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When does reputation lie? Dynamic feedbacks between costly signals, social capital and social prominence

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Performing a dramatic act of religious devotion, creating an art exhibit, or releasing a new product are all examples of public acts that signal quality and contribute to building a reputation. Signalling theory predicts that these public displays can reliably reveal quality. However, data from ethnographic work in South India suggests that more prominent individuals gain more from reputation-building religious acts than more marginalized individuals. To understand this phenomenon, we extend signalling theory to include variation in people’s social prominence or social capital, first with an analytical model and then with an agent-based model. We consider two ways in which social prominence/capital may alter signalling: (i) it impacts observers’ priors, and (ii) it alters the signallers’ pay-offs. These two mechanisms can result in both a ‘reputational shield,’ where low quality individuals are able to ‘pass’ as high quality thanks to their greater social prominence/capital, and a ‘reputational poverty trap,’ where high quality individuals are unable to improve their standing owing to a lack of social prominence/capital. These findings bridge the signalling theory tradition prominent in behavioural ecology, anthropology and economics with the work on status hierarchies in sociology, and shed light on the complex ways in which individuals make inferences about others.

This article is part of the theme issue ‘The language of cooperation: reputation and honest signalling’.

1. Introduction

Why do scientific publications published according to the same peer-review standard receive different levels of attention depending on whether their authors have been highly cited in the past [1]? Why can one winery sell a bottle of wine for \$2000 while another winery can only sell a comparable bottle for \$2 [2]? Why is the boost in reputation that a villager enjoys after taking part in a ritual at a religious festival higher if the villager is well connected than if the villager is more isolated in the village’s social network [3]? These disparate examples share a common structure: individuals’ perceptions of another’s quality depend on his or her social prominence; that is, how well-regarded he or she is. (We use the term ‘social prominence’ as an umbrella category to refer to what has elsewhere been called status, prestige or dominance.)

Within sociology, there is a large body of literature, generally overlooked by evolutionary scientists, that focuses on how status (the most commonly used term for ‘social prominence’ in this field) and quality can become disconnected. A common example of this is referred to as the ‘Matthew Effect,’ the idea that the ‘rich get richer,’ as more prominent individuals receive more recognition for their work than do less prominent individuals, regardless of underlying quality [4]. Evidence for the cumulative advantage of status has been found in arenas as distinct as academia (e.g. [5–7]), the wine industry [2] and music [8]. Sociologists have documented many examples of inequality and ‘status dispersion’ that

seem to indicate a gap between underlying quality or merit and the reputational rewards people ultimately receive (e.g. [9,10]). Experimental work [8,11–15] has shown how such patterns can emerge particularly in situations where individuals draw on the beliefs of others. These empirical findings, and some formal models (e.g. [16–18]), suggest that the use of social prominence when attempting to evaluate quality may lead to self-reinforcing dynamics that ultimately decouple the two.

Within evolutionary anthropology, there is a long-held recognition of the many benefits of social prominence (e.g. [19–23]). There is also a growing attention to and evidence for the intergenerational transfer of wealth of all forms, and how it confers sizeable advantages to those born to parents with higher embodied, relational, and material wealth [24]. In other species, such as Japanese macaques [25] and spotted hyaenas [26], there is evidence that dominance rank can sometimes be inherited, leaving rank disconnected from strength. Similarly, within the behavioural ecological work on dominance hierarchies there is increasing recognition of the critical role that social dynamics have on ranks otherwise expected to follow from differences in intrinsic attributes [27]. The intergenerational transfer of social prominence and the benefits that accrue from it suggest again that there may be cumulative advantages to social prominence.

Despite this empirical evidence, many of the models used within the evolutionary sciences posit a straightforward relationship between the social prominence of an individual and the ‘quality’ of that individual. Depending on the context, ‘quality’ may mean attributes such as fitness, strength, cooperativeness, knowledge, or skill. For example, models of cultural transmission suggest that prestigious individuals receive deference because of the skills and knowledge that they possess [28,29]. Models of indirect reciprocity use the direct history of individuals’ actions as a proxy for reputation (e.g. [30–32]), and suggest that gossip about an individual can accurately convey that reputation (e.g. [33]). Economic and evolutionary signalling models provide a framework within which quality may be accurately assessed through the relative costliness of signals. In the canonical models [34–36], individuals’ assessments of others are tightly linked to quality, although an accumulation of theory building on this early work has shown that the relationship between signal cost, signaller quality, and receivers’ perceptions is more complex (e.g. [37–40]). This theoretical literature, however, has generally not explicitly taken into account social prominence, which the empirical evidence suggests is also implicated in this more muddled relationship between quality and reputation.

Here, then, we engage with a set of tightly linked concepts, all related to different aspects of social evaluation and social connection (cf. [41]). So far, we have introduced social prominence, which generally has to do with relative standing, and is often marked by acts of deference. To this, we now add the related concept of social capital, which has to do with social connections and the resources they provide, marked not by acts of deference, but by acts of interpersonal support [42,43]. Finally, reputation refers to the beliefs that others have about an individual’s qualities, based on the assessment of their (observed or reported) actions. Building on the evidence outlined above, we expect that social prominence and social capital may both be drawn into the process of reputation formation and

assessment. Exploring the dynamic interplay between these may help to explain the conditions under which we expect them to align or *misalign*.

To do so, we extend the canonical costly signalling model [34,36] to include the signaller’s social prominence and social capital. This model predicts that by engaging in costly signals, individuals can reveal their quality. We seek to analyse how social prominence and social capital might affect the reputations individuals get from engaging in costly signals. We consider two mechanisms by which social prominence or social capital can influence signalling: (i) they impact the observer’s evaluation of the signaller, or (ii) they directly alter the pay-offs of signalling.

