Supplementary Information for

Runaway signals

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Contents

1 Baseline model

1.1 A model of costly signaling with uncertain observation

Our baseline model is adapted from Gintis, Smith and Bowles' (2001) multi-player model of costly signaling. We consider an infinitely large group, whose members are characterized by a hidden quality q. We normalize minimal and maximal possible qualities to 0 and 1 respectively: each individual's quality is drawn in the interval $[0, 1]$, according to a continuous probability density function which characterizes the group, and takes positive values (its support is the entire interval). Members know their own quality but not that of others.

Members alternate between two roles, that of Signaler and Receiver. Play occurs in two steps. First, Signalers may pay $c_1(q)$ to send a signal. Signaling is cheaper for high quality individuals: c_1 is a strictly decreasing continuous function of member quality q, which takes positive values.

Second, Receivers may enter into alliance with any one of the other group members. Receivers derive payoff $a(q')$ from allying with a member of quality

q', and null payoff from opting not to ally with anyone. Alliance is on average beneficial, and high quality individuals are more desirable social partners: we assume $\mathbf{E}(a) > 0$, and that a is a strictly increasing continuous function of a chosen ally's underlying quality q'. Alliance with low quality individuals may or may not be detrimental (depending on the sign of $a(0)$).

Receivers may monitor signals, by paying a small positive cost ν. When they do, they observe a given Signaler's action (send or do not send) with probability p_1 ($0 < p_1 < 1$). Receivers may condition alliance on the signal by accepting an observed sender at random. (Since the population is infinite, it suffices that Signalers send with positive probability for Receivers to be able to observe a sender). Each time Signalers are chosen as ally by a Receiver, they gain positive payoff s.

A pure strategy profile for the above game specifies: (i) when in the Signaler role, whether or not to send the signal given own quality q, and (ii) when in the Receiver role, whether to accept alliance with a Signaler selected at random, reject alliance, or monitor and condition alliance on the signal. We do not consider mixed strategies (in which individuals behave probabilistically).

1.2 Honest signaling equilibrium

1.2.1 Honest signaling strategy profile

There is a trivial pooling equilibrium, where Signalers never signal, and Receivers accept an ally at random. It is always a strict Nash equilibrium, and therefore always an evolutionary stable strategy (ESS; Smith & Price, 1973), since sending the signal is strictly costly for Signalers, and since Receivers strictly benefit from allying with a member at random ($\mathbf{E}(a) > 0$).

For any critical quality $\hat{q} \in (0, 1)$, we define the "honest signaling" strategy profile HS($\hat{q}$) as the strategy profile whereby: (i) Signalers send the signal if and only if their quality is greater than $\hat{q}$, and (ii) Receivers monitor and condition alliance on the signal.

Any pure strategy equilibrium where signaling occurs with positive probability must follow this form. Indeed, note first that if Receivers do not monitor the signal, Signalers strictly lose from signaling, whatever their quality: signaling can only occur when senders positively affect their chances of being accepted, i.e. when Receivers play according to (ii). Note second that $\hat{q}$ must belong to $(0, 1)$: if it is equal to 1, then signaling occurs with null probability; and if it is equal to 0, Receivers strictly benefit from deviation to not monitoring.

The below demonstration further shows that Signalers must play according to a threshold reaction norm of this form. We show that there can be only one honest signaling equilibrium, corresponding to a specific value of $\hat{q}$, and second, that this equilibrium exists under a wide range of parameter values.

1.2.2 Characteristics of the honest signaling equilibrium

When individuals play according to HS($\hat{q}$), we note $\pi(\hat{q}) = \mathbf{P}(q > \hat{q}) \in (0, 1)$ the probability that a Signaler is of relatively high quality $q > \hat{q}$, and sends.

