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Why Class Formation Occurs in Humans but Not among Other Primates

A Primate Coalitions Model

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Abstract
Most human societies exhibit a distinct class structure, with an elite, middle classes, and a bottom class, whereas animals form simple dominance hierarchies in which individuals with higher fighting ability do not appear to form coalitions to "oppress" weaker individuals. Here, we extend our model of primate coalitions and find that a division into a bottom class and an upper class is inevitable whenever fitness-enhancing resources, such as food or real estate, are exploitable or tradable and the members of the bottom class cannot easily leave the group. The model predicts that the bottom class has a near flat, low payoff and always comprises at least half the society. The upper class may subdivide into one or more middle class(es), resulting in improved payoff for the topmost members (elite). The model predicts that the bottom class on its own is incapable of mounting effective counter-coalitions against the upper class, except when receiving support from dissatisfied members of the middle class(es). Such counter-coalitions can be prevented by keeping the payoff to the lowest-ranked members of the middle classes (through concessions) well above that of the bottom class. This simple model explains why classes are also absent in nomadic hunter-gatherers and predominate in (though are not limited to) societies that produce and store food. Its results also agree well with various other known features of societies with classes.

Keywords Classes · Coalitions · Within-group skew · Exploitable resources · Revolution

The societies of many nonhuman primates, including chimpanzees, are dominance-based, especially among males (Dunbar 1988; Watts 2012), as a result of opportunities to exclude rivals from access to limiting resources (food and shelter in the case of females, access to females in the case of males). Dominance hierarchies also characterized the ancestral state of hominins (Muller et al. 2017). However, the role of

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dominance eroded during human evolution, probably as a result of the strong interdependence associated with the human foraging niche, so that extant nomadic human hunter-gatherers (also called mobile foragers) form egalitarian societies in which men do not show clear dominance relations and the limited social differentiation is based on skill or reputation (Boehm 1999; Borgerhoff Mulder et al. 2009; Knauft 1991), as did extinct nomadic foragers (Kohler et al. 2017). In our previous work we modeled these changes in dominance hierarchy in human societies as an active lowering of the environmentally imposed degree of despotism—for example, through leveling coalitions by lower-ranking males (Pandit and van Schaik 2003).

Most human societies that are no longer nomadic foragers are characterized by lack of egalitarianism, especially among men, as in most other primates. This suggests that contest for monopolizable resources (Mattison et al. 2016) again affected societies, perhaps after a phase during which men in the larger societies that arose as agriculture developed initially competed more through generosity, creating achievement-based, rather than dominance-based, hierarchies (Flannery and Marcus 2012). However, these socially nonegalitarian human societies also show a class structure (Nolan and Lenski 2009). A class is a collection of individuals with defined membership and privileges in the form of status, income, or property (Nolan and Lenski 2009), thus creating discontinuities in payoff or status between its members and those outside the class. The question addressed in this paper is why such class structures arose uniquely in humans, even though dominance hierarchies with varying degree of skew are ubiquitous in many primate species and the ancestral state in hominins.

It is not obvious why a dominance-based society should turn into one based on classes, in which an elite—essentially an alliance of powerful individuals—controls the rest of society, instead of one in which males individually exclude others from accessing resources. In 1884, Engels speculated that its origin reflected the opportunity of powerful individuals to exploit the labor of others once agriculture became more productive: “the productivity of labour develops more and more; with it, private property and exchange, differences in wealth, the possibility of utilising the labour power of others, and thereby the basis of class antagonisms” (Engels 2004 [1884]:26). Thus, he suggested that classes emerge whenever dominants can appropriate some of the labor or possessions of the other members of a society and use them to gain additional resources and thus fitness. However, Engels did not offer a theoretical explanation for why we see the emergence of classes instead of a mere hierarchy, with individuals ranked according to their power as seen in animals. Moreover, subsequent theorizing has simply taken the existence of class-based stratification for granted (Mosca 1939 [1896]; also see Roemer 1986), and although it provides an effective foundation for theorizing in political science (Acemoglu and Robinson 2008), it does not resolve the question of why classes arose in the first place.

Our goal here is to regard a class as an alliance and use this idea to extend a model of coalition formation among animals (we use “coalition” to refer to social interactions and “alliance,” to long-term relationships; a class is therefore an alliance). Specifically, we aim to show that in animal groups, dominants merely exclude subordinates from critical resources (access to which increases fitness), whereas in humans, the emergence of two or more classes is inevitable in any group in which individuals can profit from exploiting the resources produced or possessed by others, who are prevented from leaving the group.

Why Classes? A Hypothesis

The presence of classes in stable social groups is not inevitable, as shown by their absence in animals. Many species live in stable groups, implying that living in a group is adaptive and thus provides a fitness advantage to individual members relative to living alone (Alexander 1974). Nonetheless, these members have conflicts of interest over access to various limiting resources and tend to respond to them with agonistic interactions, which in many cases produce decided dominance relations based on the partners' relative fighting ability at the level of dyads, and dominance hierarchies at the level of the group (Hinde 1976; Huntingford and Turner 1987; Preuschoft and van Schaik 2000).

Males in such groups compete primarily for mating access to females, and thus paternity. In any given group, the total amount of paternity to be acquired is fixed during a given period. Males usually have decided dominance relations based on agonistic interactions, which are tightly correlated with their fighting abilities. They therefore form dominance hierarchies (Dunbar 1988). Males gain access to the sexually receptive, fertilizable females according to the "priority of access" rule (Altmann 1962), which states that the top-ranking male will be able to monopolize a particular proportion of sexually receptive, fertilizable females; the second-ranking male will be able to monopolize that same proportion among the remaining sexually receptive, fertilizable females; and so on. This principle has been empirically confirmed in various species (Alberts 2012).