In the first case (altered prior), we are suggesting that social prominence or social capital may be used as an indicator of quality by observers; if a signalling act provides an opportunity for observers to note the attention, deference, or support received by an individual, then observers may use this social information, alongside the costly signal itself, to update their assessment of the signaller’s quality (i.e. the signaller’s reputation). The idea that people often interpret social prominence or social capital as an indication of quality is well accepted in sociology (e.g. [17,18,44]), as well as in evolutionary anthropology (e.g. [29]), and social psychology [45].¹

In the second case (altered pay-off), we are suggesting that the attention or support that a signaller has may enhance the visibility of a signal or otherwise facilitate its enactment, meaning that the net benefit to more prominent signallers may be higher. Social capital is fundamentally seen as having productive potential [42,47], and sociologists have outlined the possibility that network effects may contribute to patterns of cumulative advantage [48,49], so we should have a strong expectation of this effect.²

While we think that both social prominence or social capital could operate with either mechanism, the altered prior mechanism may be more readily associated with social prominence, and the altered pay-off mechanism with social capital. We consider these two mechanisms both separately and in combination, first in an analytical model and then in a dynamic agent-based model in which signalling behaviour, social prominence/capital and social interactions coevolve. Our analytical model shows that if social prominence/capital is used as a prior for quality, then individuals with higher prominence/capital have a greater reputational gain after signalling than individuals with lower social prominence/capital. The agent-based model shows that this mechanism leads to a ‘reputational shield’ (low quality individuals able to maintain good standing thanks to initially high social prominence/capital). The analytical model also illustrates how allowing social prominence/capital to alter pay-offs introduces the possibility that high quality individuals may not be able to signal owing to their low social prominence/capital, a possibility that does not exist in the classical costly signalling model. The agent-based model shows that this mechanism leads to a ‘reputational poverty trap’ (high quality individuals who are unable to improve their standing). The ‘reputational shield’ and ‘reputational poverty trap’ can coexist if both mechanisms are present. By re-examining the sociological models of cumulative advantage in light of signalling theory, we seek to unite the signalling-based approach from behavioural ecology and economics with the sociological theory of status hierarchies.

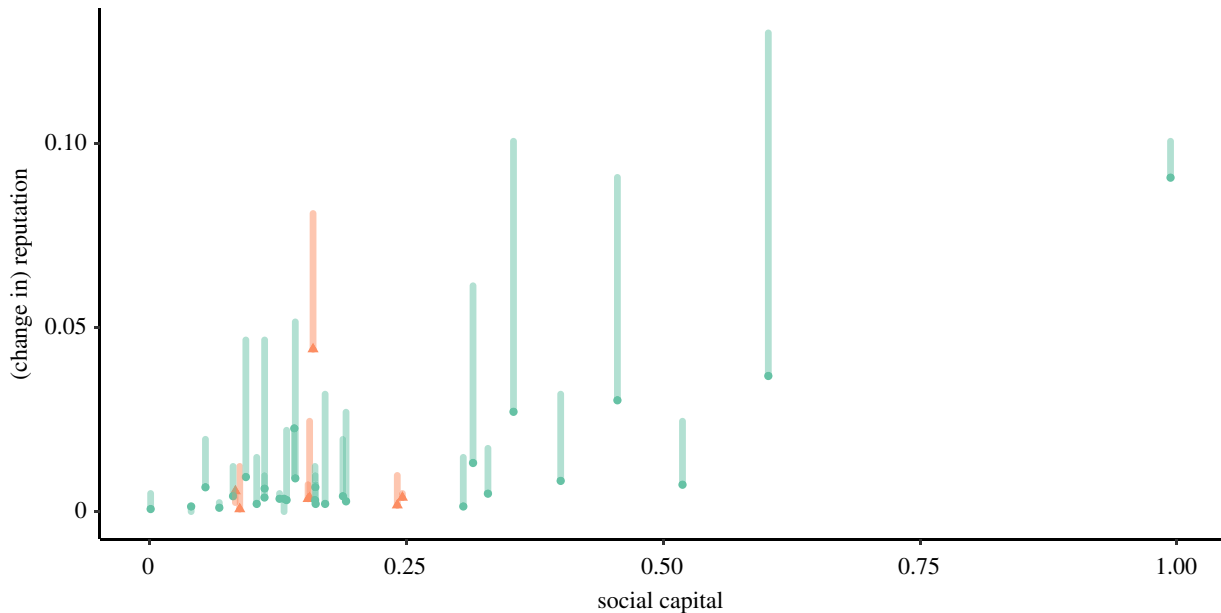


Figure 1. Reputation (as measured by the proportion of possible reputational nominations received) from before (the origin of each point) to after (the terminus of the line) the annual festival, for villagers who perform acts of vow-fulfilment, as a function of social capital (here measured by in-degree centrality in the social support network and normalized, to align with S_j). Orange triangles denote Dalit (Scheduled Caste) individuals, and green circles all others.

(a) Case study: religious signalling in South India

Throughout this paper, we draw upon the example of religious signalling in a village in South India [52,53]. At the annual festival for the village goddess, Hindu residents fulfil vows made to the goddess in gratitude for her divine assistance. These vows can range from breaking coconuts to sacrificing animals to walking across a bed of hot coals to piercing one's body with 101 spears. These acts are broadly seen as being revealing of the devotion (*bhakti*) and character (*kuṇam*) of the vow-takers, as they require not just physical endurance but also mental resolve. Those with devotion and strong commitment are understood to bear the burden of these acts more readily than others. While vow fulfilments are generally carried off without a hitch, they can 'fail,' as when a coconut fails to break when thrown or when a person trips and falls while firewalking. These failures are often interpreted as divine punishment for some fault, meaning that these acts are seen as risky, especially by those unsure of the depth of their own devotion or worthiness. Vow-takers' family and friends often accompany them as they fulfil their vows, helping them to support the weight of the spears, giving them water, or showing them respect by placing a garland on their shoulders. These acts are therefore also opportunities for observing vow-takers' social capital (as seen in the number of accompanying supporters and the density of the pile of garlands around the devotee's neck [54], pp. 162–167) and social prominence (as seen in the ordered distribution of honours (*marīyātai*) that rank devotees by their status [55]).