Proposition 1 *HS($\hat{q}$) is an ESS if and only if:*

$$\pi(\hat{q}) = \frac{s}{c_1(\hat{q})} \tag{1.1}$$

$$\nu < \mathbf{E}(a(q) \mid q > \hat{q}) - \mathbf{E}(a) \tag{1.2}$$

Proof: let us assume that individuals play according to the strategy profile HS($\hat{q}$), for a given value of $\hat{q}$. We first show that HS($\hat{q}$) defines a strict Nash equilibrium if and only if both of the above conditions are verified.

HS($\hat{q}$) is strict Nash if and only Signalers of relatively high quality $q_H > \hat{q}$, Signalers of relatively low quality $q_L < \hat{q}$, and Receivers all stand to lose from deviation. We obtain equation [1.1] by considering the case of Signalers first. A Signaler of quality q can pay $c_1(q)$ to send, in which case she will face a fraction p_1 of well-disposed Receivers in the future, who chose an ally among the fraction $p_1 \times \pi(\hat{q})$ of the population that they observe sending the signal, their chosen ally earning s. Dividing the fraction of well-disposed Receivers by the fraction of signals they chose from, we deduce that a sender on average recruits fraction $\frac{1}{\pi(\hat{q})}$ of Receivers, and obtains an expected payoff of $-c_1(q) + \frac{s}{\pi(\hat{q})}$.

Signalers who do not send earn null payoff. By comparing the above expression to 0, we deduce that Signalers of relatively high quality $q_H > \hat{q}$ stand to lose from deviation iff $c_1(q_H) > \frac{s}{\pi(\hat{q})}$, and that Signalers of relatively low quality $q_L < \hat{q}$ stand to lose from deviation iff $c_1(q_L) < \frac{s}{\pi(\hat{q})}$. Since c_1 is a strictly decreasing function of quality, these two conditions are verified for all $q_H > \hat{q} > q_L$ if and only if $c_1(\hat{q}) = \frac{s}{\pi(\hat{q})}$; re-arranging, we obtain equation [1.1]. (Note that Signalers may send or not send indifferently when their quality q is precisely equal to the threshold $\hat{q}$; since this occurs with null probability, we neglect this possibility).

We obtain equation [1.2] by considering next the case of Receivers. A Receiver pays ν to monitor the signal, and, since the population is infinite, is certain to observe at least one signal, and ally with a Signaler of relatively high quality; earning $h(\hat{q}) - \nu$ on average. If she deviates to accepting at random, she gains instead $\mathbf{E}(a) > 0$; if she deviates to rejecting, she gains null payoff. By comparing these payoffs, we deduce that Receivers can expect to lose from deviation if and only if condition [1.2] is verified.

We have proven that HS($\hat{q}$) is strict Nash if and only if conditions [1.1-1.2] are verified. Hence, under these conditions, the strategy profile is an ESS. Conversely, we show that when these conditions are not verified, HS($\hat{q}$) is not an ESS: if $\hat{q}$ is different to the critical quality determined by condition [1.1], the previous reasoning shows that the strategy profile cannot be Nash, and therefore cannot be an ESS; and if the second condition [1.2] is unverified, it can be invaded by a strategy profile in which Receivers do not monitor and accept at random. This proves the proposed equivalence.

1.2.3 Existence of an honest signaling equilibrium

When satisfied, condition [1.1] defines a unique critical quality $\hat{q}$. Condition [1.2] adds a constraint on $\hat{q}$: the critical quality must be high enough to guarantee that the net gain from allying with a sender instead of an individual at random exceeds the cost of monitoring.

