

# Collective narratives catalyse cooperation

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## Abstract

Humans invest in fantastic stories – mythologies. Recent evolutionary theories suggest that cultural selection may favour moralising stories that motivate prosocial behaviours. A key challenge is to explain the emergence of mythologies that lack explicit moral exemplars or directives. Here, we resolve this puzzle with an evolutionary model in which arbitrary mythologies transform a collection of egoistic individuals into a cooperative. Importantly, in finite populations, reflecting relative to contemporary population sizes of hunter-gatherers, the model is robust to the cognitive costs in adopting fictions. This approach resolves a fundamental problem across the human sciences by explaining the evolution of otherwise puzzling amoral, nonsensical, and fictional narratives as exquisitely functional coordination devices.

Keywords: social evolution | culture | narratives | beliefs | stag-hunt

## 16 Introduction

17 Human culture is a bewildering array of complex yet intuitively consistent, mutually  
18 beneficial arrangements. From reproductive divisions of labour and alloparenting to  
19 collective foraging, information-sharing, education, and defence, humans are cham-  
20 pions of cooperation. Large-scale cooperation traces to a deep ancestral past, built  
21 on the back of highly social hunter-gatherer modes of existence [1, 2, 3]. It has long  
22 been argued that moralising mythologies were a central feature of our cooperative  
23 adaptive complex. According to the supernatural punishment hypothesis [4, 5], natu-  
24 ral and cultural selection targeted beliefs in the reality of supernatural policing, leading  
25 to a remarkable diversity of religious belief systems. According to these scholars, the  
26 prevalence of religious beliefs is explained by religion's cooperative effects. Specifi-  
27 cally, beliefs in supernatural enforcers promote obedience to cooperative norms [6, 7].  
28 A key challenge, then, is to explain the cultural persistence of a-moral, morally am-  
29 biguous, and anti-social mythologies.

30 For example, in Māori culture, the primordial deities Rangi and Papa are con-  
31 nected in a loving embrace that encompasses all of reality. The world is created when  
32 one of their children, Tane, pushes his parents apart, thus giving rise to the separa-  
33 tion of the sky (Rangi) and earth (Papa). Since then the primordial couple has lived  
34 in longing for each other with little or no regard for their children or, for that matter,  
35 mortals. It is difficult to derive any clear moral from this story. Indeed, many cultural  
36 mythologies exhibit morally problematic features. Consider another example, in Aztec  
37 mythology, the feathered serpent god Quetzalcoatl is described as having set himself  
38 on fire the day after an intoxicating evening in which he performed sexual acts on  
39 his sister Quetzalpetlatl. Both the god's incest and the self-immolation are arguably  
40 morally excessive for a deity. Incest avoidance does not appear to be challenging to  
41 motivate. What, then, explains the emergence and propagation of mythologies that  
42 lack explicit moral instructions? Might such mythologies promote sociality some other  
43 way?

44 Previous theories speculate that amoral mythologies propagate from non-functional

45 cognitive preferences for the uncanny [8]. Here, we offer a mathematical model of a  
46 process whereby even arbitrary fictions support sociality. Our model is distinctive  
47 because it demonstrates how evolutionary dynamics could favour fiction not as an  
48 accident but for its functions.

49 **Cooperation threatened by risk: the Stag Hunt.** To illustrate a fundamental  
50 evolutionary problem of cooperation, we begin, aptly, with a mythological story called  
51 “The stag hunt”, which clarifies how the problem of cooperation arise even when coop-  
52 eration is everyone’s interest [9, 10, 11, 12]. We imagine a group of hunters deciding  
53 whether to hunt hares or stags. Hunting a hare is possible alone, but results in a small  
54 payoff. Stag hunting yields a more substantial payoff but – because it requires collec-  
55 tive action – it is threatened by risk-avoidance. In an all-or-none scenario, if even one  
56 hunter seeks to avoid the risk that cooperation fails, all hunters will fail. This reasoning  
57 makes the default equilibrium of ubiquitous hare-hunting stable because propensities  
58 toward stag hunting face downward selective pressure. How can populations transit  
59 to cooperation (stag-hunting) under these circumstances?

60 We might look to the Theory of Mind, or the capacity to represent the mental states  
61 of other people, for the solution. The consensus view is that the Theory of Mind was a  
62 critical step in achieving cooperation at scale [13]. In a stag hunt, I can represent that  
63 it is in your interests to coordinate, and you can do the same. However, it has long  
64 been observed that Theory of Mind may compromise a coordination problem with  
65 risk. Merely knowing that risk-avoidance threatens the success of a stag-hunt might  
66 inspire risk-avoidance. For example, suppose individuals would choose Stag with a  
67 probability of  $p = 0.9$ . Knowing this, agents with shared intentionality can reason that  
68 the chance of  $n$  choosing to hunt is  $p^n \ll p$  and, being risk-averse, down-grade their  
69 own  $p$  accordingly. Theory of Mind allows partners to represent each other’s uncer-  
70 tainty. The capacity to represent uncertainty in the setting of risk threatens coordi-  
71 nation, even when all parties understand that coordination is in everyone’s interests  
72 [14, 15, 16]. Example of such coordination failures abound. During a pandemic, we  
73 understand that there is ample toilet paper for all. Nevertheless, we rush to the mar-  
74 ket, and a wrestling match ensues because we predict, correctly, that the pandemic

75 will cue hoarding. Were we unable to represent the minds of others, no such problem  
76 would arise. Even successful collectives are fragile, and humans seem in need of  
77 reusable mechanisms to traverse from a world of risk aversion to one of cooperative  
78 alignment.