Drawing on signalling theory, such acts of vow fulfilment can be seen as credible demonstrations of commitment to the religious community and its moral tenets (e.g. [56–58]). Such information may be useful in determining who to form supportive relationships with. Consistent with this, residents who invest more in the religious life of the village are seen as more devout and more prosocial [52], and are more likely to be named as providing others with support [53]. These individuals thus appear to benefit through both improved

reputations and supportive relationships with others. However, while these social benefits do exist, the size of the benefit varies between individuals [3,59]. Specifically, among the vow-takers who perform particularly dramatic and demanding acts (such as firewalking) during the annual festival, those who already have higher social capital and greater pre-existing reputational standing receive relatively larger reputational boosts than those who are less well positioned (figure 1), indicating that there may exist increasing reputational returns to social capital.

Throughout this paper, we draw on the example of this signalling system to motivate and interpret the models developed here. We note, however, that we expect the phenomena we are modelling to be quite general: costly signals modified by social prominence/capital have the potential to be quite common in humans, and probably also happen in other group-living species that draw on social information.

2. Analytical model: costly signalling game with social prominence/capital

Before introducing the role of social prominence/capital, we present the basic elements of the model. We posit a game with N individuals who differ in some underlying quality $q \in \{0, 1\}$, 0 for low quality and 1 for high quality. Initially, everyone holds the same prior belief about i 's quality, denoted π_{1i} with $\pi_{1i} = 0.5$.

During a public event, each individual simultaneously has the opportunity to engage in a costly signal. Denoting a_i an individual's chosen action, we have $a_i \in \{r, \neg r\}$, where r is the action to signal and $\neg r$ the action not to signal. The cost of signalling depends on the individual's quality, where c_1 is the cost for an individual of quality $q = 1$ and c_0 is the cost for an individual of quality $q = 0$, with $c_0 > c_1$. For each player i who decides to signal, a move of nature decides the outcome $o_i \in \{s, \neg s\}$ of their signal. Namely, the signal can succeed ($o_i = s$) or fail ($o_i = \neg s$). The probability of success

depends on quality, where θ_1 and θ_0 are the probabilities of success for $q=1$ and $q=0$ individuals, respectively, with $\theta_1 > \theta_0$. The signal and its outcome are public and are observed costlessly. Thus, all players observe all the other players' decision to signal. Having observed this, they make the same inference $\hat{q}_i|a_i, o_i$ about i 's quality, conditional on the decision to signal and the signal's outcome.

Having separate terms for success/failure is not a usual feature of signalling models, but it is implicit in many signals, as when a vow-taker trips while firewalking, a big game hunter returns empty-handed, or a gazelle staggers instead of stotting properly. Some models have considered errors in signal fidelity [38], where the signal received is not exactly the same as the signal sent, but in this scenario, the probability of success is not linked to quality. Others have more explicitly considered success/failure [60], but differ in that receivers are unable to distinguish between a failed signal and no signal.

The solution concept for this static signalling game is the Bayesian Nash equilibrium. We allow for mixed strategies and denote $P(r|q=1)$ and $P(r|q=0)$ the probabilities that high and low quality individuals respectively engage in the costly signal. Applying Bayes' formula, the inferences \hat{q}_i made by all players $j \neq i$ about i 's quality after the public event are:

$$\begin{aligned} \text{individual } i \text{ signals and succeeds: } \hat{q}_i|r, s \\ = \frac{\theta_1 P(r|q=1) \pi_{1i}}{\theta_1 P(r|q=1) \pi_{1i} + \theta_0 P(r|q=0)(1 - \pi_{1i})}, \end{aligned} \quad (2.1)$$

$$\begin{aligned} \text{individual } i \text{ signals and fails: } \hat{q}_i|r, -s \\ = \frac{(1 - \theta_1) P(r|q=1) \pi_{1i}}{(1 - \theta_1) P(r|q=1) \pi_{1i} + (1 - \theta_0) P(r|q=0)(1 - \pi_{1i})} \end{aligned} \quad (2.2)$$

and

$$\begin{aligned} \text{individual } i \text{ does not signal: } \hat{q}_i|-r \\ = \frac{(1 - P(r|q=1)) \pi_{1i}}{(1 - P(r|q=1)) \pi_{1i} + (1 - P(r|q=0))(1 - \pi_{1i})}. \end{aligned} \quad (2.3)$$

The pay-off function is given by $\Pi(q_i, \hat{q}_i, a_i)$. This function satisfies the following properties: (i) signalling is less costly for quality 1 than for quality 0, which is expressed as $\Pi(1, \hat{q}_i, r) - \Pi(1, \hat{q}_i, -r) < \Pi(0, \hat{q}_i, r) - \Pi(0, \hat{q}_i, -r)$, and (ii) it is beneficial to be perceived to be of high quality, which is expressed as $\frac{d\Pi(q_i, \hat{q}_i, a_i)}{d\hat{q}_i} > 0$.

We have defined the basic elements of a static game of incomplete information, which we now alter to introduce the role of social prominence/capital via two different mechanisms. For each, we will then solve for the signalling probability for high and low quality individuals (i.e. the Bayesian Nash equilibrium strategy profiles), as a function of their social prominence/capital.