Proposition 2 *When the signal is overly costly for the lowest quality Signalers, there exists a range of possible values for the cost of monitoring* $(0, \hat{\nu})$ *for which an honest signaling equilibrium can be defined. In particular, there exists an honest signaling equilibrium where the cost of monitoring is arbitrarily small if and only if:*

$$c_1(0) > s \tag{1.3}$$

Proof: when q varies in $[0, 1]$, $\pi(q)$ strictly decreases from 1, and $\frac{s}{c_1(q)}$ strictly increases from $\frac{s}{c_1(0)}$. Following the intermediate value theorem, a non-trivial critical quality $\hat{q} \in (0, 1)$ which satisfies condition [1.1] can be found if and only if condition [1.3] is verified (Figure 1 gives a graphic argument). In addition, condition [1.2] is verified if and only if the cost of monitoring is smaller than:

$$\hat{\nu} = \mathbf{E}(a(q)|q > \hat{q}) - \mathbf{E}(a).$$

$\hat{\nu}$ is positive since $\hat{q}$ is greater than the minimum quality 0. Condition [1.2] is verified whenever the cost ν of monitoring is smaller than $\hat{\nu}$.

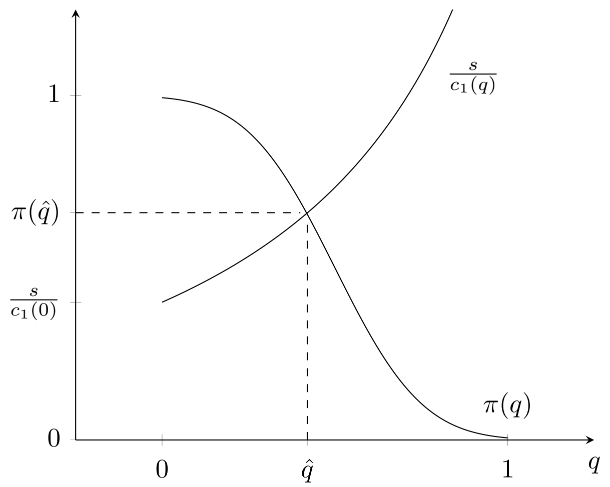


Figure 1: Graphic determination of the critical threshold $\hat{q}$

1.3 Interpretation

1.3.1 To evolve, a signal cannot be overly widespread

Following equation [1.2], signaling can only be evolutionary stable when the relative benefit of conditioning alliance on the signal outweighs the cost of monitoring. In equilibrium, the signal is informative: when they observe the signal, Receivers can infer the sender is of relatively high quality $q > \hat{q} > 0$. More widespread signals (lower minimum bar $\hat{q}$) are less informative to Receivers, and less likely to evolve (depending on the cost of monitoring). In particular, a universal signal ($\hat{q} = 0$) is always uninformative, and can never be evolutionarily stable (even when monitoring is free).

1.3.2 In equilibrium, desirable individuals signal and obtain a net benefit

Following equation [1.1], the equilibrium value of the threshold quality $\hat{q}$ is the value which balances cost $c_1(\hat{q})$ and benefit $\frac{s}{\pi(\hat{q})}$ of signaling. In equilibrium, desirable individuals of quality $q > \hat{q}$ signal, and obtain a net benefit. When $\hat{q}$ tends towards maximum quality 1, the benefit of signaling tends towards infinity: we can always expect signaling to emerge in the presence of a large motivated audience, since the first individuals to send will gain a large following.

When in contrast $\hat{q}$ tends towards 0, the benefit of signaling falls to s. For signaling to remain informative, joining in with everyone else must be prohibitively costly for minimum quality individuals, i.e. we must have $c_1(0) > s$. Proposition 2 shows there is a form of equivalence; signals which are prohibitively costly for minimum quality individuals can evolve as long as monitoring is sufficiently cheap.

2 Runaway signal game

2.1 Adding outrage as a second-order signal

2.1.1 A three-step game

We modify the previous model by adding the possibility for senders to express outrage at non-senders. Outrage is construed as a *second-order signal*, which refers to the signal studied above (the first-order signal). Outraged senders negatively comment on a target's absence of investment in the signal, and increase the visibility of their own signal.

The game is now structured in three steps instead of two. First, just as before, Signalers may opt to pay $c_1(q)$ to send a signal.