79 Distinct from the Theory of Mind – the capacity to represent the mental states of  
80 others – we define “inter-subjectivity” as the capacity of multiple individuals to share  
81 the same subjective beliefs [17]. Inter-subjective reality then is a belief, whether ac-  
82 curate or not, accepted by all parties concerned. To solve a coordination problem  
83 that involves risk, such as a stag hunt, requires an alignment of motivations. We next  
84 introduce a model in which arbitrary fictions cause a form of inter-subjectivity that  
85 supports risky cooperation.

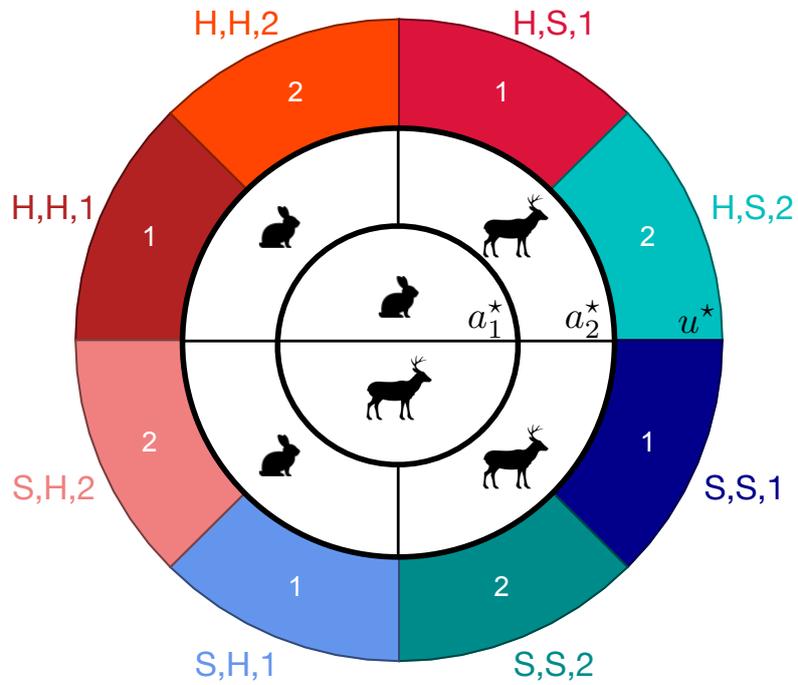
## 86 **Model & Results**

### 87 **2.1 Traversing the dilemma**

88 A tribe of individuals decide to form a group to go get food. The group consists of  $G$   
89 individuals, each of whom could opt to pursue a hare or the stag. If enough people are  
90 hunting stag, then the hunt will be successful and yield  $\Pi_S$  for each active participant.  
91 A failed hunt results in no payoff at all. All hare hunters have a fixed payoff of  $\Pi_H$   
92 regardless of the group composition. The hare hunters payoff is, therefore, “risk-free”,  
93 being achievable regardless of the decisions of the other hunters.

94 We label objective and alternate realities as 1 and 2 respectively, and each indi-  
95 vidual has a preference (belief) in favour of one or the other. Groups form, come to a  
96 consensus regarding reality 1 vs 2, and each member then adopts the behaviour (H  
97 or S) they prefer in that consensus reality. Thus we have eight types of individual to  
98 consider, as shown in Fig. 1. We begin in a world where everyone favours objective  
99 reality and is a hare hunter, hence a population consisting of type (H,H,1).

100 Before setting off on a hunt, the group  $G$  arrives at a consensus reality. A sim-  
101 ple way to do this is to choose one member of the group and coalesce around their



**Figure 1: The types of individuals in the world.** Individuals are aware of the realities 1 the objective or 2 alternate. However they believe in only one of them. The actions of the individuals in each reality could be  $H$  or  $S$ . Thus a focal individual ( $\star$ ) is defined by  $(a_1^*, a_2^*, u^*)$  where  $a_i^*$  is the hunting strategy of the focal individual when in reality  $i$  and  $u^*$  is the reality that the individual believes in. Following their own narratives, the red-tinged strategies would hunt hares, and blue-tinged, stags.