(a) Mechanism 1: altered prior

Our first intervention is to allow the prior π_{1i} to depend on S_i , our term for either social prominence or social capital. S_i is benchmarked against the individuals with the highest and lowest prominence/capital, so that it ranges from 0 to 1, with the highest value assigned to the individual with the highest prominence/capital. An individual's social prominence/capital is revealed when they signal (regardless of

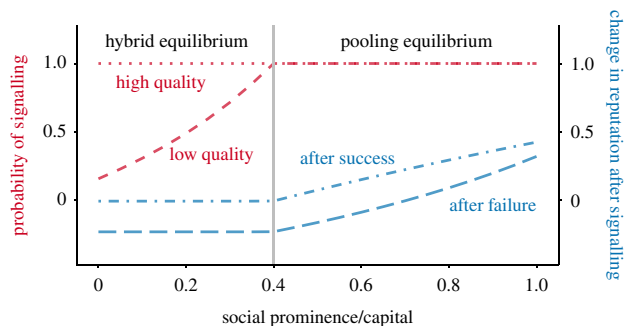


Figure 2. Altered prior mechanism. Red lines indicate the probability of signalling for each type of player (high or low quality). Blue lines show the changes in reputation after signalling, depending on whether the signal failed or succeeded. The parameters used are $c_1 = 0.2$, $c_0 = 0.4$, $\theta_1 = 0.8$, $\theta_0 = 0.6$, $\Pi = \hat{q}_i - c_i$ and $f(S_i) = 0.1 + 0.8S_i$.

the success or failure of that signal). Using this social information, observers change their prior about the quality of that individual. In other words, multiple streams of information are collected at the event: (i) observation of the signal, (ii) its success or failure, and (iii) information about the social prominence/capital for those who chose to signal. Mathematically, this means that the prior is a function of S_i , increasing as S_i increases (that is, $\pi_{1i} = f(S_i)$, with $f' > 0$). Importantly, S_i is only observed if the individual signals. Thus, it replaces π_{1i} in equations (2.1) and (2.2) above.

The strategy profiles that form a Bayesian Nash equilibrium therefore depend not only on quality (which affects the probability of success and the cost), but also on S_i . Thus, in the electronic supplementary material, §1.2, we solve for the Bayesian Nash equilibrium strategy profiles ($P^*(r|q=1, S)$, $P^*(r|q=0, S)$) with $S \in [0, 1]$, and demonstrate the different signalling regimes that can arise.

Figure 2 illustrates how the strategies vary with S_i . As S_i increases from its minimum value of 0 to its maximum of 1, the strategies change according to the following sequence:

- (i) a hybrid equilibrium where the high quality individuals all signal and the low quality individuals signal with some probability that increases with their social prominence/capital: $P(r|q=1, S) = 1$ for all S ; and $0 < P^*(r|q=0, S) < 1$ with $dP^*(r|q=0, S)/dS > 0$; and
- (ii) a pooling equilibrium in which all signal: $P^*(r|q=0, S) = P^*(r|q=1, S) = 1$ for all S .

Figure 2 also shows the change in reputation that each type of individual gains after signalling. We define this change in reputation as $\Delta\hat{q}_i = \hat{q}_i - \hat{q}_{i,t-1}$, the difference in reputation after the public signalling event compared to before the event (reputation before the event is assumed to be 0.5 for all individuals).

In the hybrid equilibrium, S_i does not affect change in reputation. Although S_i directly increases reputational gain, this effect is offset by the fact that $P^*(r|q=0, S_i)$ increases with S_i , which reduces the reputational gain. In the pooling equilibrium in which everyone signals, signalling itself is not informative. Only the success/failure of the signal and S_i are informative. As S_i increases, it becomes more and more informative relative to the outcome, so that at high S_i , both successes and failures are thought to emanate from high quality individuals with high probability.

We thus find that the gains from engaging in costly acts that are supposed to demonstrate quality can be higher for those with higher social prominence/capital. As social prominence/capital increases, it gains in importance in the public event because it becomes the main carrier of information (as it leads to a pooling equilibrium in which the act of signalling itself is no longer informative).

(b) Mechanism 2: altered pay-off

Our second intervention is to make the pay-off to the signal contingent not only on quality but also on social prominence/capital. Individuals with higher social prominence/capital may incur lower costs from signalling, for example, if they are buffered by support from others, or those with higher social prominence may accrue greater benefits, for example if information about their signalling success is broadcast more widely. To reflect this, we now consider a general pay-off function $\Pi(q_i, \hat{q}_i, S_i, a_i)$ with the property that social prominence/capital increases the pay-off from being perceived as high quality: $\partial^2 \Pi / \partial S_i \partial \hat{q}_i > 0$.

We find that at low values of S_i we have a pooling equilibrium in which no one signals. This is because the benefit of signalling is too low relative to the cost if S_i is low, even for high quality individuals (full details are presented in the electronic supplementary material, §1.3, with strategies plotted in figure SI.2b). As S_i increases, we move to a fully separating equilibrium ($P^*(r|q=0, S)=0$, $P^*(r|q=1, S)=1$). Then, as S_i increases further still, we move to a hybrid equilibrium in which high quality individuals always signal and low quality individuals signal with a probability that increases with S_i , until we reach the pooling equilibrium in which all signal and observers can only distinguish $q=1$ and $q=0$ individuals because of the different frequency of success and failure. Thus, under some threshold S_i , observers cannot distinguish high and low quality individuals (because no one signals). Above that threshold, the capacity of observers to distinguish low and high quality individuals decreases with S_i .

In the electronic supplementary material, figure SI.2c, we also present the strategies that emerge with the combination of these two mechanisms. It is similar to what we described for the altered pay-off mechanism alone. The difference is that low quality individuals are more eager to signal, and so the probability of them signalling increases faster with S_i than when the altered pay-off mechanism operates alone. This causes the pooling equilibrium in which both types signal to prevail over a larger range of S_i values. This is because the altered prior mechanism increases the pay-offs from signalling for high social prominence/capital, low quality individuals. In the agent-based model below, this will affect the reputational dynamics for these individuals relative to a scenario in which only the altered pay-off mechanism is at play.

3. Agent-based model: the coevolution of reputation and social prominence/capital

We now develop an agent-based model to explore the feedbacks between social prominence/capital and the signalling behaviours analysed above. We lay out the key elements here, with the details of the model and of the simulations in the electronic supplementary material, §2.

In this model, we combine multiple mechanisms by which individuals attempt to learn each other's quality.