Second, Signalers who sent the (first-order) signal may now subsequently opt to express outrage, at fixed positive cost c_2. Individuals who do not send cannot express outrage. We assume outrage is aimed in priority at non-senders, i.e. at individuals who are observed not sending the signal. In order to express outrage, one must therefore first send a signal, and second, monitor the (absence of) signals of others. To account for this, we assume that the cost of monitoring ν is included in the cost of outrage (hence we must have $c_2 > \nu$). We continue to assume Signalers who monitor observe non-senders with probability p_1.

Investment in the second-order signal makes the first-order signal easier to spot: when individuals send and express outrage, their signal is observed with increased probability p_2 ($p_1 < p_2 < 1$) by all those who monitor the signal. A specific case occurs when the entire population sends, and senders who pay the cost of outrage are unable to find a non-sender to target. In this case, we assume that they target individuals whose signaling behavior is ambiguous, i.e. individuals who they did not observe sending the signal (since the population is infinite and $p_2 < 1$, such ambiguous targets are always available).

We assume outrage harms its target. Each time an individual opts to send and express outrage, a target is selected at random amongst all potential targets (i.e. among all Signalers the individual observed not sending, or, if there are none, among all Signalers the individual did not observe sending the signal). That target loses h.

In the third step, Receivers may monitor the signal, and ally with another individual, as before.

A pure strategy profile for the modified game specifies: (i) when in the Signaler role, whether to send the signal and express outrage, send the signal and not express outrage, or not send the signal, given own quality q, and (ii) when in the Receiver role, whether to accept alliance with a Signaler selected at random, reject alliance, or monitor and condition alliance on the signal.

2.1.2 Effect of outrage on the previous signaling equilibrium

For any critical quality $q \in (0, 1)$, we define the "honest signaling with outrage" (HSO($\hat{q}$)) strategy profile as the strategy profile whereby: (i) Signalers send and express outrage if and only if their quality is greater than $\hat{q}$, and (ii) Receivers monitor and condition alliance on the signal.

Let us assume individual play according to HSO($\hat{q}$), for a certain critical quality $\hat{q}$. We are in a situation akin to the previous signaling equilibrium, the only difference being that senders now express outrage. $\pi(\hat{q}) = \mathbf{P}(q > \hat{q})$ is now the proportion of Signalers who send both signals.

As before, sending the signal allows a Signaler to recruit followers, and gain on average benefit $\frac{s}{\pi(\hat{q})}$. In addition, sending the signal allows a Signaler to evade others' outrage. Senders express outrage targeted at the $p_1(1 - \pi(\hat{q})) > 0$ percent of individuals they observe not sending the signal, one of whom loses h. If a Signaler does not send, she is targeted by an average of $p_1 \times \pi(\hat{q})$ individuals; if she does send, she evades others' outrage with certainty. Dividing, and multiplying by the cost of being outraged h, we deduce that the equilibrium benefit of evading others' outrage is equal to: $\frac{\pi(\hat{q})h}{1-\pi(\hat{q})}$.

Signalers now compete to attract followers *and* evade others' outrage. For HSO($\hat{q}$) to be an ESS, Signalers of relatively high quality $q > \hat{q}$ must benefit from sending, and Signalers of relatively low quality $q < \hat{q}$ must benefit from not sending. In an honest signaling equilibrium where senders express outrage, $\hat{q}$ will be the quality which equalises total cost and total benefit of sending both signals. $\hat{q}$ must must therefore verify:

$$c_1(\hat{q}) + c_2 = \frac{s}{\pi(\hat{q})} + \frac{\pi(\hat{q})h}{1 - \pi(\hat{q})} \tag{2.1}$$

2.2 Generalized signaling

2.2.1 Condition under which $HSO(\hat{q})$ cannot be an ESS

When $c_2 < \frac{\pi(\hat{q})h}{1-\pi(\hat{q})}$, the equilibrium value of $\hat{q}$ is lower than in the baseline case. Outrage then increases the incentive to signal, pushing more individuals to send both signals. Under certain conditions, the minimum bar $\hat{q}$ will be pushed all the way to 0, making the signal uninformative. When this occurs, honest signaling can no longer be stable. The below proposition gives a sufficient condition.