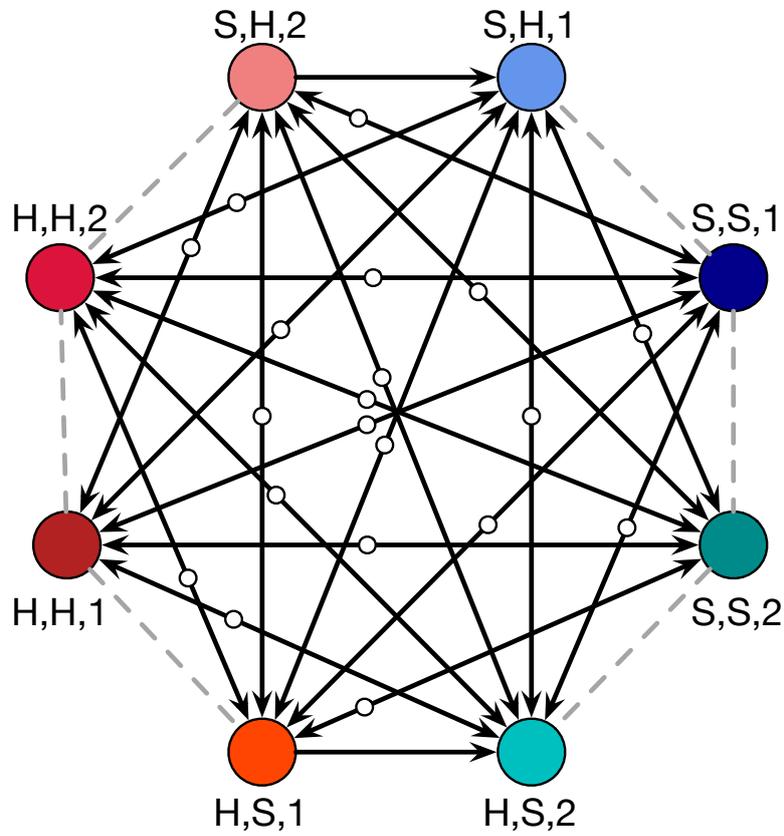
102 view - a dynamics of Groupthink [18]. Humans frequently depend on the percep-  
103 tions of others to inform themselves [19], and the notion of Groupthink captures the  
104 phenomenon in which a group minimises conflict by accepting a particular viewpoint  
105 without a critical evaluation of the decision or the alternatives. In this view, under-  
106 standing is a contagion [20] that allows for fast decision making without conflicts.  
107 Again we illustrate using a pessimistic approach, taking a random individual as the  
108 source of the contagion. This amounts to a pure frequency-dependent ruling to reach  
109 a group decision. Group formation and composition itself can be a complex process  
110 but as this is not our focus we assume it takes place with no assortment, via random  
111 draws from the population. Some other ways of reaching a consensus are discussed  
112 in the Supplementary Material. Charismatic leaders could impose one view of reality  
113 [21], or objectivity might prevail, or everyone could simply decide for themselves. A  
114 simple majority vote is another appealing possibility supporting normative behaviour  
115 [22, 23]. The evolutionary dynamics of conformist behaviour can very well feed into  
116 the decision making process [24].

117     Upon consensus, the individuals decide on their actions conditioned on that reality,  
118 and the consequences of the ensuing hunt unfold in the evolutionary dynamics.

## 119 **2.2 Evolutionary dynamics in infinite populations**

120 In infinitely large populations, deterministic dynamics reign supreme. Tracking all the  
121 possible types of individuals, the dynamics of the strategy evolution proceeds in a  
122 seven-dimensional simplex whose vertices correspond to strategies, with intermedi-  
123 ate points being a mixture of different strategies.

124     This simplex is projected in Fig. 2 as a two-dimensional graphic. The edges  
125 connect pairs of pure strategies, and the arrows denote the direction of selection  
126 when only those strategies are in play. Neutral dynamics exist between strategies  
127 that choose the same reality and the same strategy, such as (H,H,2) and (S,H,2), or  
128 even if they have different realities but the same strategy in both, such as (H,H,1) and  
129 (H,H,2). Only two strategies ((S,H,1) and (H,S,2)) are dominant and selected over



**Figure 2: Dynamics on the edges of the simplex.** The dashed edges are neutrally stable whereas the directed edges show dominance. The edges with an open circle on them are all bi-stable (the circle marking the position of an unstable threshold as per Fig. [Sl.1](#)), hence along those edges there would be no movement once the population is at a vertex. Once the population reaches the  $(H,S,2)$  or  $(S,H,1)$  state, it gets locked into the stag equilibrium. Parameters are  $G = 5$ ,  $M = 4$ ,  $P_S = 4$  and  $P_H = 1$ .

130 the corresponding Hare strategies ((S,H,2) and (H,S,1)). The population can thus  
131 move into the Stag state where it can again evolve neutrally. The logic behind the two  
132 traversals beginning at (H,H,1) is as follows: (i) The bottom path allows for the neutral  
133 evolution of individuals that might hunt stags in reality 2. This choice is not selected  
134 against because the consensus reality is always the objective one, 1, in which they  
135 hunt hares, and thus we have neutral drift  $(H,H,1) \rightleftharpoons (H,S,1)$ . From (H,S,1) to (H,S,2)  
136 inter-subjectivity can break out en masse. If the group chooses reality 2 then the  
137 payoff is larger as they will get the stag and the belief in alternate reality 2 increases  
138 until it becomes the inter-subjective reality – an accepted belief. (ii) The top path is  
139 possible in a similar fashion where it is belief in the objective reality 1 that forms the  
140 stag-inducing inter-subjective reality.

