scenarios were the upper and the lower limit of our model, implying that all other less apparent hierarchical structures that we sought to include should sit between these two extremes of cooperation probability equal to either 0 or 1.

We assumed that multiple leaders at the top level would obscure the group’s hierarchy structure, attenuate the leaders’ authority, and would therefore be relatively ineffective in terms of motivating cooperation in the group. Importantly, this assumption has been supported in empirical studies. Members of multi-leader teams simply need more resources (e.g., time) to communicate and achieve consensus on shared goals³¹. This then increases the risk of failing to achieve consensus for which group members, especially subordinates, can work together and cooperate with one another. Furthermore, even if leaders can enclose distinct domains of leadership with4, say, different specialties, allowing them to pursue independent objectives at the same time—similar to what we modeled—encounters the possibility that they would get in each other’s way, competing for common resources

such as material and human resources³². Though organizing leaders into a larger system may help them coordinate and therefore mitigate the problem³³, 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. Consequently, we used the clarity of hierarchicalness of a group as the proxy to the likelihood that status cooperators can coordinate and then collaborate: the more clearly hierarchical a group, the more its cooperative members will cooperate.

We adopted the measure of hierarchicalness developed by²⁶; however, since this measure is defined for any arbitrary complete network, we restricted it 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:

$$GRC(G) = \frac{1}{n-1} \sum_{i \in V} [c_R^{max} - c_R(i)], \quad (2)$$

where c_R^{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 of the case with only one leader at the top level, therefore, represents the (apparent) hierarchy with the highest possible hierarchical score.

To keep generalizing the GRC to two-level groups of nodes, we considered that the players above, however many, have control over others at the bottom and, therefore, each one at the top has an out-edge toward every other one at the bottom. We then defined the hierarchicalness $H_n(x)$ of this kind of two-level cooperation structure with group size n and x players at the top level using the GRC of network G . That is,

$$H_n(x) = \begin{cases} \frac{(n-x) \cdot \frac{n-x}{n-1}}{n-1} = \left(\frac{n-x}{n-1}\right)^2 & \text{if } 0 < x \leq n \\ 0 & \text{if } x = 0. \end{cases} \quad (3)$$

Notice here that, when $0 < x \leq n$, eq. (3) applies eq. (2) to a two-level network with x players at the top level. In this case, $c_R^{max} = \frac{n-x}{n-1}$ because players at the top show

Figure 1: Illustration of $H_5(x)$, $x = 0, 1, \dots, 5$. Note that $H_n(x)$ always takes a value between 0 and 1. Specifically, in the two extreme cases in the figure with no player (subplot (a)) or every node at the top (subplot (f)), $H = 0$.

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, we set $H_n(0) = 0$ to represent the lack of leadership in the group. $H_n(x)$ always takes the value between 0 and 1. Figure 1 demonstrates all group structures and the corresponding H values that a group with size $n = 5$ can have. Specifically, in the two extreme cases in the figure with no player or every node at the top, $H = 0$, or, with every node being equal in status, there is zero hierarchy/hierarchicalness in the network. Notice that when $x = 1$, the H value becomes 1, the highest among all scenarios. Finally and critically, except for the special case of $x = 0$, for which we stipulate its $H = 0$, $H_n(x)$ is a decreasing function of x . This decreasing trend indicates that the more the leaders at the top level, the less apparently hierarchical the commanding system.

Given its useful mathematical properties, $H_n(x)$ is used as the proxy to the probability that a status cooperator would contribute b to the group or keep a benefit of magnitude c for herself. Given a group of size n and x players at the top level, we ascribed $H_n(x)$ to be the probability of a status cooperator contributing in any group structure emerging from the prepay communication. If only one player signals their interest in higher status and, thus, rises to the top, all status cooperators will contribute, with a probability $H_n(1) = 1$. If there is no player at the top level, no status cooperators will contribute, i.e. $H_n(0) = 0$. Moreover, the cooperation process, wherein there is an arbitrary number of players in the leader role, can be delineated.

2.2 Random mixing

We first assumed the rate of meeting cooperators and defectors in a group to be random. To fully explore the model, we built an agent-based simulation (see the Methods Section) of our EVG and an analytical approximation with regard to the model (see the Methods section). In Figure 2, we compared the analytical and the simulated results 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 . The equations that based the predicted lines—equations (8) and (9)—yielded almost 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 $W(D) < W(C)$. Cooperators will thus increase in the next iteration.