The result of this competitive process is a distribution of paternities, or fitness payoffs, that is a monotonically decreasing function of dominance, closely corresponding to a geometric distribution (Pandit and van Schaik 2003) (for convenience, we will always refer to males with high rank or high dominance as males with a low indexical rank number). Variation in the steepness of the payoff curves (skew) or environmentally imposed degree of despotism, β (see Pandit and van Schaik 2003), is linked to the different degrees to which males can monopolize access to females (reflecting the number of sexually receptive females, the duration of the receptive period of each female, and female behavior). This basic description of the fitness distribution in groups of male animals in relation to dominance and thus fighting ability holds for all groups with a fixed amount of individually monopolizable resources.

In such groups, males can form coalitions (social interactions) and alliances (social relationships) in a variety of dominance-rank configurations (Chapais 1995; van Schaik et al. 2006). Coalitions are only expected when they are both feasible (i.e., the combined fighting ability of the partners exceeds that of the opponent or opponents) and profitable (i.e., each member of the alliance gains a fitness benefit from joining). This basic model provides a reasonably successful description of the actual coalitions and alliances observed in primate groups of various species, with the only major deviations depending on the need for alliances against other groups, not incorporated into the model (Bissonnette et al. 2009; van Schaik et al. 2006; Young et al. 2014).

Importantly, in none of these modeled cases do we see the formation of all-down alliances—in other words, alliances of high-ranking individuals systematically excluding lower-ranked others. Although the higher rankers could successfully form such an alliance (the feasibility criterion), they do not gain from doing so (the profitability criterion) because they cannot gain more than they already do from excluding the bottom-rankers from the resources. Consistent with these model results, there are no reports of all-down alliance formation among animals (the breeding pair in cooperative breeders might appear to be such, but the breeding male and female individually assert their positions against same-sex rivals: Clutton-Brock et al. 2006). Thus, animals do not form intraspecific "classes" based on dominance and coercion.

Although the animal models use the term "fighting ability," in humans it is best broadened to refer to *power* (Lewis 2002; von Rueden and Jaeggi 2016), because this also includes leverage: influence over others not based on physical ability alone. Thus, power may be influenced by anything from tactical prowess or access to special weapons or training in the use of "magical abilities." However, power will continue to follow the same geometric distribution. Justifications for this simplifying assumptions are discussed in detail in the model section of this paper.

This striking contrast in the formation of an upper class between animals and humans requires an explanation. Explanations based on cognitive or cultural differences may immediately come to mind, but they are unlikely because nomadic human foragers also do not exhibit class formation (Boehm 1999; Kelly 2013). Here, we explore the hypothesis, inspired by Engels (2004 [1884]), that classes emerged whenever dominants could not merely exclude subordinates from critical resources (access to which affects fitness) but also usurp some of their possessions, and thus achieve additional fitness. This exploitation becomes possible when individuals begin to produce resources themselves, such as food, through pastoralism or agriculture, or have possessions, such as arable land, buildings, and artifacts, which can be converted into fitness. We will develop this hypothesis by extending a model developed for alliance formation among primates and examine the consequences when we add the exploitation of individuals' resource production to the preexisting exclusion from resources. To formalize the terminology used in this paper, Fig. 1 shows a schematic description of the classes realized within this model. We note that the group is primarily divided into an upper and lower ("bottom") class. The upper class may be further divided into an elite and one or more middle class(es).

Some other approaches might appear to be alternatives but in fact describe the specific mechanisms through which results of our model can be realized. First, the presence of classes may reflect institutions: contracts in a group of players that determine the payoffs of social exchanges or interactions, based on negotiations that have determined these payoffs (Hurwicz 1996; Powers et al. 2016). This negotiation can take the form of voluntary coordination (Hooper et al. 2010), in which case classes

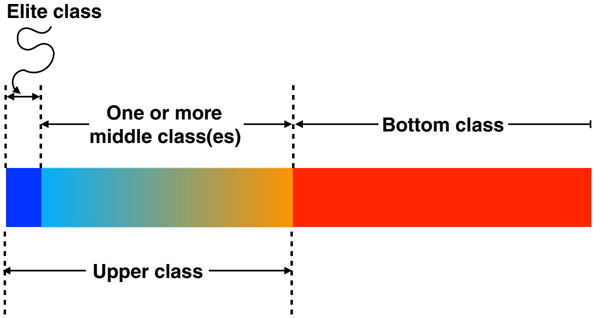

Fig. 1 Schematic representation of the terminology of classes used in this study

form based on competence. However, this will often be mixed with, or degrade into, coercion (Hooper et al. 2010), in which the "negotiation" involves communication and agreements among the elite, just not the agreement of the bottom class. Second, the relationship between the elite and the bottom class can sometimes be described as a patron-client relationship, as reported for example among some sedentary foragers (Boone 1992; Prentiss et al. 2012; Smith and Choi 2007). This structure is a perfect example of a special case of class formation: a powerful preexisting lineage allowing a subordinate lineage, with no other options, to enter the territory and share the resources, at a price.

Thus we think that all classes are alliances, explicit or implicit, that can engage in effective coalitions when needed. For instance, landowners will come together to defend collectively against land-grabbing peasants, or all slave-owners have an agreement to round up each other's runaways and return them to their owner or jointly equip search parties, etc. Classes therefore have well-defined membership with inclusion and exclusion and usually a discontinuity in expected payoff.

The Model

We assume a discrete group of finite size, containing self-interested individuals (in most cases men) who strive to maximize their payoffs, and thus their fitness. These individuals compete for access to resources, leading to dominance ranks based on power. As in our previous work, we assume that the payoff distribution among all the group members follows the priority of access (PoA) model (Altmann 1962). Our PoA model assumes that the payoff distribution as a function of dominance rank (related to fighting ability) is a geometric series, which essentially means the top ranker takes whatever he can, then the second ranker takes whatever he can out of the remaining, and so on for the rest of the individuals in the group. To keep the model simple, we assumed that each individual takes the same fraction out of the remaining resources. We called this fraction the *environmentally imposed degree of despotism* (β): $\beta \to 1$ means the group is highly despotic, whereas $\beta \to 0$ implies it is egalitarian.

Individuals can also form coalitions. However, the payoff distribution under PoA is primarily determined by the dyadic interactions. Since the timescale of equilibrating to the PoA distribution is orders of magnitude faster than that of formation and maintenance of alliances, it is a reasonable assumption that the members follow PoA, even within alliances. This assumption also implies that the individual fighting ability (also denoted by power) referred to in the model is an individual property (expressed in dyadic interactions) and not one derived from coalitionary behavior (even if the ability to form effective coalitions is an individual property).