141 Following either path, we see that the population can go through a step in which  
142 the inter-subjectivity evolves (widespread belief in either the alternate reality (bottom)  
143 or the objective (top)) and catalyses a transition in behaviour. The dual transition is  
144 also evident in the future coexistence of the diversity of stag hunters, both believing  
145 in different realities but still trusting each other to hunt the stag. Thus while essential  
146 for mediating the transition, eventually the exact choice of belief becomes immaterial.

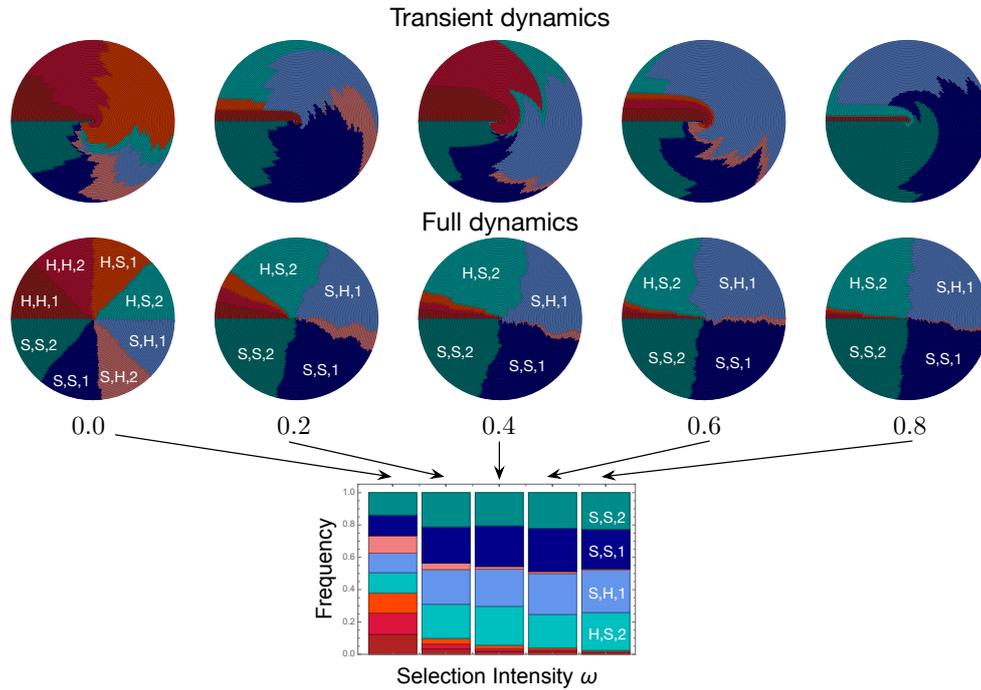
147 The mechanism leading to the bypassing of the unstable equilibrium of a stag hunt  
148 game is similar to the scenario of the evolution of cooperation by tag-based selection  
149 [25]. The narratives can be interpreted as different tags which the individuals bear  
150 and then can choose to discriminate between partners - cooperators and defectors  
151 in a Prisoner's Dilemma. However, in our case, individuals do not discriminate based  
152 on the narratives they believe. The disentangling of actions and narratives in our  
153 case leads to extremely complex dynamics, given the complicated nature of the pay-  
154 off structure (see Supplementary Information (SI)). The complexity prevents us from  
155 analysing the interior of the seven-dimensional simplex in detail. However, progress  
156 is possible using a more realistic picture of the model for finite populations, together  
157 with analytical tools and computer simulations.

## 158 **2.3 Evolutionary dynamics in finite populations**

159 Typical prehistoric communities were of small size. To analyse the dynamics of traits  
160 in tribes living together in countable population sizes needs different mathematics  
161 [26]. Assuming the population size of the tribe is  $N$ , a sample of  $G$  individuals from  
162 it decide to hunt. This sampling follows a hypergeometric distribution [27, 28]. Given  
163 the population composition, the calculation of payoffs is denoted in the Appendix.  
164 As before, we assume the initial population, and hence also the hunting group  $G$   
165 consisting of (H,H,1) types. New strategies can arise due to mutations. From (H,H,1)  
166 if mutations to types such as (H,H,2) , and (H,S,1) occur, they will be hunting Hare  
167 in the objective reality. Thus the fitness of these types are the same in the objective  
168 reality and thus neutral evolution proceeds.

169 In finite populations, drift allows for the strategies such as (H,S,1) and (H,S,2)  
170 to rise to appreciable frequencies in the population (as in [25]). However, now that  
171 (H,S,2) increases in frequency. In case the alternate belief is chosen as the group  
172 reality, the individuals who have  $S$  action as their second reality option will hunt a  
173 stag. If there are more than the critical number  $M$  of stag hunter in the group  $G$ , then  
174 the stag hunt will be successful. Given these multiple conditionals, the calculation of  
175 fitness becomes a complicated matter of bookkeeping. From the payoff of a strategy  
176  $i, \pi_i$ , we can calculate the fitness of the strategy as  $\psi_i = 1 + \omega \pi_i$  where  $\omega$  is the in-  
177 tensity of selection. The selection intensity dictates the impact of the game on the  
178 fitness of a strategy. For  $\omega = 0$ , all strategies are equal with fitness of 1. As the value  
179 of  $\omega$  increases, the game has an increasing impact on fitness. In a finite population,  
180 the Moran process translates game success into an increase in the frequency in the  
181 population (Appendix). For smaller population sizes, the stochastic effects are pro-  
182 nounced (see SI). Given a population size, we can explore the effect of the different  
183 selection intensities on the evolutionary dynamics as well as the eventual abundances  
184 of the strategies as illustrated in Fig 3.