Fixing a group number, say $n = 10$, the more cooperators in a group, the more likely one of them will show an interest in leading. However, the more cooperators are there, the more likely a multi-leader group will surface and reduce group contribution. If there are multiple leaders competing for the status, then it creates a send order collective action problem and the cooperative level drops. The phenomenon echoes with our above reasoning that, when there are too many cooperators competing for leadership in a group, forcing the group to choose more leaders and compromise (collaborative) members’ willingness to contribute, cooperators in effect become partial defectors, and that creates more harm than good. Even if there are few defectors in a group, cooperators may still break up the team among themselves, as can be seen in everyday experiences³⁴. This result of the current study consequently extends the previous single leader work of²⁷ and helps shed light on why everyone in this world today does not behave collectively and collaboratively and why that may in fact make societies function better.

Now we present the results of the analysis of 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 bounds within which cooperation remained stable. Specifically, the lower bound is the threshold below which the situation players, encounter is no longer a social dilemma, and the upper bound is the threshold above which defection invades status cooperation. If the cost-to-benefit ratio is smaller than $\frac{1}{n}$, b becomes too large relative to c to keep the game a dilemma: Cooperation will always outperform defection regardless of whom cooperators interact with and how the two interact. The lower bound of the ratio is $\frac{1}{n}$. For the upper bound, 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 more stable strategy against defection. Mathematically, this conceptual analysis entails first computing 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 conditions in equations (8) and (9) to find the bound-

Figure 2: Comparison of simulations and analytics for different group size n . 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.

ary of c/b . The bounds of the cost-to-benefit range, wherein status cooperation is a stable evolutionary strategy in social dilemmas, are shown in Figure 3. Note that, although there are more chances to form a hierarchical structure with multiple leaders, it is less probable that status cooperators will contribute when there are more leaders. This makes it easier for the defectors to invade the group of status cooperators. We also examined the region of c/b in larger groups, because it can be derived analytically that the upper bound will approach 0 and, thus, the region can be eliminated altogether as n goes to infinity.

Figure 3: Cooperation is a stable strategy in social dilemmas. The region between upper and lower bounds is where status cooperation is a stable evolutionary strategy in social dilemmas.

2.3 Assortative mixing

We kept generalizing our model to explore how it behaved under non-random, assortative mixing. In²⁷, 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. The bias parameter $\tau \in [0, 1]$ is used to manipulate the strength of the assortative bias in the formation of groups. The case $\tau = 0$ yields unbiased random mixing, and $\tau = 1$ yields perfect assortativity, i.e., every group member will be homogeneous. When a player meets another player in the group, τ is the proportion of pairs constrained to consist of players of the same type and the remaining $1 - \tau$ of pairs are formed under unbiased random mixing.

As before, to validate equations (10) and (11), we built an agent-based simulation of our

multi-leader model, now with the possibility of assortative mixing (see the Methods section for the code). Following the same simulation procedure, Figure 4 shows 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 τ . The results indicated that equations (10) and (11) yield nearly perfect matches with the simulations.

Figure 4: Comparison of simulations and analytics of the lines $W(C) = W(D)$ with different mixing ratio τ . A dot in the figure is an average of 100,000 simulations of a given pair of τ and f_c , and the lines are the analytical predictions of their same-color dots. We fix group size $n = 10$ here.

Now, given that our analytical equations match the agent-based simulations, we used the

equations (10) and (11) to investigate the behavior of our model. The results in Figure 4 suggest that the internal equilibrium between cooperation and defection increases as τ increases, supporting the fact that assortativity protects cooperation against defection at any given level of the cooperator-to-defector ratio. Our model further shows that the ability of assortativity to heighten this equilibrium, though still existing, decays as f_c increases. Assortativity’s contribution to the evolutionary strength of cooperation against defection wanes at high f_c ; we found that it reduces to such a great extent that the common benefit of high f_c is compromised and even reversed. For instance, as can be seen in Figure 4, when a group is fully assortative, c/b in fact decreases as f_c increases, i.e., the more the cooperators in an assortative group relative to defectors, the *less* the cooperation that will evolve against defection.