The power of a coalition is assumed to increase monotonically with the number of participating individuals and their individual power. In order to keep the calculations simple and tractable we will assume that the power of a coalition is a simple sum of the power of the individuals in the coalition. In reality the coalitionary power can be "super-" or "sub-" additive, but this will not affect the qualitative results of the model. In these models we previously introduced the individual payoff and individual power as a geometric sequence representing the PoA:

$$x_i = \frac{X\beta(1-\beta)^{i-1}}{1-(1-\beta)^N}; s_i = \frac{S\sigma(1-\sigma)^{i-1}}{1-(1-\sigma)^N} \quad (1)$$

where N is the number of individuals in a group, i is the rank-index of an individual, x_i and s_i are the individual payoffs and power, X and S are the total amount of resources and total power (which we will set to N in this work) of the entire group, and β and σ are the environmentally imposed skews in payoff and power in the group, respectively. As a further simplification we assumed that the skews in power and payoff are sufficiently correlated to be able to consider them equal: in other words, $\sigma = \beta$ (this does not imply $s_i = x_i$, but they will be correlated).

In Pandit and van Schaik (2003) and van Schaik et al. (2004, 2006) we have examined various configurations of viable coalitions in nonhuman primate groups. However, we never addressed the viability of all-down coalitions because they are always feasible but never seem to be profitable in primates. To make them not just feasible but also profitable, the higher rankers would have to be able to take some part of the resource base from the rest of the group's individuals and divide it among themselves (the members of the all-down alliance). In the animal models studied so far the coalitionary aggression among males was over access to matings, which only concerns exclusion of lower-ranking males by the higher-ranking males. Thus, the higher-ranked (i.e., lower-rank-indexed) individuals in a group cannot gain access to more matings by forming all-down coalitions than is afforded by the natural β of the group.

To extend these ideas to humans we introduce a new parameter, the exploitability (or equivalently, tradability or normalized price) of the contested resources, $\mathfrak{F}$, which is 0 if the resources are not exploitable or tradable and 1 if they are fully exploitable or equivalent to the currency used by the group. Formally one can write

$$\mathfrak{F} = \begin{cases} 0 \text{ if } \chi_i \leq \chi_a \\ 1 \text{ if } \chi_i - \chi_a \geq \xi \\ \frac{\chi_i - \chi_a}{\xi} \text{ otherwise} \end{cases}$$

where χ_i is the cost of acquiring the resource in question without competing with other individuals (when it is not "owned" by someone), χ_a is the cost of appropriating the same resource through competition with another individual, and ξ is the benefit of acquiring the resource. Thus, for example, primate males competing over access to estrous females yield $\mathfrak{F} = 0$ because a higher-ranking male who exploits the mate-guarding of a lower-ranking male merely stands to lose owing to the opportunity cost of giving up his own, optimal guarding schedule and the cost of controlling the lower-ranking male's behavior (in economics terms we may say that these matings are not tradable or have zero value). Similarly, a higher-ranking individual trying to exploit the fruit-harvesting activity of a lower-ranking individual will not gain from focusing on that at the expense of getting its own fruit, unless the other has a unique, superior harvesting technique. Obviously, stored food, as found in sedentary or complex foragers (Keeley 1988) or food-producing societies, or real estate is much more easily appropriated or taxed, and therefore exploited, especially if these resources are in high demand and their supply can be controlled. Once resources become even more easily tradable and transferable, $\mathfrak{F}$ will approach 1. By definition, the currency decided by a group will have $\mathfrak{F} = 1$. Thus, all-down coalitions become potentially profitable if the resource over which individuals compete has high enough $\mathfrak{F}$.

Model Results and Predictions

Feasibility Analysis of All-Down Coalitions

The feasibility of all-down coalitions requires a "pivot point" in rank index, N_u, such that the combined power of the individuals ranked above the pivot is greater than that of the individuals ranked below it:

$$\sum_{i=1}^{N_u} s_i > \sum_{i=N_u+1}^{N} s_i \tag{2}$$

Using the PoA distribution for power (eq. 1) we compute the N_u in terms of σ:

$$N_u = \left\lceil \frac{ln\left[\frac{1}{2} + \frac{1}{2}(1-\sigma)^N\right]}{ln(1-\sigma)} \right\rceil \tag{3}$$

Thus a feasible all-down coalition of individuals from rank-numbers 1 to N_u, if profitable, forms the upper class and the individuals from $N_u + 1$ to N form the bottom class. We note that the N_u solely depends on the skew in power σ and the initial group size N. Figure 2 shows the relative size of the bottom class as a function of σ. We note that the bottom class constitutes at least half of the group and its size is a monotonically increasing function of the skew in power. Only in the limiting case of complete scramble ($\sigma = 0$) does the bottom class become exactly half the group size.

In the following, we will denote with *bottom class* the class of the lowest-ranking individuals, and *upper class* for all others. The upper class can subdivided into an elite at the top and one or more middle classes.

Profitability of All-Down Coalitions and a Two-Class Model

The formation of an upper class through an all-down alliance is viable only if it is also profitable. Its profitability depends on the extent to which the upper class can exploit the bottom class—in other words, the amount of resources it can extract ($\delta X = \mathfrak{F}\Delta X$).