Proposition 3 *For every positive threshold $\hat{q}$, HSO($\hat{q}$) is not an ESS if:*

$$c_1(0) + c_2 < s + 2\sqrt{hs} \tag{2.2}$$

Proof: For HSO($\hat{q}$) to be an equilibrium, $\pi_S = \pi(\hat{q})$ must verify equation (2.1). Multiplying by $\pi_S(1-\pi_S)$ (π_S is always positive and smaller than 1 at such an equilibrium), we obtain equivalently:

$$(c_1(\hat{q}) + c_2 + h)\pi_S^2 - (c_1(\hat{q}) + c_2 + s)\pi_S + s = 0$$

We recognize a second-order equation in π_S, whose discriminant is equal to:

$$\Delta = (c_1(\hat{q}) + c_2 + s)^2 - 4(c_1(\hat{q}) + c_2 + h)s = (c_1(\hat{q}) + c_2 - s)^2 - 4sh$$

Outrage will push $\hat{q}$ all the way to 0 when the above equation has no solution in the interval $(0,1)$. A sufficient condition for that to occur is $\Delta < 0$. Since $c_1(\hat{q})$ increases when $\hat{q}$ decreases, and since we necessarily have $c_1(0) + c_2 > c_1(0) > s$ (otherwise there is no signaling equilibrium to start from following Proposition 2), we deduce that the squared term is positive when $\hat{q}$ is sufficiently small. We can then take the squared root and obtain a sufficient condition by replacing $\hat{q}$ with 0; we obtain the proposed condition.

2.2.2 Outrage may sustain generalized signaling

When harm h is high, as per the above condition, honest signaling is no longer possible. In addition, we show that generalized signaling can then be stable. More precisely, let us consider the generalized signaling with outrage (GSO) strategy profile, whereby: (i) Signalers send and express outrage whatever their quality, and (ii) Receivers do not monitor the signal, and accept a Signaler at random.

Proposition 4 *GSO is an ESS if and only if:*

$$c_2 < (p_2 - p_1) \times \frac{h}{1 - p_2} \tag{2.3}$$

Proof: let us assume individuals play according to the GSO strategy profile. Since Receivers do not monitor the signal, senders do not recruit more followers than non-senders. All signalers send and express outrage, by targeting one of the $1-p_2$ individuals they each do not observe sending. With probability $1-p_2$, a Signaler will constitute a potential (ambiguous) target for another Signaler; dividing, we deduce that each individual loses h, on average.

No individual benefits from deviation to not sending. Any individual who does so risks become a priority target for other individuals with probability p_1, and faces an infinite loss. If an individual opts not to express outrage, she saves on cost c_2, but increases her chance of constituting a target for others from $1 - p_2$ to $1 - p_1$, losing $\frac{1-p_1}{1-p_2}h$ on average. By comparing with h, we deduce that GSO is strict Nash, and therefore ESS, if (2.3) holds. Conversely, if this condition is unverified, senders do not lose from deviation to not expressing outrage; mutants who do not express outrage can then invade. This proves the proposed equivalency.

2.3 Sufficient condition for outrage

Under the conditions derived in this section, outrage may transform the honest signaling equilibrium into a stable equilibrium where all individuals signal, and the signal is completely uninformative. When condition (2.2) is verified, outrage should push all individuals to signal, destabilizing the honest signaling strategy profile. As long as it is sufficiently cheap, as per condition (2.3), we may end up with generalized signaling.

More precisely, we derive a sufficient condition for outrage to exist in all the potential situations under consideration. To simplify, we assume $\nu = 0$ in the below proposition; such that we should either be in a case of the form HSO($\hat{q}$), when $\hat{q} > 0$, and otherwise be in the case of GSO.