First, individuals engage in pairwise interactions. Individuals 'visit' each other and in so doing make an inference about the probability that the person they visit is of high quality (e.g. they note that this person is more or less cooperative or helpful). Their observation of other's quality is noisy (see the electronic supplementary material, §2 for the exact way the inference is made).

Second, there are public events. We consider a baseline public event in which individuals observe each other's current level of social prominence/capital (i.e. S_i is revealed). Using S_i they infer quality $\hat{q}_i = f(S_i)$. This is the 'cue only' mechanism in which individuals do not have the opportunity to perform a public signal.³ This baseline represents the sociological tradition (e.g. [16,17,61]). We then move to public events in which individuals have the opportunity to engage in a costly signal, following the strategies derived in the analytical model. As above, their social prominence/capital impacts either how the acts are interpreted (altered prior mechanism) or the pay-offs they receive (altered pay-off mechanism), or both simultaneously. We model different scenarios that combine these mechanisms of learning (pairwise interactions, cue only mechanism, altered prior mechanism, and altered pay-off mechanism) in different ways.

Individuals are linked in a network defined by interaction weights (cf. [16,17,61,62]). These interaction weights determine who visits whom during the pairwise interactions, and also determine S_i . These weights are updated as the individuals learn about each other's quality through the mechanisms above. Formally, the weights evolve as $w_{ij,t} = \delta w_{ij,t-1} + \hat{q}_i$ where $w_{ij,t}$ is the weight j gives to i at time t , and δ is a discount parameter (for memory decay, or present bias). That is, the weight w_{ij} accumulates information about i 's observations of j 's quality through the pairwise interaction and the public events. In turn, the interaction weights influence who engages in pairwise interactions, as well as each individual's social prominence/capital (which we model as a function of the sum of these weights). Hence, while S_i was exogenous in the analytical model, it is now fully endogenised.

We wish to understand the role of quality versus current social prominence/capital in shaping reputation and building up social prominence/capital over time. To do so, we introduce an initial bias in the interaction weights at the start of the simulation, which is unrelated to quality (cf. [12,63]). Hence, some individuals start with a higher initial social prominence/capital level S_i . We then consider four types of individuals: (i) individuals of high quality who start with higher S_i , (ii) individuals of high quality who start with lower S_i , (iii) individuals of low quality who start with higher S_i , and (iv) individuals of low quality who start with lower S_i .

We present the results of four scenarios, all of which include learning through pairwise interaction, but include different learning mechanisms in the public event. These four scenarios are: (i) cue only mechanism (a baseline), (ii) altered prior mechanism, (iii) altered pay-off mechanism, and (iv) altered prior and pay-off combined. In the electronic supplementary material, §2.2, we consider more scenarios, including a baseline with only private learning through pairwise interactions, and a baseline with a pure signalling game that is not influenced by social prominence/capital. Figure 3 shows individual trajectories, while figure 4 shows the distribution of S_i across all rounds, for each type of individual.

In the cue only baseline model, the agent-based model produces dynamics that align with the sociological work

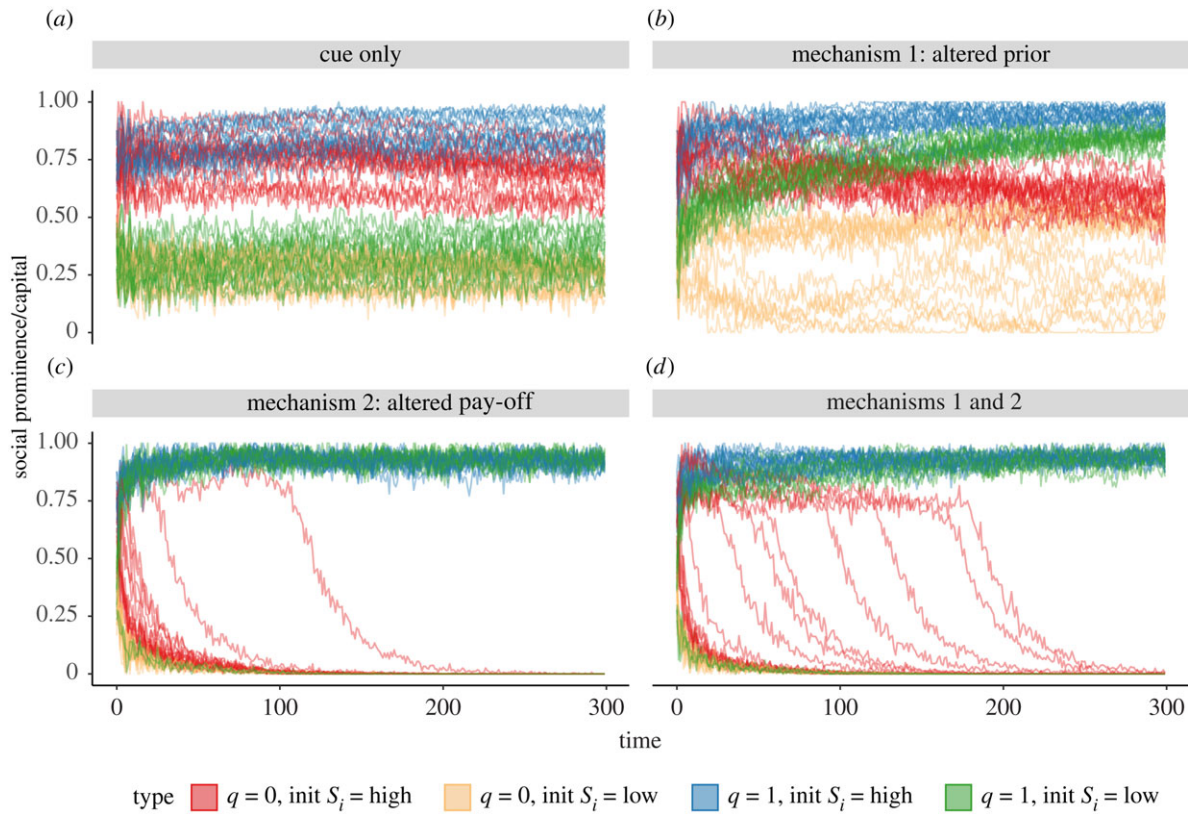


Figure 3. Representative individual time series of S_i (social prominence/capital) for individuals of different quality and initial social prominence/capital. $N = 300$, $\delta = 0.98$, $\theta_1 = 0.8$, $\theta_0 = 0.6$, $c_1 = 0.2$, $c_0 = 0.4$ and $f(S_i) = 0.1 + 0.9 S_i$. The pay-off function is $\Pi_i = \hat{q}_i - c_i$, except under the altered pay-off mechanism when it is $\Pi_i = (S_i^2 + 0.1)\hat{q}_i - c_i$.