The ΔX in this expression is the amount of resources appropriated from the bottom class if the resource in question is completely exploitable. The upper class can maximize ΔX by imposing two key conditions on the bottom class (because their all-down coalitions are always feasible):

1. It can set the payoff of the lowest ranker in the bottom class at a minimum sustenance level (b_0). Clearly, for this arrangement to be profitable the b_0 must

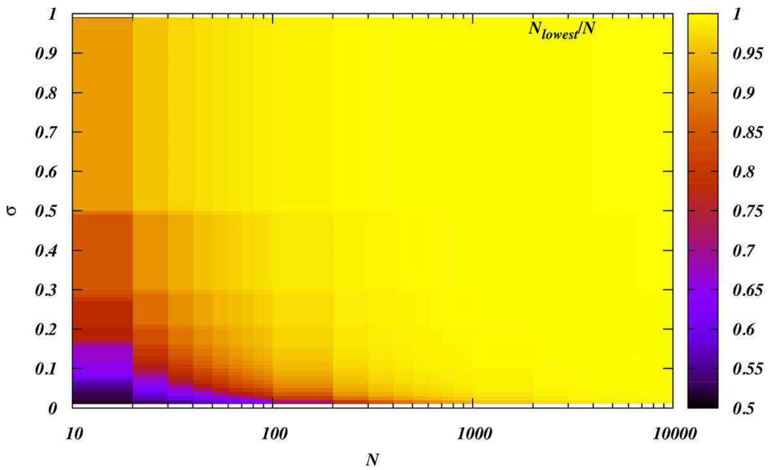

Fig. 2 The fraction of individuals in the bottom class as a function of the initial skew in power (σ), and of group size (*N*). *N* is plotted on a logarithmic scale. We note that the size of the bottom class is always greater than or equal to half of the group size. At lower σ levels, the size of the bottom class is reduced

satisfy $x_N \geq b_0 > 0$. We note that the lower the b_0, the higher the profitability of the all-down alliance.

2. It can impose absolute equality among the bottom class, thus assigning a payoff of b_0 to all the members of the bottom class (i.e., $\beta_{\text{bottom}} = 0$). In real-world applications of the model the bottom class may not have true equality, but the lower the β_{bottom}, the higher the profitability of all-down coalitions.

As a result, there should always be a discontinuity between the payoff of the lowest-ranking member of the upper class and the highest-ranking member of the bottom class, as seen in Fig. 3.

The maximum ΔX can be computed as

$$\Delta X = X\left[\frac{(1-\beta)^{N_u}-(1-\beta)^{N}}{1-(1-\beta)^{N}}\right]-b_0(N-N_u)$$

The excess acquired payoff $\mathfrak{F}\Delta X$ can be distributed among the members of the upper class in various ways:

1. The most egalitarian approach would be to distribute the $\mathfrak{F}\Delta X$ equally within the upper class. Thus, each individual in the upper class receives the payoff $\Delta x_i = \frac{\mathfrak{F}\Delta X}{N_u}$, which depends neither on the rank nor the initial β. Unless the contribution in power of the lower-ranking individuals in the upper class is crucial, the top rankers are not likely to prefer such a distribution.
2. The additional payoff $\mathfrak{F}\Delta X$ could be distributed according to the initial β (i.e., before class formation). Thus each individual receives an additional payoff of

$$\Delta x_i = \frac{\mathfrak{F}\Delta X(1-\beta)^{i-1}}{1-(1-\beta)^{N_u}}$$

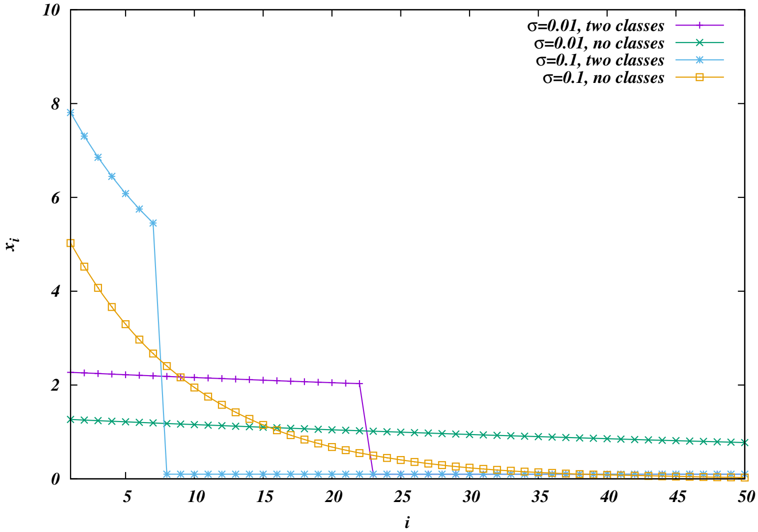

Fig. 3 Distribution of payoffs, x_i, as a function of rank in a group. Curves are for two values of the initial skew in power, $\sigma = 0.1, 0.01$, comparing the situation with two classes to that without class formation. We represent dominance rank as its index. We see a distinct discontinuity in the payoff of the upper and bottom class whenever the group has classes

Since β is correlated with σ, this approach will produce the most stable group structure with minimum conflict because it retains the status quo among the upper class. However, the top-ranking individuals in the upper class can do better.

3. The top rankers in the upper class can do better by increasing the within-class $\beta^{(1)}$. To this end, they may set the excess payoff of the lowest ranker in the upper class to b_1. The payoff distribution is determined by $\beta^{(1)}$, which satisfies the equation

$$b_1 = \frac{\mathfrak{F}\Delta X \beta^{(1)} \left(1 - \beta^{(1)}\right)^{N_u - 1}}{1 - \left(1 - \beta^{(1)}\right)^{N_u}}$$

To prevent the individual from leaving the all-down alliance, they must set b_1 such that $0 \le b_1 \le \frac{\mathfrak{F}\Delta X}{N_u}$. Figure 4 shows the numerical solution of $\beta^{(1)}$ as a function of b_1 and σ. Clearly for larger b_1, the new $\beta^{(1)}$ is smaller, but always higher than the natural β determined by σ. Figure 4 illustrates these points for a group of 1000 individuals with total resources of 1000 units. The b_0 is close to zero. Figure 5 shows the graph of $\beta^{(1)}$ vs. σ for the case where the value of b_1 is also close to zero. Clearly, the top rankers in the upper class can indeed increase their payoff by controlling the b_1. However, we note that b_1 cannot be made arbitrarily small. At $b_1 \approx 0$, the lowest rankers in the upper class may begin leaving the all-down alliance that forms the upper class and perhaps join a bottom class coalition, which can shift the balance of power described by eq. 2. This could lead to the complete collapse of the class structure within the group. Thus based on eq. 2 we conclude that the class structure is vulnerable to “revolution” when b_1 is set too low by the top-ranking members of the upper class. Note that this discussion is about distribution of excess payoff as a result of class formation, and that the basic payoff that all the top class members is still according to their natural β.