We believe the cause of this trade-off between τ and f_c can be traced back to the fact that our model allows multi-leader structures. The multi-leader hierarchy comes with a price: it attenuates group members’ willingness to contribute and makes cooperators partial defectors. As a result, when the group is large and most of its members are cooperators (i.e., f_c is large), multiple leaders will likely emerge among the cooperators, and the group can effectively be deemed as having more defectors than when there are fewer leaders. Non-randomly pairing these partial defectors with one another—assorting the group—subsequently contradicts the idea of protecting cooperators from defectors; cooperators are potentially, defectors here, since it is less probable that they will contribute. Indeed, the detrimental effect of high f_c explains why there is a backfiring effect reported above that leads to the inverted U-shape equilibrium for randomly mixed structures but no inverted U here. This is not about the eventual upward or downward change in the direction of the influence of f_c , but about the consistent risk of mitigating cooperation when it is too high, for both non-assortative and assortative groups. In summary, the present paper reports that assortativity does not merely independently add to the effect of the cooperator-to-defector ratio; the two interact. This changes the very dynamics of the evolution of cooperation in groups, where both assortativity and large numbers of cooperators can jeopardize the emergence of cooperation.

3 Discussion

With both analytical and numerical examination, we present a two-layer multiple-leadership model of the relationship between the hierarchicalness of different multiple-leader hierarchies and the level of cooperation mobilized by the leaders. The model shows that group cooperation generally goes hand-in-hand with status hierarchy. To verify this analytical result, we developed an agent-based model, ran computer simulation using the model over tens of thousands of random replications, and demonstrated that the results of the simulation matched those of our calculations. Since we have publicized the simulation code

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 extend our current findings.

Notably, our model shows it is possible that the more the individuals competing for leadership in a group, the less the stability of cooperation as 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, but also when the rising challenge of finding consensus among high-status group members; having talented investors on the team eventually backfires and reduces team profits³⁵. Anecdotally, many might also remember the surprising bumpy start of the Miami Heat in the 2010-11 NBA season, when LeBron “King” James first joined forces 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 losses. Indeed, commentators regularly attributed the Heat’s championship success in the following years to the fact that the three finally found a way to literally play at different positions in one united system, again implying that the more “independent” the leaders, the less the cooperation that may be achieved.

In the model, we assumed that the more the 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’s³⁶ research. Darley and Latané demonstrated 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. Even if presumably everyone wanted to escape the fire, when the group was large, few would emerge to lead the rest. By contrast, it was found that people could easily lead themselves and simply leave the room. Moreover, our major contribution to the literature—that cooperation is possible not only in a single—but also in a multi-leader hierarchy—was built on the premise that, the more the leaders in the group, the less the likelihood of the rest following. 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. A single leader can have multiple goals that need to be reconciled with each other, or different leaders have different have different goals and need to reconcile their differences among themselves. Either way, if the goals cannot be integrated, the resources of the organization would be divided among the goals and thereof 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, even on non-political daily economic issues, with those who follow a different political ideology³⁷. Human resources in general in the country would be arranged along party lines and, as in our model, inefficiently organized to achieve the common good for all. 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 leaders as individual persons who

may or may not hold contradictory opinions, we defined the agents as paradoxical opinions that the group has to juggle and allocate resourceful cooperation between, thus opening up the implications of the current paper for information processing and integration within groups and even within individuals' minds.

Multiple directions can be considered to extend our current work. First, our model merely considered the 2-level hierarchy 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; this system can easily have more than two levels. Further, however prevalent linear systems are in the dominance structures of social animals³⁸, they still do not characterize all human status structures. For one, in many contests, such as sporting ones, while high-ranked contestants by definition win more in a tournament, they may still lose to low-ranked contestants 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 dominates A, thus forming a cyclical structure in the group. Together, future work may contribute 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 intra-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 different levels of emphasis on status egalitarianism in groups influence cooperation within groups. Social norms are arguably among the strongest propellants for the evolution of group cooperation³⁹. Combining cultural evolution models⁴⁰, 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 cover the co-evolution of social hierarchy, group cooperation, and culture.

Further, one may dig deeper into individuals' minds to study the psychology that associates being in a hierarchical situation with the decision to act or not to act cooperatively. In the management and organizational psychology literature, scholars have shown that, although subordinates may follow orders and cooperate with one another, the motivating reasons for following orders still have a significant impact on whether cooperation persists into the future. For instance, if one contributes to their group while feeling autonomous in doing so, cooperation may be more likely to continue than when one feels compelled⁴¹. It has been found that, those who approach the decision from an exchange-orientated perspective, even if similarly willing, are motivated to contribute more easily, but, in the meanwhile, are demotivated more easily as well and "pull out" more quickly, than those who approach

the decision of cooperation from a communal perspective⁴².