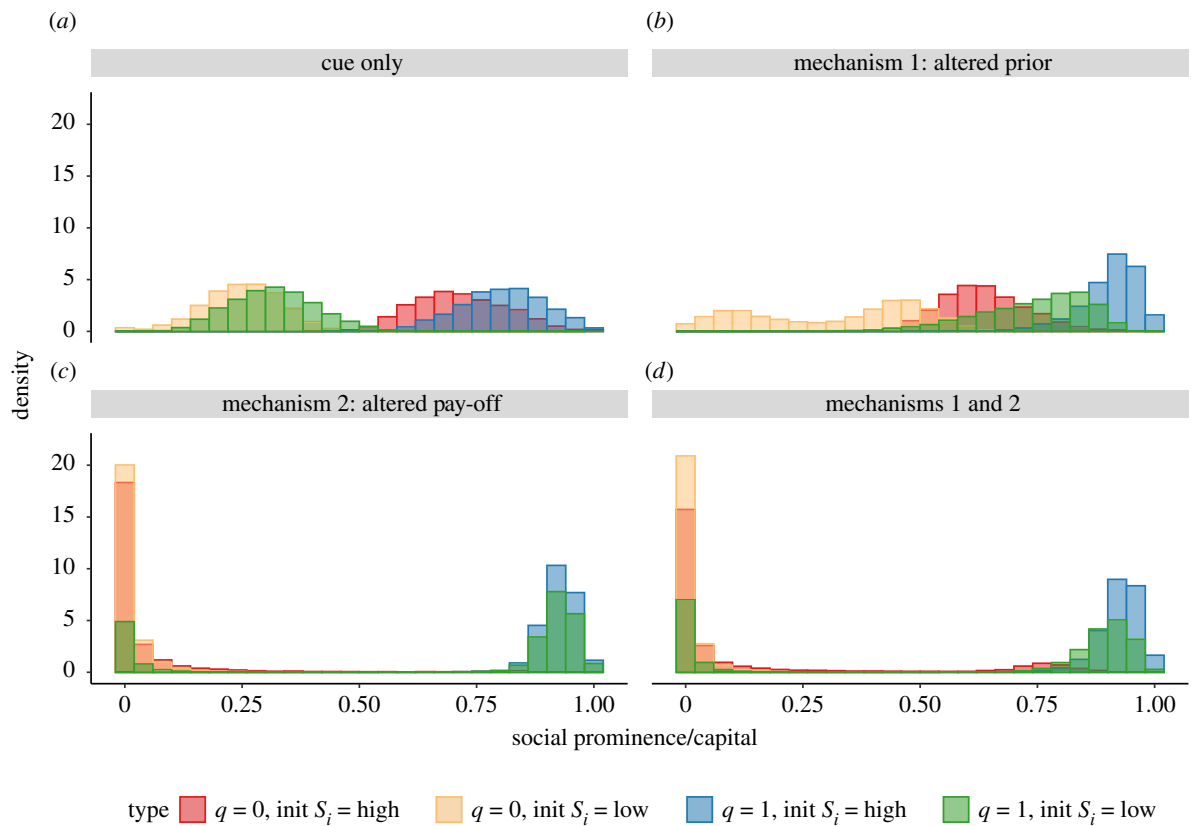


Figure 4. The distribution of S_i (social prominence/capital) in each model, as a function of the individual's quality and initial social prominence/capital. The parameters are the same as in figure 3.

on the decoupling of status and quality researched by Gould [61], Lynn *et al.* [16] and Manzo & Baldassarri [17]. As expected, initial social prominence/capital powerfully shapes reputation. Individuals with low quality but high

initial social prominence/capital are able to maintain a high level of social prominence/capital over many rounds, while individuals with high quality but low initial social prominence/capital struggle to build up their reputation (i.e.

perceived quality) and social prominence/capital (figure 3a). Gradually, the learning that occurs via the pairwise interactions leads to declining social prominence/capital for low quality individuals and increasing social prominence/capital for high quality individuals but this process takes many rounds. As a result, quality and social prominence/capital are weakly coupled (figure 4a).

The electronic supplementary material provides a few more baselines. First, the electronic supplementary material, §2.2 shows that if we have only the pairwise interactions, individuals learn about each other's quality faster. By contrast, if pairwise interactions are uninformative, social prominence/capital perfectly reproduces itself and stays fully decoupled from quality. Second, if individuals can signal but social prominence/capital plays no role in that signal (pure signalling) then types separate out quickly if the equilibrium of the signalling game is separating or hybrid (see the electronic supplementary material, figure SI.4). Pure signalling fully neutralizes the effect of an initial social prominence/capital advantage even though social prominence/capital shapes the pairwise interactions.

Having established these baselines, we consider the role of signalling under the altered prior mechanism. The model runs show that thanks to costly signals, observers gain useful information about quality (figure 3b). In particular, high quality individuals are revealed over time as such, and enjoy increasing levels of social prominence/capital, independent of their starting point. By contrast, low quality individuals tend to lose reputation and social prominence/capital over time, owing to the fact that they sometimes do not signal, and experience failures more frequently. This feeds back on pairwise interactions, which become less frequent (see the electronic supplementary material, figure SI.5).