The Case of More Than Two Classes

The upper class can be further spit into an elite and a middle class or classes, resulting in further improvement in elite payoff without creating instabilities within the upper class. In groups with only two classes, the bottom class has no direct role in the decision concerning the distribution of the excess payoff among the upper-class members. Thus we introduce a hierarchical model where the upper class can be considered as its own group with its own pivot point (e.g., eq. 3). Formally, we introduce the hierarchy level as a superscript for all the model parameters used in the two-class situation. For example, in the current two-class model, the N would be denoted by $N^{(0)}$, $\beta^{(0)}=\beta$, $N_u^{(0)}=N_u$, and $\delta X^{(0)} = \mathfrak{F}\Delta X$. In the three-class model, with an elite, a middle class, and a bottom class, we choose $N^{(1)}=N_u^{(0)}$. Therefore,

$$N_u^{(1)} = \left\lceil \frac{ln\left[\frac{1}{2}+\frac{1}{2}(1-\sigma)^{N^{(1)}}\right]}{ln(1-\sigma)} \right\rceil$$

is the pivot point for the upper class alone. Thus we now have three classes, with $N_u^{(1)}$, $N_u^{(0)}-N_u^{(1)}$, and $N-N_u^{(0)}$ number of individuals. The elite can maximize their payoff by equally distributing $\Delta X^{(0)}$ among the middle class, with each middle-class member getting b_1. Note that the total payoff of the middle-class members is b_1+x_i, where x_i is from eq. 1. Hence, by splitting the group into three classes, the elite members get to disperse $\delta X^{(1)}=\delta X^{(0)} - b_1(N_u^{(0)}-N_u^{(1)})$ amount of payoff among them.

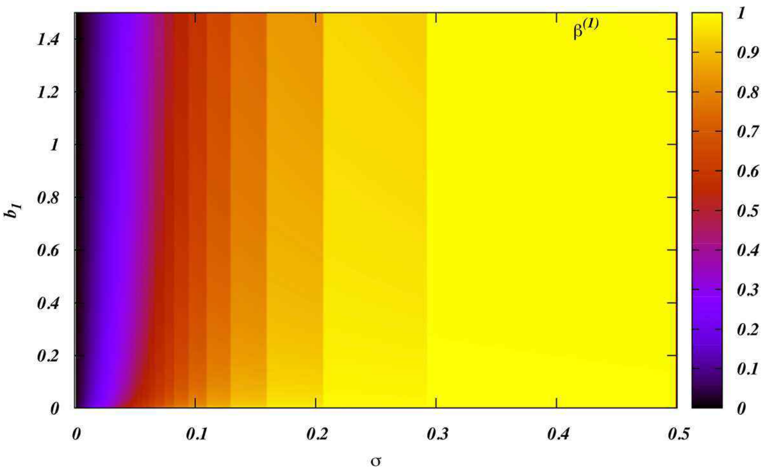

Fig. 4 The possible skew in payoffs within the upper class. The skew measure $\beta^{(1)}$ (set up by the elite to distribute the excess payoff among itself) is a function of the excess payoff to the lowest-ranked member of the upper class (b_1) and the initial skew in power (σ). We note that the $\beta^{(1)} \nrightarrow \sigma$ unless the initial $\sigma \approx 0$

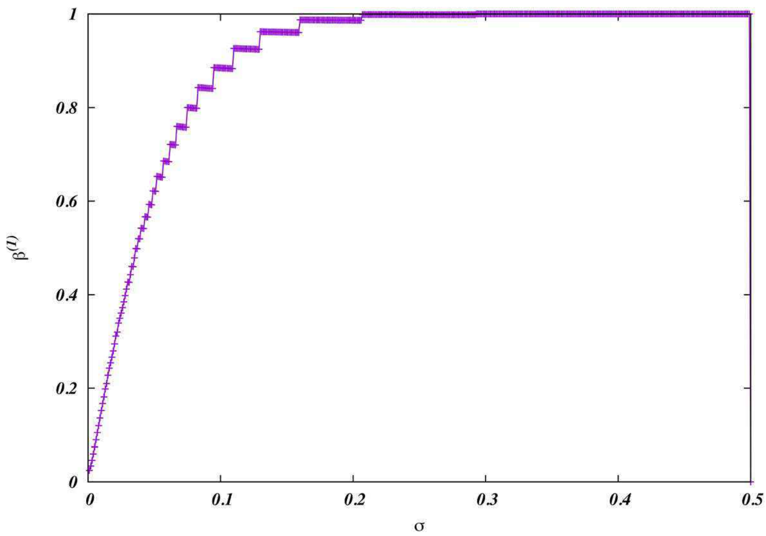

Fig. 5 Possible skew in payoff within the upper class, $\beta^{(1)}$, as a function of skew in power, σ. We note that $\beta^{(1)} \nsim \sigma$ unless the initial $\sigma \approx 0$

In principle this processes can be repeated up to a point where the uppermost class has only single individual left. So we write general expressions as

$$N^{(\alpha)} = N_u^{(\alpha-1)}; 1 \leq \alpha,$$

$$N_u^{(\alpha)} = \left\lceil \frac{ln\left[\frac{1}{2}+\frac{1}{2}(1-\sigma)^{N^{(\alpha)}}\right]}{ln(1-\sigma)} \right\rceil, \quad \text{and}$$

$$\delta X^{(\alpha)} = \delta X^{(\alpha-1)} - b_\alpha \left(N_u^{(\alpha-1)} - N_u^{(\alpha)}\right)$$

However, in practice, because of costs involved in coalition formation, the top-most class may have more than one member.