Proposition 5 *When monitoring is free ($\nu = 0$), in any ESS where signaling occurs with positive probability, senders express outrage if:*

$$c_2 < (p_2 - p_1) \times \min\{\frac{s}{p_2}, \frac{h}{1 - p_2}\} \tag{2.4}$$

Proof: let us assume we are in an ESS where signaling occurs with positive probability, and where senders express outrage. Since the cost of sending both signals $c_1(q) + c_2$ is a decreasing function of individual quality q, Signaler behavior can be described according to a threshold $\hat{q} \in [0, 1)$ above which they send both signals.

If $\hat{q} > 0$, we must be in the case of honest signaling with outrage. Since $\nu = 0$, Receivers strictly benefit from using the signal. Let us consider a Signaler of quality $q \geq \hat{q}$, who sends both signals, and earns on average $p_2 \times \frac{s}{p_2 \pi(\hat{q})} - c_1(q) - c_2$. Were such an individual to deviate to not expressing outrage, she would save on the cost of outrage c_2, but decrease her chances of being observed from p_2 to p_1. On average deviation to not expressing outrage for a sender leads to payoff differential: $c_2 - (p_2 - p_1)\frac{s}{p_2 \pi(\hat{q})} \leq c_2 - (p_2 - p_1)\frac{s}{p_2}$. Since we are in an ESS, and since $\hat{q} < 1$, we deduce that we must have: $c_2 < (p_2 - p_1)\frac{s}{p_2}$.

If $\hat{q} = 0$, we must be in the case of the GSO ESS, and therefore have $c_2 < (p_2 - p_1)\frac{h}{1-p_2}$, following Proposition 4. This proves the implication.

Finally, let us assume instead that players are playing according to a strategy profile in which signaling occurs with positive probability, and senders do not express outrage. We prove the strategy profile cannot be ESS when the above condition holds. First, note that we must be in the baseline honest signaling equilibrium, with $\hat{q} > 0$, and where senders are observed with probability p_1, and gain $\frac{s}{p_1 \pi(\hat{q})}$ when observed. Deviating to expressing outrage costs c_2 and increases one's visibility, leading to benefit $(p_2 - p_1)\frac{s}{p_1 \pi(\hat{q})} > (p_2 - p_1)\frac{s}{p_2}$. When the above condition holds, that deviation is net beneficial, and the strategy profile under consideration cannot be an ESS. This proves the proposed equivalency.

3 Simulation

3.1 Presentation of the simulation

We develop a multi-agent simulation. The simulation is written in Python and is based on the *Evolife*[1] platform. Agents differ by their quality. Agent qualities are uniformly distributed between 0 and 100. They may signal at a certain level at a cost that smoothly decreases with their quality. Agents

[1] All programs are open source and are available at this website. The program described here can be found in the *Evolife* package at `Evolife/Apps/Patriot/Patriot.py`

can learn several features through a simple local search. Features include their investment in signaling and their probability of expressing outrage. Investment in signal monitoring can also be a learned feature.

All interactions in the simulation are meant to be local. Individuals meet each other in a randomized order within interacting groups. During their first encounter (Algorithm 1), they observe each other's signal with a certain probability which depends on a global parameter called $InitialVisibility$ (parameter p_1 in the model) and on a feature, $MonitoringProbability$ (ν in the model), learned by individuals.

Algorithm 1 Observe

```
Input: self, Partner
if random() ≤ self.MonitoringProbability
and  random() ≤ InitialVisibility then
    if self.signal < Partner.signal then
        ▷▷ self remembered as potential outrage target
        add (self, self.signal) to Partner's outrage memory
    end if
    ▷▷ self remembered as potential affiliation target
    add (self, self.signal) to Partner's affiliation memory
end if
```

During a second randomized encounter (Algorithm 2), individuals may express outrage toward third parties. The point of outrage is to indicate that one's own signal is superior to the target's signal (this translates in the apparent signal $Target.signal + 1$ in the algorithm). Each individual learns a feature named $OutrageProbability$ and decides to be outraged accordingly.