185 Note that in the eventual distribution, mixtures of individuals believing in both re-  
186 alities are possible, indeed likely. Initially, lone strategists believing in the alternate



**Figure 3: Abundance plots for the eight strategies in a finite population.** All simulations begin with a population consisting of (H,H,1). *Transient*: For different selection intensities the initial conditions are all the same - starting in a (H,H,1) population. With a mutation rate of  $\mu = 10^{-3}$  new strategies appear and spread in the population. Every 20<sup>th</sup> time-step up to 1000 time-steps are plotted, from inside to outside. *Full*: Over time ( $5 \times 10^6$  time-steps) the population reaches stationarity. Every 1000<sup>th</sup> time-step is plotted. The final distribution of strategies (outermost layer of the circles) is collated in the bar-chart. *Bottom*: The final distribution of the strategies at time-step  $5 \times 10^6$  is plotted as a stacked bar chart for the different selection intensities. When selection intensity  $\omega = 0$  the dynamics is neutral and all the strategies evolve to similar abundances. When selection intensity is increased even slightly  $\omega = 0.2$  the population is made up predominantly of stag hunters. Note that it is not necessary that all stag hunters share the same inter-subjective reality. Parameters are  $N = 32$ ,  $G = 5$ ,  $M = 4$ ,  $P_S = 4$  and  $P_H = 1$ .

187 reality would be considered as irrational. However, since selection acts only via the  
188 action taken, the belief can spread neutrally as long as the action performed in the  
189 prevalent reality remains hare hunting. Thus, although shared narratives facilitate the  
190 transition from hare hunters to stag hunters, the narratives themselves do not nec-  
191 essarily fix in the population but are merely a catalyst. Even non-believers in the  
192 narrative end up hunting stags, because since the majority of the population is in a  
193 stag hunter, to hunt stags is a rational choice.

## 194 **Discussion & Conclusion**

195 Belief in shared narratives can enforce rules on normative behaviour leading to a  
196 productive society [29]. By affecting human morality [30], beliefs can result in reduced  
197 cheating [31] and increased pro-social behaviour [32, 6, 33, 34]. We propose that  
198 since establishing a social contract became possible via the capacity for generating  
199 fictions, the potential for subjective reasoning could come under biological and cultural  
200 evolution [35, 3, 36, 37, 38, 39]. Numerous verbal or computational models exist  
201 which extol the role of prosocial mythologies in the spread of cooperation [30, 31].  
202 Our model clarifies how mythologies that lack moralising features might nevertheless  
203 propagate as cooperative assurance mechanisms.

204 As with any model, ours has its limitations. We have modelled the evolution of a  
205 capacity for inter-subjective belief, assuming this capacity to be a single trait. Com-  
206 plex modern human behaviour is a combination of multiple traits, a package [40, 7],  
207 the contents of which can interact in to amplify or depress cooperative outcomes.  
208 Linking cultural traits resulting in a cumulative cultural evolution and exploring the  
209 evolution of this joint ‘package’ has been recently explored using agent-based simu-  
210 lations [41, 42]. Additionally, we do not explain the origin of tendencies nor attempt to  
211 clarify debates about origins of fictional capacities [43, 44, 45]. The arguments in the  
212 directions of origins need to be augmented further by studies in behavioural sciences  
213 and cultural anthropology. Combining multiple qualities, once humans acquired the  
214 ability to fictionalise their experiences, this ability would also need to be heritable. Our

215 theory assumes the actions and the ability for subjective inference to be genetically  
216 encoded. Using gene-culture coevolution models, it might be possible to introduce a  
217 transmission of not only the strategies but the fictions themselves [34]. The advent of  
218 storytelling as a cultural trait perhaps could be coupled together with the passage of  
219 genes for actions. The cultural evolution of successful stories (which couple with ac-  
220 tions that provide a fitness advantage) could lead to a thriving society [46]. Imagining  
221 stories or the ability to invent fictions indeed comes with a cognitive cost. Also, the  
222 ability to distinguish one narrative from another involves a cost as well. Hence a cost  
223 of inventing and recognising narratives is paid by all individuals - the alternate reality  
224 believers and the objective reality believers who can discern the difference. In the SI,  
225 we have explored the case where only the alternate reality believers pay the cognitive  
226 cost. A pronounced catalyst nature of an alternate reality appears in the presence of  
227 costs. After enabling a transition to the stag equilibrium in finite populations, the belief  
228 in an alternate reality disappears, leaving the population at the social optimum.