However, the model runs illustrate that the altered prior mechanism leads to incomplete information revelation and unequal reputational gains. Low quality individuals with high initial social prominence/capital can maintain a high level of both social prominence/capital and reputation for many rounds, despite costly signalling events; we term this a 'reputational shield'.

To understand this shield, remember from the analytical model that when individuals have high social prominence/capital, both types signal and information on quality is only gleaned by the rate of success or failure of the signal. Signalling is thus mostly an opportunity to reveal and advertise one's high social prominence/capital. As a result, even though low quality individuals fail more often than high quality individuals when they undertake the risky costly signal, they are shielded by their high social prominence/capital: onlookers use social prominence/capital as a prior, which favourably colours their interpretation of the signalling act. These low quality individuals, however, do show a general decline in their reputation over time, so this shield is temporary. It is more long-lived when pairwise interactions are uninformative (or do not happen), and when memory is perfect ($\delta=1$, electronic supplementary material, figure SI.7), which allows misapprehensions to linger (see the electronic supplementary material, §§2.4.1 and 2.4.2). We note also that the fragility of the shield stems from the fact that signals can fail with differential probability (the probability of success is such that $\theta_1 > \theta_0$). The number of successes and failures, as well as the pairwise interactions, create a gradual flow of information that slowly reveals quality. If we instead set $\theta_1 = \theta_0$,

such that success and failure is now random, we find that the reputational shield is much more robust and long-lived (see the electronic supplementary material, §2.4.3).

Next, we turn to signalling with the altered pay-off mechanism, where the pay-off of signalling is contingent not just on quality, but also on social prominence/capital. Here again we find a slight 'reputational shield', but it is short-lived, at best, with low quality individuals eventually experiencing a rapid 'fall from grace' and losing the initial advantage of high social prominence/capital. This is because individuals are not shielded by their social prominence/capital if their signal fails, as they are with the altered prior mechanism, and as a result, signalling is less attractive for low types. They thus signal less often (hybrid equilibrium). Low quality individuals, then, are eventually identified as such and consequently lose social prominence/capital.

More notable is what happens for high quality individuals. The agent-based model shows that the consequence of the altered pay-off mechanism is that it leads to a 'reputational poverty trap', where high quality individuals who start with sufficiently low social prominence/standing do not engage in the public signalling event (see strategies in the electronic supplementary material, figure SI.2b). This is best seen by observing the trajectories for $q=1$, initial $S_i = \text{low}$ in figure 3c. Despite being reliably revealed as high quality in the pairwise interactions, they remain stuck in an equilibrium of low social prominence/capital and low reputation because the costs of signalling are too high, greatly limiting their ability to build themselves up. This in turn limits the number of pairwise interactions they engage in, which also prevents them from building social prominence/capital. By contrast, high quality individuals who start with high social prominence/capital reap yet greater benefits from their signalling acts: they are involved in a larger proportion of the pairwise interactions, meaning that there is substantial inequality in the number of interactions that individuals have (see the electronic supplementary material, §2.3, cf. [63,64]). Of course, we also observe a similar pattern of relative disadvantage for high quality individuals with low initial S_i in the 'cue only' condition, but it is more absolute in this scenario.

Finally, when both the altered prior and pay-off mechanisms are operating simultaneously (following the strategies shown in the electronic supplementary material, figure SI.2c) we see the continuation of the 'reputational poverty trap' and a more pronounced 'reputational shield' (because with the addition of the altered prior mechanism, we have added back the shielding effect of S_i in the interpretation of the signals). This reputational shield does not last indefinitely: eventually, as evidence from pairwise interactions and failed public signals accumulates, S_i decreases to the point where we reach the separating equilibrium. That equilibrium fully reveals quality, which is why we see this rapid 'fall from grace' (figure 3d). When memory is perfect ($\delta=1$), as well as when pairwise interactions are uninformative, the reputational shield is more protracted (see the electronic supplementary material, figures SI.4 and SI.7).

In the electronic supplementary material, §2.4, we show the robustness of our results to different assumptions.

4. Discussion

Making inferences about others on the basis of their actions is complicated. Generally, we should expect receivers of any

signal to use the information they have at their disposal to infer the attributes and intentions of signallers. This could include the signallers' past actions or, as we have explored here, their social prominence or social capital. In our models, the production of a costly signal reveals public 'social information' (i.e. information gleaned from observing others). Widely used in group-living species [65–67], social information can provide additional information that may be costly or time-consuming to acquire directly. On average, social information should be beneficial, as it can reduce uncertainty and increase the accuracy of individuals' assessments. However, our models highlight a point largely overlooked in the behavioural ecology literature (cf. [68]), although noted by the sociological literature on status: the potential for some assessments to be less accurate, not more.

Most notably, our models show how drawing on this additional information may generally be informative, but can also result in systematic bias. In particular, we show that if social prominence colours observers' interpretation of a costly signal (by altering the observer's prior about the individual's quality), then low quality individuals with high social prominence/capital enjoy a 'reputational shield' in which they 'pass' as high quality for a prolonged period. Second, we show that if social prominence/capital alters the pay-offs from signalling, then we can obtain a 'reputational poverty trap,' where high quality individuals are unable to reap the reputational benefits of their acts if they start with low social prominence/capital. Echoing other work demonstrating that signal costs may not be sufficient guarantors of signal honesty [69–72], we find, then, that reputation can lie.

Here, we have aimed to bridge the signalling models developed by economists and evolutionary scientists on the one hand and the status models developed by sociologists on the other. Sociologists' models of status formation importantly demonstrate the possibility of the decoupling of quality and status, as we too see in our 'cue only' model. However, they do not give individuals the agency to undertake costly acts to reveal their underlying quality. By situating our work within the signalling theory framework, we allow for more agency on the part of individuals, with a stronger pull towards truthful revelation and interpretation because of the strategic incentives to maximize pay-offs. Hence, a mechanism that shows such reputational misapprehensions within the signalling theory framework is likely to be robust to selection, learning, and strategic reasoning.