Algorithm 2 Outrage

```
Input: self, Partner
if self.Outrage then
    ▷▷ self communicates outrage target
    Target ← worst individual in self's outrage memory
    if Target.signal < Partner.signal then
        add (Target, Target.signal) to Partner's outrage memory
    end if
    add (self, Target.signal + 1) to Partner's affiliation memory
end if
```

In a third randomized encounter, individuals attempt to establish friendship based on the observed signals (Algorithm 3).

After these three rounds, payoffs are computed (Algorithm 4): individuals get rewarded for having attracted affiliates (they receive $FollowerImpact$, corresponding to parameter s in the model) and for being affiliated with high quality individuals (they receive $FollowingImpact \times Partner.Quality$ for each partner; function $a(q')$ in the model). Individuals get punished if they were the target of outrage (parameter h in the model). Agents' memory is reset after the assessment phase. However, they store payoffs and learn periodically from them. Agents have a limited lifespan and get fully reinitialized when being

Algorithm 3 Interact

Input: $self$, $Partner$
if $Partner$ **in** $self$**'s affiliation memory then**
  $PartnerSignal \leftarrow Partner$**'s memorized signal**
else
  $PartnerSignal \leftarrow 0$
end if
if **self's affiliation set is not full**
or $PartnerSignal \geq self$**'s current worst friend's signal then**
  ▷▷ *Partner becomes self's friend*
  $self.affiliate(Partner, PartnerSignal)$
end if

reborn with the same quality.

Algorithm 4 Assessment

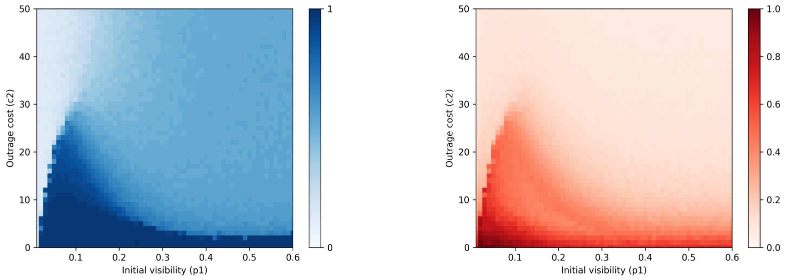
Input: $self$
for F **in** $self$**'s friends do**
  ▷▷ *payoff for having attracted a follower (s)*
  $F.Points \mathrel{+}\leftarrow FollowerImpact$
  ▷▷ *payoff for being affiliated with F (depends on F's quality)*
  $self.Points \mathrel{+}\leftarrow FollowingImpact \times F.Quality$
end for
$self.Points \mathrel{-}\leftarrow$ **cost of signaling for self**
$self.Points \mathrel{-}\leftarrow OutrageProbabilityCost \times self.OutrageProbability$
$self.Points \mathrel{-}\leftarrow MonitoringCost$
if $self.Outrage$ **then**
  $Target \leftarrow self$**'s outrage memory worst individual**
  ▷▷ *outrage target is harmed*
  $Target.Points \mathrel{-}\leftarrow OutragePenalty$
end if
$self.resetMemory()$

The simulation program relies on a variety of parameters. The most relevant ones are listed in table 1. Individuals get 'Follower Impact' (s in the model) for each agent that affiliates with them. 'Signaling cost coefficient' provides the scale of signal cost: it corresponds to the the cost paid by a medium quality individual that would send the maximal signal (highest level). 'Signaling cost decrease' controls the variation of cost of signaling function with quality ($c_1(q)$ in the model)(0: no variation; 1: linear decrease; higher values: steeper, non-linear decrease). 'Outrage penalty' (h in the model) is endured by individuals each time they are someone's outrage target. Individuals pay a cost of outrage which is proportional to their propensity to express outrage, and the parameter 'Outrage cost' (gradual version of model's fixed cost c_2). Finally, 'Initial visibility' is the probability of individuals' signal being seen during the observation round (p_1 in the model).