The Number of Feasible Classes

Figure 6 shows the number of feasible classes as a function of the skew in power, σ, and the original group size, $N^{(0)}$. The actual number of classes depends on various factors. It will be lower where the costs of class formation is high and the exploitability of the resource ($\mathfrak{F}$) is low. We note, however, that the number of feasible classes has a very weak dependence on group size. Thus, for the $N^{(0)}$ in the typical range of human group sizes, the number of classes only depends on σ. Intriguingly, at lower σ we expect to find more classes. Among human groups, σ may be lower when power is more or less uniformly distributed as a result of fighting weapons that do not require specific skill or training. The number of feasible classes (m) implicitly depends on the number of individuals in the upper class: fewer members in the upper class leads to a potentially smaller number of middle classes. The size of the upper class is largest for

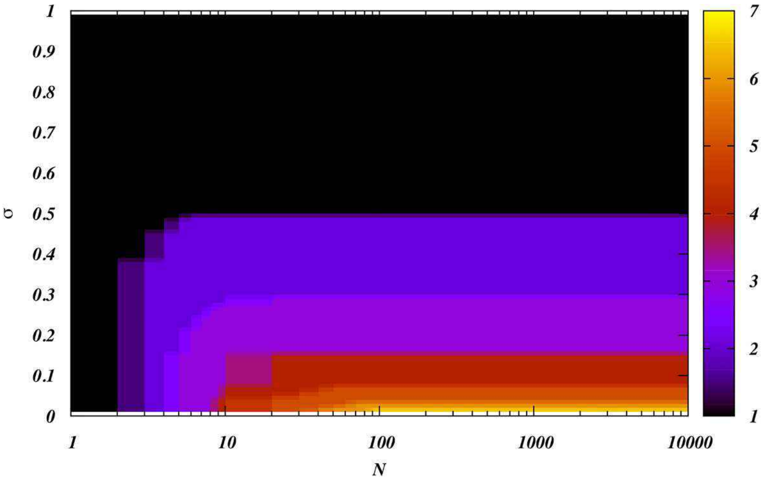

Fig. 6 The maximum number of possible classes as a function of the initial skew in power, σ, and group size, N

$\sigma \to 0$ (~ half of the group), thus potentially leading to a large number of middle classes.

We note that the profitability and stability of the hierarchy of classes critically depends on the values of the b_α; $\alpha = 0, \ldots, m$ parameters. If any of these, except for b_0, are too low (relative to the individual cost of class formation), the lower-ranking individuals from any of the middle classes may form a feasible and profitable (i.e., viable) coalition with the individuals from the bottom class to counter the class-forming all-down coalitions. Essentially, under these conditions we have a "revolution." We emphasize that such a successful coalition is possible if and only if this coalition involves members from the middle class. The bottom class alone cannot successfully establish such a coalition.

On the other hand, if the b_α; $\alpha = 0, \ldots, m$ are too high compared with the individual payoff, the elite does not find class formation significantly profitable and the group may end up with two or even no classes. The minimum payoff of the bottom class b_0 can, in principle, be reduced to arbitrarily small values. However, that may result in a reduced size of the bottom class due to starvation or escape, and consequently the net profit derived by the elite through class formation, especially if the total resources, $X^{(0)}$, depends on how many individuals are contributing to "production." Thus, the overall stability of a class structure depends on the elite choosing values for the b_α; $\alpha = 0, \ldots, m$ that prevent revolutionary coalitions.

How Can the Top Rankers Improve Their Payoff?

We define the maximum relative skew in payoff as $P = \frac{x_1 - x_N}{x_N}$, where $x_1$is the payoff of the topmost individual and x_N is the payoff of the lowest-ranking individual. The top individual always benefits from increasing P, and since class formation is always feasible, such an increase in P only depends on profitability. To keep the analysis simple, we assume that all the b_α; $\alpha = 0, \ldots, m$ values are equal. Figure 7 shows P as a function of b_α; $\alpha = 0, \ldots, m$ and the number of classes. We observe that P is highest at the lowest possible values of b_α; $\alpha = 0, \ldots, m$ and the highest possible number of classes. However, as discussed above, the excessive lowering of the various b_α; $\alpha = 0, \ldots, m$ values may destabilize the class structure, but the top-ranking individual may realistically improve P by subdividing the upper class into multiple classes. In fact, for sufficiently low values of b_α; $\alpha = 0, \ldots, m$ the top ranker can achieve a thousandfold relative skew in payoff. The analysis in Fig. 7 is performed for $\mathfrak{F} = 1$, which means these are the maximum payoffs the top rankers are able to achieve.

The second option for the top ranker is the manipulation of the $\mathfrak{F}$. Figure 8 shows the relative skew in payoff as a function of b_α; $\alpha = 0, \ldots, m$ and $\mathfrak{F}$. It shows that the top rankers can achieve high skew by making the fitness-improving resources more exploitable, for instance by making the resource "more expensive."

Options for the Bottom Class

Figures 6 and 7 suggest that the bottom class will benefit from reducing the $\mathfrak{F}$ as much as possible. We can therefore predict that there will be a conflict between the elite and the bottom class over its value. We will examine these predictions in the discussion.

On Revolutions

For the purpose of this model we will define the term "revolution" as a successful coalition that prevents viable class-forming all-down coalitions, essentially eliminating the entire class structure (at least temporarily). One of the key results of the model is that the bottom class alone can never mount an effective revolution. However, inclusion of few members from one of the middle classes makes this coalition feasible. This confirms the common notion that revolutions require the participation of at least part of the middle class. According to our model, then, it is in the interest of the majority of the upper class to monitor the sizes as well as