229 While we have not focused on the content of stories *per se*, the narratives of  
230 fictions in hunter-gatherer communities often focus on pro-social qualities [7, 47]. An-  
231 thropological and cognitive sciences have long highlighted the importance of belief  
232 systems in the social evolution of humans. The exact distinction between the moral-  
233 ising effect of mythologies versus their effects is still debated [48]. Large-scale coop-  
234 eration via belief in gods, money, contracts, banks has resulted in immense growth  
235 in arts and trade, ultimately benefiting humanity. Since we show that the content of  
236 the belief does not necessarily matter, post-truths, conspiracies, and ideologies can  
237 spread as well. Beliefs might, therefore, be viewed as selfish elements. The effect  
238 on the population as a whole is inconsequential; thus, superficially, the rise and fall of  
239 beliefs might be likened to fashion dynamics [49].

240 Inter-subjective realities rule our world today. Differing from fashions; religions,  
241 states, nations, and companies exert enough power in the natural world to change its  
242 evolutionary course. Narrative beliefs about marital rituals, vaccination programmes,  
243 financial/government entities and money itself control the biological output of large  
244 swathes of populations around the globe [50, 51, 52, 53]. The importance of narra-

245 tive in economics and politics is becoming increasingly relevant [54]. Such shared  
246 narratives between many individuals, help us achieve cooperation on a large-scale.  
247 Extending our theory to include ecological dynamics would thus be a natural exten-  
248 sion [55, 32, 34]. Populations that reach the stag equilibrium can increase their car-  
249 rying capacity and competition between populations would then be important [56].  
250 However as evidenced from the agricultural revolution, an increase in population  
251 size also comes with problems, such as lower nutritional content [57], widespread  
252 diseases[58, 59, 60] and the further cognitive pressures for social engineering. Thus  
253 the benefit and costs of larger population size would need to be balanced out [61, 62].  
254 If the costs are too high, an evolutionary model might revert us to the hare state, a  
255 reduction in population size and to a hunter-gatherer community.

256 We have chosen the stag hunt as a primary example of the problem of estab-  
257 lishing a social contract. The model establishes a tension between a secure private  
258 gain and an unreliable but more considerable social gain. Dynamically speaking, if a  
259 model affords an unstable equilibrium between these two actions, then it will be an  
260 appropriate candidate for posing as an appropriate problem for a social contract. We  
261 have considered only two different types of realities. Once the population has sur-  
262 mounted one social dilemma, it will reach a plateau where a co-existence between  
263 inter-subjective beliefs is possible. Then the process can start again with a new chal-  
264 lenge, thus leading to higher social gains but at the same time, accumulating several  
265 narratives, from personal beliefs to institutionalised systems. From hunter-gatherers  
266 to the stock-exchange, the amount of cooperation that we see in human communities  
267 is impressive in scale and achievements. By providing a mathematical model resolv-  
268 ing a social contract, we show that such massive advent of cooperation can emerge  
269 when people have shared narratives.

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424 **Supplementary material**

425 **Evolutionary dynamics in an infinite population**

426 In total, there are eight different strategies. The strategies can be enumerated by  
 427 the generic profile  $(a_1^*, a_2^*, u^*)$  where  $a_i^*$  is the hunting strategy of the focal individual  
 428  $(\star)$  when in reality  $i$  and  $u^*$  is the preferred reality of the focal individual (objective or  
 429 alternate here-on referred to simply as reality 1 and 2). The individuals in the tribe  
 430 form a group of size  $G$ , and they need to decide which reality they choose to believe.  
**Group decision** For the group to decide on a choice of reality, 1 or 2, we use a  
 frequency-dependent process (for other methods of reality resolution, see below).  
 The group thus choose to believe in the reality 1 with probability,

$$f(k, u^*) = \frac{k + \delta_{u^*}}{G}. \quad (\text{SI.1})$$

431 and in the reality 2 with probability  $1 - f(k, u^*)$ . The number of individuals, besides  
 432 the focal, who believe in reality 1 is denoted by  $k$ . The Kronecker delta  $\delta_{u^*}$  returns 1 if  
 433 the focal individual prefers reality 1 (i.e. if  $u^* = 1$ ) and 0 otherwise.

434 **Individual action.** After the group decides the reality they believe in, each individual  
 435 in the group chooses the appropriate action. In the reality 1, the focal individual is a  
 436 hare hunter if  $\delta_{a_1^*}$  return 1 and a stag hunter otherwise. A similar reasoning works for  
 437 reality 2 ( $\delta_{a_2^*}$ ).