Most relevant parameters

Description	*Typical value*
Follower Impact (s)	30
Signaling cost coefficient	200
Signaling cost decrease	5
Outrage penalty (h)	50
Outrage cost (c_2)	30
Initial visibility (p_1)	0.1

Table 1: List of most relevant parameters.



(a) Fraction of senders

(b) Average probability of outrage

Figure 2: Fraction of senders and average probability of outrage, as a function of initial visibility and outrage cost, when only one level of signaling is available.

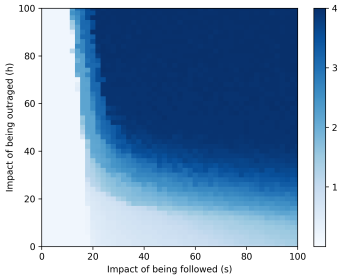
3.2 Results

The simulated signal runaway phenomenon is robust and occurs for a wide range of parameters. Figure 2 shows how investment in both first- and second-order signaling depends on 'Initial visibility' (p_1). Figure 3 shows how signals may gradually runaway, and reach high levels (computed for 4 non-null levels of signaling), depending on the stakes (payoff s for attracting a follower and penalty h for being the target of outrage). Both these figures are present in the main article. In addition, Figure 4 shows how attained investment in signaling (4 non-null levels of signaling) varies with the other parameters of table 1, namely 'Signaling cost coefficient' and 'Outrage cost'. All figures are parameter values are available on the website.

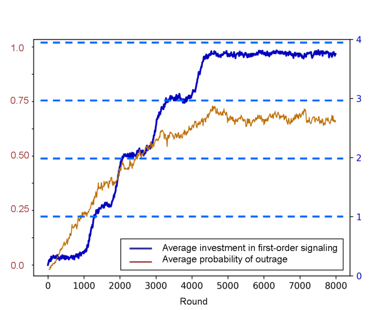
3.3 Differences between model and simulation

In the model, we consider an infinite population, such that one individual's strategy does not affect overall probabilities. In addition, Receivers may monitor, observe and choose senders in a perfectly balanced way. In contrast, the simulation program is meant to implement a more realistic setting in which all interactions remain local. As a consequence, there is a variance in the number of affiliates each visible sender may attract, due to chance. To prevent a winner-take-all effect, we limited the number of affiliates each sender may recruit.

Another source of variance comes from the fact that agents do not always



(a) Average level of signaling



(b) Step-by-step runaway

Figure 3: Average attained level of signaling as a function of the stakes, and evolution over time, when four levels of signaling are available.

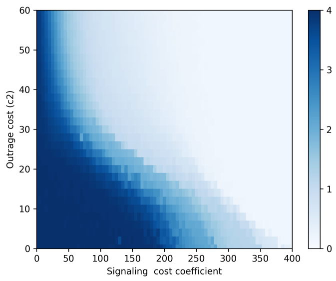


Figure 4: Average level of signaling (four non-null levels available) as a function of 'Outrage cost' and 'Signaling cost coefficient'.

adopt the ideal strategy corresponding to their quality. They need time to learn their various options (sending the signal, monitoring others' signals, expressing outrage) and they constantly explore alternatives with a certain probability. Despite behavioral variance due to chance and to this "learning noise", the simulation is robust, i.e. it produces similar outcomes for a wide range of parameter values.

Variance can be even seen as an advantageous feature of the simulation. When all individuals end up sending the same signal, there are no obvious outrage targets. Hence the possibility introduced in the model of expressing outrage at ambiguous individuals, i.e. individuals that either do not send or were not observed while sending. By contrast, in the simulation, the constant existence of exploring individuals maintains potential outrage targets.

References

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