Here, it is especially pertinent to our present research on leader hierarchy 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 leadership⁴³. Therefore, it is the case that the psychology underlying cooperation behavior influences the ability of this behavioral strategy to shield 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 significant body of literature on the methodology of measuring hierarchicalness. While one can always try a different measure to enhance the performance of their model, not all of the alternatives would work equally well. Our model does not consider information about individuals differentials in a social hierarchy. This makes the first kind of hierarchicalness measure discussed in section two (i.e., social hierarchy and cooperation) inapplicable. Even if other methods are logically applicable—take the measure used by Kackhardt⁴⁴ for example—while the measure shares a similar idea with the method developed by²⁶ and adopted by the present paper, only the latter 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. 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 by²⁶ 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.

4 Methods

4.1 Random mixing

Now we want to derive the formula for $W(C)$ and $W(D)$, and then analyze the corresponding changes in predicted cooperation as a result of changed expected payoffs. To illustrate 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 (4) and (5), 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 (4), the first and the second line are the expected payoff for a status cooperator meeting another cooperator and a defector, respectively. Particularly, there are three terms in the first line of equation (4); 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, and hence does 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.

$$\begin{aligned}
 W(C) = f_c \cdot & \left\{ \binom{2}{2} \left(\frac{1}{2}\right)^2 \left(\frac{2-1}{2}\right)^0 \cdot c + \binom{2}{0} \left(\frac{1}{2}\right)^0 \left(\frac{2-1}{2}\right)^2 \cdot c + \binom{2}{1} \left(\frac{1}{2}\right)^1 \left(\frac{2-1}{2}\right)^1 \cdot b \right\} \\
 & + (1 - f_c) \cdot \left\{ \binom{1}{0} \left(\frac{1}{2}\right)^0 \left(\frac{2-1}{2}\right)^1 \cdot c + \binom{1}{1} \left(\frac{1}{2}\right)^1 \left(\frac{2-1}{2}\right)^0 \cdot \frac{b}{2} \right\}
 \end{aligned} \tag{4}$$

Turning to the expected payoff for the defector, here we express it in equation (5) 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.

$$W(D) = c + f_c \cdot \left\{ \binom{1}{1} \left(\frac{1}{2}\right)^1 \left(\frac{2-1}{2}\right)^0 \cdot \frac{b}{2} \right\} \tag{5}$$

Now, generalizing the equations, the hierarchicalness function $H_n(x)$ joins in to form the payoffs for a larger group size n . Notice that $x = 1$ is always a special case. Here, 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 the expected payoffs for the cooperator and the defector when $n = 3$, in equation (6) and (7), respectively.

$$\begin{aligned}
W(C) = & (1 - f_c)^2 \cdot \left(\frac{2}{3}\right) \cdot c \\
& + \binom{2}{1} f_c (1 - f_c) \cdot \left\{ \left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 (1 - H_3(2)) \right\} \cdot c \\
& + (f_c)^2 \cdot \left\{ \left(\frac{2}{3}\right)^3 + \binom{3}{2} \left(\frac{1}{3}\right)^2 \left(\frac{2}{3}\right)^2 (1 - H_3(2)) + \left(\frac{1}{3}\right)^3 \right\} \cdot c \\
& + (1 - f_c)^2 \cdot \left(\frac{1}{3}\right) \left(\frac{1}{3}\right) \cdot b \\
& + \binom{2}{1} f_c (1 - f_c) \cdot \left\{ \binom{2}{1} \left(\frac{1}{3}\right) \left(\frac{2}{3}\right) \left(\frac{2}{3}\right) \right. \\
& + \left. \binom{2}{2} \left(\frac{1}{3}\right)^2 \cdot \left[\binom{2}{1} (H_3(2))(1 - H_3(2)) \left(\frac{1}{3}\right) + \binom{2}{2} (H_3(2))^2 \left(\frac{2}{3}\right) \right] \right\} \cdot b \\
& + (f_c)^2 \cdot \left\{ \binom{3}{1} \left(\frac{1}{3}\right) \left(\frac{2}{3}\right)^2 + \binom{3}{2} \left(\frac{1}{3}\right)^2 \left(\frac{2}{3}\right)^1 \right. \\
& \cdot \left. \left[\binom{3}{1} (H_3(2))(1 - H_3(2))^2 \left(\frac{1}{3}\right) + \binom{3}{2} (H_3(2))^2 (1 - H_3(2))^1 \left(\frac{2}{3}\right) + (H_3(2))^3 \right] \right\} \cdot b
\end{aligned} \tag{6}$$