**Values of Hares and Stags.** The value of hunting a Hare is denoted by  $P_H$ . The total  
 probability that an individual gets a hare payoff is then denoted by

$$\Pi_H = P_H \sum_{k=0}^{G-1} \binom{G-1}{k} x_1^k (1-x_1)^{G-1-k} (f(k, u^*) \delta_{a_1^*} + (1-f(k, u^*)) \delta_{a_2^*}) \quad (\text{SI.2})$$

438 where  $x_1 = x_{HH1} + x_{HS1} + x_{SH1} + x_{SS1}$  the sum of the frequencies of individuals  
 439 believe in reality 1 and thus  $1-x_1 = x_{HH2} + x_{HS2} + x_{SH2} + x_{SS2}$ , the reality 2 believers.  
 440 The value of a stag is given by  $P_S$ . The focal individual is a stag hunter according  
 441 to the **Individual action** section. The group composition is a key determinant of  
 442 the stag payoff since there is a minimum number of stag hunters necessary ( $M$ ) for

443 successful stag hunt. Besides the the focal individual,  $k$  individuals believe in reality  
 444 1 and  $G - 1 - k$  in reality 2. However we need to sort how many of these individuals  
 445 are stag hunters. The composition of the group is then denoted by,

$$P_{comp} = \sum_{\substack{l=0 \\ m=0 \\ n=0 \\ o=0}}^k \sum_{\substack{p=0 \\ q=0 \\ r=0 \\ s=0}}^{G-1-k} \binom{k}{l, m, n, o} \binom{G-1-k}{p, q, r, s} x_{HH1}^l x_{HS1}^m x_{SH1}^n x_{SS1}^o \\ \times x_{HH2}^p x_{HS2}^q x_{SH2}^r x_{SS2}^s \chi(u^*) [Q(l, m, n, o, p, q, r, s)] \quad (\text{SI.3})$$

where the Iverson bracket [63] is used to test the statement  $Q = (l + m + n + o = k) \wedge (p + q + r + s = G - 1 - k)$  with,

$$[Q(l, m, n, o, p, q, r, s)] = \begin{cases} 1, & \text{if } Q \text{ is true} \\ 0, & \text{otherwise.} \end{cases} \quad (\text{SI.4})$$

The function  $\chi(u_*)$  is a step function which (when  $\chi(u_* = 1)$ ) ascertains if the focal individual prefers reality 1 and returns the function  $\theta(1 + n + o + r + s - M)$  (checking if the number of stag hunters meet the required threshold  $M$ ). If  $u_* = 2$  then the focal individual believes in the reality 2 and  $\chi(u_*)$  returns  $\theta(1 + m + o + q + s - M)$  (again checking if the number of stag hunters meets the required threshold  $M$ ). Putting  $P_{comp}$  together with the rest of the probabilities we get the probability of successfully hunting a stag as,

$$\Pi_S = P_S \sum_{k=0}^{G-1} \binom{G-1}{k} P_{comp} [f(k, u^*) (1 - \delta_{a_1^*}) + (1 - f(k, u^*)) (1 - \delta_{a_2^*})] \quad (\text{SI.5})$$

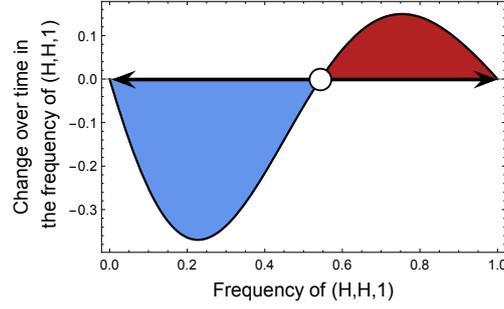
446 The average payoff of an individual with strategy  $(a_1^*, a_2^*, u^*)$  is then given simply by,

$$\pi_{(a_1^*, a_2^*, u^*)} = \Pi_H + \Pi_S \quad (\text{SI.6})$$

The population dynamics can then be represented by the set of replicator equations [64],

$$\dot{x}_i = x_i (\pi_i - \bar{\pi}) \quad (\text{SI.7})$$

447 for each strategy  $i$ . There are eight possible strategies and hence the dynamics  
 448 resides in a seven-dimensional simplex.



**Figure SI.1: Dynamics on the edge between the pure strategies  $(H, H, 1)$  and  $(S, H, 1)$ .** If only a small fraction of the population plays the  $(H, H, 1)$  strategy in a population predominantly composed of  $(S, H, 1)$  individuals then the group form will consist mostly of stag hunters. While  $(S, H, 1)$  individuals hunt stag it will be a stable strategy. If the number of  $(H, H, 1)$  individuals is above the unstable threshold then stag hunting is not viable since the minimum number of stag hunters required for a successful hunt will not be present but the  $(H, H, 1)$  individuals thrive. Parameters are:  $G = 5, M = 4, P_S = 4; P_H = 1$ .

**Dynamics between pure states** The eight vertices of the simplex represent the pure strategies, homogeneous states where all individuals play the same strategy. We study the dynamics between all the pairwise combinations of these pure states. Assume a population which can have only  $(H, H, 1)$  and  $(S, H, 1)$  individuals. For a group size  $G = 5$  with a threshold number of stag hunters required for a successful hunt set at  $M = 4$  a stag provide a payoff of 4 while a hare is worth 1. Using these values the average payoff of a  $(H, H, 1)$  strategist is simply  $\pi_{HH1} = (x_{HH1} + x_{SH1})^4$ . The average payoff for a  $(S, H, 1)$  player on the other hand is,

$$\pi_{SH1} = 4(4x_{HH1}x_{SH1}^3 + x_{SH1}^4) \quad (\text{SI.8})$$

449 Plotting the replicator equation for a population of just these two types gives us  
 450 Figure SI.1. In this manner we can describe the dynamics between all the eight  
 451 vertices, as shown in the main text.