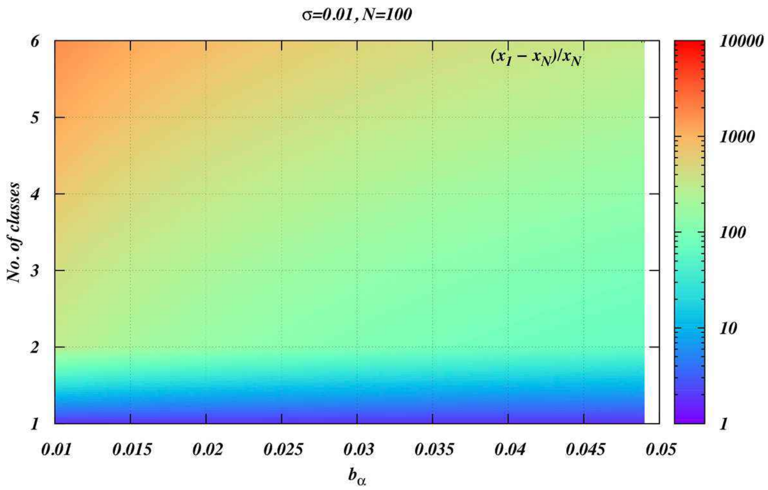

Fig. 7 The maximum skew in payoff P as a function of the number of classes, m, and the b_α; $\alpha = 0, \ldots, m-1$. The plot is generated for fixed values of $\sigma = 0.01$ and $N = 100$. It is assumed that b_α has the same value for all α. We note that the elites can increase P (where $P = \frac{x_1 - x_N}{x_N}$) by increasing the number of classes in the group

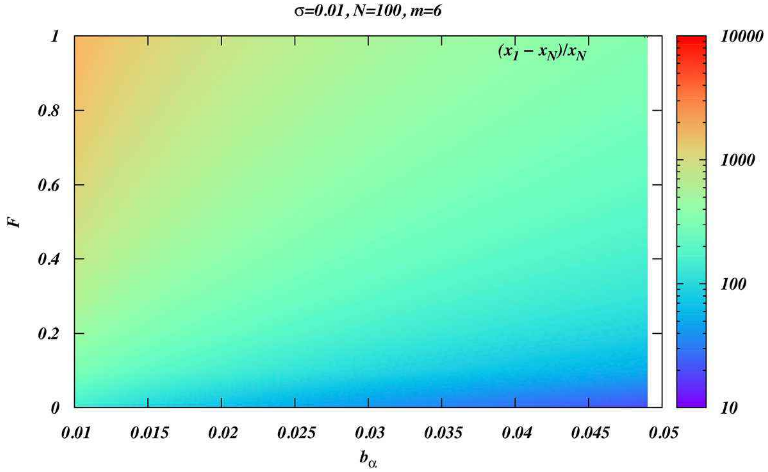

Fig. 8 The maximum skew in payoff P as a function of the exploitability of the fitness-enhancing resource, $\mathfrak{F}$, and the b_α; $\alpha = 0, \ldots, m - 1$. The plot is generated for fixed values of $\sigma = 0.01$ and $N = 100$, and with six classes ($m = 6$) where $P = \frac{x_1 - x_N}{x_N}$. It is assumed that b_α has the same value for all α. High payoff can be achieved by the elites by pushing the value of $\mathfrak{F}$ closer to one

the b_α; $\alpha = 0, \ldots, m$ values for all the middle classes. Revolutions can be prevented only by appropriately controlling the values of b_α; $\alpha = 0, \ldots, m$ such that successive classes perceive a distinct, acceptable gap in payoff from the class immediately below it.

Discussion

No animal groups are known to form classes, in which an elite exploits other same-sexed individuals in the group. Importantly, neither do mobile foragers and simple horticulturalists among humans, whereas in human societies with intensive farming, class formation became ubiquitous (Boehm 1999; Mattison et al. 2016; Nolan and Lenski 2009). We developed a model to explain this watershed in human social evolution by showing that groups of competing individuals inevitably form classes whenever some group members are not merely excluded from critical resources but can also be exploited by others who can take away some of their possessions.

The model indicates that the size of the bottom class increases as the skew in power (σ) gets higher but will always minimally contain at least 50% of the group's members. It never splits further into classes. It has a low skew in payoff, which is determined by the upper class. On its own it can also do nothing to prevent elite formation. A class structure can be recognized by the existence of a clear discontinuity in the payoffs (see Fig. 2). The upper class sets its internal skew in payoff, with the top-ranking member having an inordinately strong influence. This skew determines the payoff of their lowest-ranking member of the upper class, which must, however, remain high enough to prevent this member from joining the bottom class and engaging in a "revolution." The upper class may split up in two or more classes, with higher classes becoming ever smaller, potentially until a single despot remains at the top. In our analysis, the eventual number of classes is set most strongly by the skew in power. This analysis ignores the costs of class-splitting, and in practice the number of classes will tend to be smaller than suggested by the model.

The model indicates that the bottom class is indifferent to the structural changes within the upper class—for example, whether or not it splits into several subclasses, or how the elite internally apportions its gains. Under the model, revolutions can only happen when disaffected members of the middle class(es) join the bottom class because their payoffs have become too low to set them apart and they would be able to improve their payoff after a revolution and the subsequent renewed elite formation, which is inevitable under the model. The top members of the elite should therefore be especially concerned with preventing the lowest members of the upper class from defecting. History generally supports this notion (Collier 1999; Leventoğlu, 2014) rather than the Marxist notion of immiseration of the masses (Marx and Engels 2002 [1848]), which expects them to mount an effective revolution.

Exploitability of the resources ($\mathfrak{F}$) is a key variable. Importantly, provided classes are formed, the higher the exploitability, the higher the skew in payoffs. The intrinsic skew in payoff characterized by β does not depend on $\mathfrak{F}$. Among nomadic foragers, the fitness-improving resources have a $\mathfrak{F}$ close to zero because mates and harvested food (which is not stored) cannot be exploited by others without incurring much higher opportunity costs than are gained from the exploitation. Hence, the absence of classes among mobile foragers is due to the absence of resources that can be hoarded and thus exploited: food is consumed immediately, and not stored (Sahlins 1972). The same condition is found among simple horticulturalists: they also store little food because they tend to harvest resources (e.g., tubers) as needed (Scott 2017). The exploitability increased as foragers became sedentary and began to store massive amounts of food on a seasonal basis. Farming further increased the $\mathfrak{F}$, especially if it involves the seasonal production of storable harvests of one major crop, which can easily be taxed (Scott 2017).