$$\begin{aligned}
W(D) = & c + 2f_c(1 - f_c) \cdot \left\{ \left(\frac{1}{3}\right) (H_3(1)) \left(\frac{1}{3}\right) \right\} \cdot b \\
& + f_c^2 \left\{ \binom{2}{1} \left(\frac{1}{3}\right) \left(\frac{2}{3}\right) \left(\frac{2}{3}\right) + \left(\frac{1}{3}\right)^2 \left[\binom{2}{1} (H_3(2))(1 - H_3(2)) \left(\frac{1}{3}\right) + (H_3(2))^2 \left(\frac{2}{3}\right) \right] \right\} \cdot b
\end{aligned} \tag{7}$$

The first three lines in equation (6) represent the situation in which a status cooperator doesn't contribute and take back its cost c , lines 4 to 8 represent the situation in which the cooperator can earn the benefit b . In each scenario, we need to consider the focal status cooperator meets two defectors (with probability $(1 - f_c)^2$), one cooperator and one defector (with probability $\binom{2}{1} f_c (1 - f_c)$), and two cooperators (with probability f_c^2). Here, we focus on explaining the last two lines, where the status cooperator meets two

cooperators as the rest is obtained following the same calculation. The status cooperator can always take back b if there is one cooperator at the top level. Assuming there are two cooperators at the top level (i.e., $x = 2$), 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. 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. Consequently, the focal player can take $\frac{k}{3}$ shares of b if there are k cooperators who end up contributing.

On the other hand, equation (7) is the expected payoff for the defector when $n = 3$. Note that, again, a defector can always take back c . They then obtain additional fractions of b if they meet one status cooperator—with probability $2f_c(1 - f_c)$ (the second term in the first line) and two cooperators—with probability f_c^2 (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. The second term in 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 in the square bracket 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 (8) and (9), 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 (8) 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 (9) indicates that the defector always keeps c with extra shares of b similarly depending on (i), (ii), and (iii).

$$\begin{aligned}
W(C) = & \sum_{i=0}^{n-1} \binom{n-1}{i} (f_c)^i (1-f_c)^{n-1-i} \cdot \left[\sum_{j=0}^{i+1} \binom{i+1}{j} \left(\frac{1}{n}\right)^j \left(\frac{n-1}{n}\right)^{i+1-j} (1-H_n(j)) \right] \cdot c \\
& + \sum_{i=0}^{n-1} \binom{n-1}{i} (f_c)^i (1-f_c)^{n-1-i} \cdot \left\{ \sum_{j=0}^{i+1} \binom{i+1}{j} \left(\frac{1}{n}\right)^j \left(\frac{n-1}{n}\right)^{i+1-j} \right. \\
& \cdot \left. \left[\sum_{k=0}^{i+1} \binom{i+1}{k} (H_n(j))^k (1-H_n(j))^{i+1-k} \left(\frac{k}{n}\right) \right] \right\} \cdot b
\end{aligned} \tag{8}$$

$$\begin{aligned}
W(D) = & c + \sum_{i=0}^{n-1} \binom{n-1}{i} (f_c)^i (1-f_c)^{n-1-i} \\
& \cdot \left\{ \sum_{j=0}^i \binom{i}{j} \left(\frac{1}{n}\right)^j \left(\frac{n-1}{n}\right)^{i-j} \cdot \left[\sum_{k=0}^i \binom{i}{k} (H_n(j))^k (1-H_n(j))^{i-k} \left(\frac{k}{n}\right) \right] \right\} \cdot b
\end{aligned} \tag{9}$$

4.2 Assortative mixing

To construct the analytical solutions in the assortative mixing model, the only change to make lay in the rate of meeting a cooperator f_c . We thus derived the expected payoffs for a status cooperator and a defector in a multi-leader model with assortative mixing in equations (10) and (11) as follows.