One way to understand the public act we model is as the simultaneous production of a costly signal (of quality) and an 'index' (of social prominence/capital) (cf. [73]). The latter provides intrinsically reliable information, as when the roar of a red deer unfakeably indicates its body size [46,74]. The public act in our models is thus a 'multicomponent' or 'multimodal' signal [75–78], which should generally improve reliability and transmissibility. But here again we show that in some cases it can lead to misapprehensions. Johnstone [76] notes this possibility, but dismisses it, as the aggregate assessment will still be improved. While this may be the case, we argue that more attention should be paid to the cases where inaccurate assessments occur, and to their effects: the structural inequalities they can foster may not be inconsequential.

The second mechanism we explore, where social prominence/capital directly affects the pay-offs of the signal, demonstrates these potential consequences. Our finding that disparities in initial endowments (here, of social prominence/

capital) relegate some individuals to sustained and largely inescapable reputational deficit is the essence of a poverty trap, shown by economists to afflict both individuals and whole economies [79,80]. Note that this simple alteration of the pay-off function not only results in this trap, but more generally increases inequality: we see a much more skewed distribution of social prominence/capital, reputation, and pairwise interactions. While signalling here may generally be reliable, the benefits of signalling fall very unevenly.

In the South Indian case, villagers differ substantially in their social capital and social prominence, and some of that variation is driven by factors beyond their control. In this context, the most obvious factors to consider are those of gender and caste, where women [41] and Dalits (figure 1) often have lower social prominence or social capital. Such starting disadvantages may be sufficient to jump-start the feedbacks that we explore here, reinforcing gender-, caste- or class-based inequality (cf. [81]). While the details will differ in other social contexts, when certain groups suffer an initial social disadvantage, this can be amplified by signals that reveal social prominence/capital even though individuals have the agency to pro-actively 'prove their worth' through costly signals. So, for example, beyond general evidence of cumulative advantage in academic citations, we also see systematic biases in citation on the basis of gender or race and ethnicity (e.g. [82,83]).

5. Conclusion: future directions

We have explored how signalling theory can be extended to include an individual's social prominence/capital in the decision to signal and in receivers' assessments. Our focus has been less on the stable set of strategies that may be employed, and more on their consequences (cf. [12,63,84]). We hope that this emphasis on the structural outcomes of individuals' strategic decisions will prompt more exploration in the evolutionary sciences.

Changing how (and how many) interactions take place could add new complexity to the dynamics studied here. As our model does not limit the number of pairwise interactions individuals can have, or allow individuals to refuse or select specific partners, those of higher social prominence/capital have more interactions. This means these individuals are more thoroughly assessed, while those of lower social prominence/capital have fewer chances to correct any misapprehensions (but see the electronic supplementary material, §2.4.1). If all individuals had a larger number of interactions, the quality of all individuals might be more readily revealed; we do not currently explore how these balance. The interactions in our model also have no value beyond the information they provide; revising them to entail an exchange or game with its own pay-off would add an important new dimension. Here, we have chosen to interpret our key term S_i as a proxy for either social capital or social prominence. While this agnosticism emphasizes the wide applicability of our model, it also conflates two distinct concepts, which is not without risk (cf. [41]). By adding more specificity to the process and nature of interactions, we may be able to establish the distinct effects of social prominence versus social capital on reputational formation and assessment.

Our model is also currently agnostic on exactly how social prominence/capital influences the pay-off of signalling. Further work should investigate the form that these costs and

benefits take. While costs are often assumed to be production costs directly entailed in the enactment of the signal, this need not be the case. They may instead be social costs imposed by receivers on ‘cheats’ [71,85], exemplified by ‘badges of status’ in sparrows [86]. One finding from the altered prior mechanism is that even failed signals may be interpreted as indicating high quality if individuals have sufficiently high social prominence/capital. This implies that such individuals would not be seen as ‘cheats,’ and so would not face these socially imposed costs; instead, the burden of such costs would fall most heavily on individuals with lower social prominence/capital, further exacerbating their disadvantage. To explore this possibility, future work should explicitly explore the consequences of modelling the costs of signalling as being receiver-dependent.

An important feature of our model is that everyone observes the public signalling events (and learns aggregate information of everyone’s assessments with the revelation of S_i). However, it is plausible that social network structure could impact who is able to observe whose signals [87]. Relatedly, we do not extensively explore how the relative weight of private versus public information—and the extent to which these distinct information sources agree or conflict with each other—may impact the updating process [88] (though see the electronic supplementary material, §§2.2 and 2.4.1). It would be fruitful to model how widely information is aggregated, how extensively acts are observed, and how receivers balance the varied and potentially conflicting inputs they receive.

Finally, future modelling work should investigate the coevolution of strategies with social structure, drawing on empirically validated models of learning in strategic interactions [89]. ‘Quality,’ too, could be seen as malleable, if, for example, it is seen as embodied or human capital itself

[42,47], and so may also coevolve with an individual’s social prominence/capital.

Ethics. The fieldwork was approved by the Stanford University Human Subjects Institutional Review Board.

Data accessibility. Code and anonymized data are available at <https://github.com/eapower/when-does-reputation-lie/>.

Competing interests. The authors declare no competing interests.

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Endnotes

¹One way to understand this is that social prominence/capital is being used as a cue of quality. We avoid using the term ‘cue’ here, however, because it has a very particular and narrow meaning in the behavioural ecology literature [46].

²We note that although the behavioural ecological literature has considered differential benefits, from early costly signalling theory to explain begging by chicks (e.g. [50]) to more recent models [51], they consider the *opposite* scenario to the one on which we focus here: that is, where the hungrier chicks beg more and receive more food, unlike the ‘rich get richer’ dynamic exemplified by the case study below.

³Here, it is reasonable to call this a ‘cue’ both in the general sociological sense, and in the behavioural ecological sense, as individuals do not have any control over the revelation of their S_i .

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