The model thus provides an explanation for the fact that elites are described for sedentary foragers (Keeley 1988) and chiefdoms and states among food-producing societies (Diamond 2012; Flannery and Marcus 2012; Nolan and Lenski 2009), but not for nomadic foragers and simple horticulturalists (Boehm 1999; Kaplan et al. 2009). This distribution suggests that, historically, elites first arose less than 20,000 years ago, after the first foragers became sedentary at highly productive sites (Flannery and Marcus 2012; Nolan and Lenski 2009).

Interestingly, the lower the intrinsic payoff skew (determined by β), the more classes we expect to emerge and the steeper the actual skew in payoffs (P) in the group as a result of classes. Thus, where the intrinsic skew in fighting abilities becomes quite high (indicating high $\sigma \sim \beta$), as when the elite monopolizes both the acquisition and use of especially effective weapons, a small elite (not presenting itself as a class) can rule a large bottom class (this may have happened in the Bronze Age, for instance: Earle and Kristiansen 2010). In other situations, elites may try to increase the number of classes (m) to enhance their payoff (x_1).

Elites will also have an incentive to increase the exploitability of the bottom class, either deliberately or by selectively retaining measures that are effective. They may achieve this by favoring practices that make fitness-enhancing resources more exploitable. Perhaps the introduction of coinage, the production of which was monopolized by the elite (Cook 1958), further increased $\mathfrak{F}$ and hence supported increased skew, P.

Thus, the introduction of $\mathfrak{F}$-enhancing measures can be seen as an attempt by the elite to increase P (the payoff ratio of the topmost and the lowest group member).

The bottom class cannot prevent the subdivision in the upper class, but it can potentially make exploitation by the elite less profitable. Whenever the total amount of resource depends on production by the bottom class, they may refuse to produce the resources exploited by the elite, or they may escape altogether if emigration is possible. The combined fighting ability of the bottom class cannot overcome the fighting abilities of all the classes above it; thus such refusal to produce resources or attempts at emigration are often not successful (unless supported by some members from the upper class). Irrespective of the type of the contested resource, the bottom class may also lower the "value" (exploitability) of the contested resource by changing either the availability of the resource or the nature of resource itself—for example, instead of relying on farming products, rely more on hunted or gathered resources that have lower $\mathfrak{F}$.

An obvious feature of the model is that it focuses on men. The reason is historical. Among primates, males compete through priority of access, which produces the monotonically decreasing access to critical resources required by the model. Females also often compete through contest (Sterck et al. 1997), but the payoff curve need not be monotonically decreasing, and their alliances are far less determined by skew in power and far more by genetic relatedness, which reduces the applicability of our model. In human societies, as gains from monopolizing access to limiting resources increase, benefits increase more steeply for men because of the potential for serial monogamy or polygyny. Men historically had the same dominant role (Boehm 1999; Flannery and Marcus 2012; Lerner 1986) and often still constitute the elites into which women marry.

The model makes several simplifying assumptions that can be relaxed in future work. One assumption is that groups are isolated, and thus that relations with neighboring groups do not affect their internal dynamics. When groups must deal with other hostile groups, this may affect the relationship between the elite and the bottom class and may increase skew (e.g., Bowles and Gintis 2011) or decrease it (Pandit et al. 2016). Finally, the model, at this point, does not include genetic relatedness. While in itself this is acceptable in larger societies, it therefore also leaves out attempts by the elite, historically invariably patrilineal, to ensure that their sons achieve at least the same social position as their father (Flannery and Marcus 2012). Such inheritance of class membership will obviously make the model considerably more complex, but the model may be worth developing because class inheritance clearly threatens the stability of the arrangements and is in fact a well-known consequence of social stratification in human societies (Lerner 1986).

With all the simplifying assumptions the model is successful in predicting the emergence of elite class in food-producing and -storing human groups. At this point we will speculate and extend the applicability of the model results (at least qualitatively) to more modern societies. The nature of the source of power has changed historically, from an elite based on superior fighting ability to an increasingly prominent role of influence and leverage. This makes it possible to qualitatively connect our model to historical changes after state formation. The model's use of class fits the definition coined by Dahrendorf (1959), which he developed as a correction of Marx's class concept: a relationship of authority or control leading to the exploitation of others through coercion.

The model's elite, founded on joint coercion of the weak and comparable to the feudal systems that evolved everywhere upon the advent of agriculture, gave way to another elite: the *bourgeoisie*, which in Engels's (2004 [1884]) words are "the class of modern capitalists, owners of the means of social production and employers of wage labour." In other words, property (land, machinery, capital) eventually became the source of power, dwarfing the effect of fighting ability. The model's bottom class became Marx's *proletariat*, which Engels called "the class of modern wage labourers who, having no means of production of their own, are reduced to selling their labour power in order to live."

The model may also have other qualitative implications that may be relevant to understanding modern societies. First, many people still possess the preference found among mobile foragers for militant egalitarianism (Boehm 1999), aimed at preventing the origin of elites. There may therefore be a mismatch between the more egalitarian system most people profess to prefer and the one that inevitably arises when powerful people follow their interests and form elites that end up coercing the least powerful members, pooling them into the bottom class (Norton and Ariely 2011). A plausible outcome is revolutions, where the bottom class supports leaders who promise to overthrow the class system but then are tempted soon thereafter to follow their interests and create a new class system (Acemoglu and Robinson 2008). Second, the stability of the class system is lower than that of the egalitarian system that historically preceded it. Since individual power inevitably fluctuates over time, and as old players disappear and new ones appear, the power of the elites will fluctuate, and overthrows may therefore be expected, especially if measures are taken to make positions of power heritable (which will exacerbate the problem of class memberships not reflecting actual power).

In conclusion, our simple model indicates that for societies in which resources available to individuals can be appropriated or traded, a class structure will spontaneously emerge, especially if less-powerful individuals cannot easily emigrate. It was developed with prehistoric small-scale societies with simple agriculture in mind to explain the transition from the egalitarian social system of nomadic foragers to a society with an elite, one or more middle classes, and a bottom class. Nonetheless, it also generated various other features generally associated with modern, complex states, which suggests that a class-based social structure is a fundamental feature of societies in which resources are exploitable or tradable, with considerable historical continuity.

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