$$\begin{aligned}
W(C) = & \sum_{i=0}^{n-1} \left\{ \left(\frac{i+1}{n} \right) \left\{ \left(\frac{1}{i+1} \right) \binom{n-1}{i} [\tau + (1-\tau)f_c]^i [(1-\tau)(1-f_c)]^{n-i-1} \right. \right. \\
& + \left(\frac{i}{i+1} \right) f_c \binom{n-1}{i} [\tau + (1-\tau)f_c]^{i-1} [(1-\tau)(1-f_c)]^{n-i-1} \Big\} \\
& + \left(\frac{n-i-1}{n} \right) \left\{ (1-f_c) \binom{n-1}{i} [(1-\tau)f_c]^i [\tau + (1-\tau)(1-f_c)]^{n-i-2} \right\} \Big\} \\
& \cdot \left[\sum_{j=0}^{i+1} \binom{i+1}{j} \left(\frac{1}{n} \right)^j \left(\frac{n-1}{n} \right)^{i+1-j} (1 - H_n(j)) \right] \cdot c \\
& + \sum_{i=0}^{n-1} \left\{ \left(\frac{i+1}{n} \right) \left\{ \left(\frac{1}{i+1} \right) \binom{n-1}{i} [\tau + (1-\tau)f_c]^i [(1-\tau)(1-f_c)]^{n-i-1} \right. \right. \\
& + \left(\frac{i}{i+1} \right) f_c \binom{n-1}{i} [\tau + (1-\tau)f_c]^{i-1} [(1-\tau)(1-f_c)]^{n-i-1} \Big\} \\
& + \left(\frac{n-i-1}{n} \right) \left\{ (1-f_c) \binom{n-1}{i} [(1-\tau)f_c]^i [\tau + (1-\tau)(1-f_c)]^{n-i-2} \right\} \Big\} \\
& \cdot \left\{ \sum_{j=0}^{i+1} \binom{i+1}{j} \left(\frac{1}{n} \right)^j \left(\frac{n-1}{n} \right)^{i+1-j} \right. \\
& \cdot \left. \left[\sum_{k=0}^{i+1} \binom{i+1}{k} (H_n(j))^k (1 - H_n(j))^{i+1-k} \left(\frac{k}{n} \right) \right] \right\} \cdot b
\end{aligned} \tag{10}$$

$$\begin{aligned}
W(D) = & c + \sum_{i=0}^{n-1} \left\{ \left(\frac{i}{n} \right) \left\{ f_c \binom{n-1}{i} [\tau + (1-\tau)f_c]^{i-1} [(1-\tau)(1-f_c)]^{n-i-1} \right. \right. \\
& + \left(\frac{n-i}{n} \right) \left\{ \left(\frac{1}{n-i} \right) \binom{n-1}{i} [(1-\tau)f_c]^i [\tau + (1-\tau)(1-f_c)]^{n-i-1} \right. \\
& + \left(\frac{n-i-1}{n-i} \right) (1-f_c) \binom{n-1}{i} [(1-\tau)f_c]^i [\tau + (1-\tau)(1-f_c)]^{n-i-2} \Big\} \Big\} \\
& \cdot \left\{ \sum_{j=0}^i \binom{i}{j} \left(\frac{1}{n} \right)^j \left(\frac{n-1}{n} \right)^{i-j} \cdot \left[\sum_{k=0}^i \binom{i}{k} (H_n(j))^k (1 - H_n(j))^{i-k} \left(\frac{k}{n} \right) \right] \right\} \cdot b
\end{aligned} \tag{11}$$

Equations (10) and (11) may look complex, yet they are merely incremental from the general random-mixing equations (8) and (9). As mentioned, only terms related to the fraction of status cooperators f_c are modified, and there are only two such terms.

In the first and the second line of the equation (8), the term

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

is substituted with

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

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 $\frac{i}{i+1}$ 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 (10) was then obtained. Importantly, when $\tau = 0$, i.e., random mixing, this equation (10) reduces to equation (8) as expected. Similarly, equation (11) was obtained by changing the terms related to f_c in equation (9). The term in first line of (9)

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

is substituted with

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

The first line of the expression shows the scenario wherein the first member of a group is a cooperator and they meet $i-1$ 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 $\frac{1}{n-i}$ 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 (11) was subsequently formed. Again, when $\tau = 0$, this equation (11) reduces to equation (9).

4.3 Simulations and analytic codes

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

https://github.com/waynelee1217/status_cooperation

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