## 452 Evolutionary dynamics in finite populations

453 We assume a finite population of size  $N$ . From this population we choose individuals  
 454 to form a group of size  $G$ . If the number of individuals with strategy  $j$  is given by  $i_j$   
 455 encapsulated in the vector  $\mathbf{i}$ , then the average payoff of a strategy  $(a_1^*, a_2^*, u^*)$  is given  
 456 by,

$$\pi_{(a_1^*, a_2^*, u^*)} = \sum_{k=0}^{G-1} \left( P_H \frac{\binom{i_1 i_3 i_5 i_7}{k} \binom{i_2 i_4 i_6 i_8}{G-1-k}}{\binom{N-1}{G-1}} (f(k, u^*) \delta_{a_1^*} + (1 - f(k, u^*)) \delta_{a_2^*}) \right. \quad (\text{SI.9}) \\ \left. P_S P_{comp}(k, u^*, \mathbf{i}) (f(k, u^*) (1 - \delta_{a_1^*}) + (1 - f(k, u^*)) (1 - \delta_{a_2^*})) \right).$$

The composition of the group  $P_{comp}$  is reevaluated for finite populations as,

$$P_{comp} = \sum_{\substack{l=0 \\ m=0 \\ n=0 \\ o=0}}^k \sum_{\substack{p=0 \\ q=0 \\ r=0 \\ s=0}}^{G-1-k} \frac{\binom{i_1}{l} \binom{i_2}{p} \binom{i_3}{m} \binom{i_4}{q} \binom{i_5}{n} \binom{i_6}{r} \binom{i_7}{o} \binom{i_8}{s}}{\binom{N-1}{G-1}} \chi(u^*) [Q(l, m, n, o, p, q, r, s)] \quad (\text{SI.10})$$

457 again with  $Q$  as defined in Eq. (SI.4). With this approach we can calculate the av-  
 458 erage payoff of each strategy when playing with another strategy. However for finite  
 459 populations, we convert the payoff  $\pi_i$  of a strategy  $i$  to its fitness  $\psi_i$  via a mapping of  
 460 the form  $\psi_i = 1 + \omega \pi_i$  where  $i$  encompasses the strategies encoded by  $(a_1^*, a_2^*, u^*)$ .  
 461 Such a combination with  $\omega$  allows us to tune the impact of the game on the fitness  
 462 [65]. If  $\omega$  the selection intensity is very low  $\omega \rightarrow 0$  then the strategies are neutral with  
 463 respect to each other. Evolutionary dynamics would then be a random walk between  
 464 the eight strategies. On the other hand for  $\omega \rightarrow 1$  the game completely determines  
 465 the difference between the strategy fitness. All of this definitely assumes that the  
 466 strategies do not go extinct, i.e. the mutation probability is non-zero  $\mu > 0$ .

Assuming small mutation rates  $\mu \rightarrow 0$ , the dynamics typically takes place between  
 two strategies only. Hence a pairwise comparison of the fitnesses of the strategies  
 proves to be instructive. The fitness of a strategy  $i$  playing against strategy  $j$  is given  
 by  $\psi_{i,j}$ . This allows us to calculate the fixation probability of a single strategy  $i$  player

in a population of  $N - 1$  strategy  $j$  players as,

$$\rho_{i,j} = \frac{1}{\sum_{k=1}^{N-1} \prod_{m=1}^k \frac{\psi_{j,i}}{\psi_{i,j}}} \quad (\text{SI.11})$$

Collating the fixation probabilities between all pairwise combinations provides us with the following transition matrix  $\mathbf{A}$ ,

$$\mathbf{A} = \begin{pmatrix} 1 - \sum \text{column} & \rho_{1,2} & \rho_{1,3} & \rho_{1,4} & \rho_{1,5} & \rho_{1,6} & \rho_{1,7} & \rho_{1,8} \\ \rho_{2,1} & 1 - \sum \text{column} & \rho_{2,3} & \rho_{2,4} & \rho_{2,5} & \rho_{2,6} & \rho_{2,7} & \rho_{2,8} \\ \rho_{3,1} & \rho_{3,2} & 1 - \sum \text{column} & \rho_{3,4} & \rho_{3,5} & \rho_{3,6} & \rho_{3,7} & \rho_{3,8} \\ \rho_{4,1} & \rho_{4,2} & \rho_{4,3} & 1 - \sum \text{column} & \rho_{4,5} & \rho_{4,6} & \rho_{4,7} & \rho_{4,8} \\ \rho_{5,1} & \rho_{5,2} & \rho_{5,3} & \rho_{5,4} & 1 - \sum \text{column} & \rho_{5,6} & \rho_{5,7} & \rho_{5,8} \\ \rho_{6,1} & \rho_{6,2} & \rho_{6,3} & \rho_{6,4} & \rho_{6,5} & 1 - \sum \text{column} & \rho_{6,7} & \rho_{6,8} \\ \rho_{7,1} & \rho_{7,2} & \rho_{7,3} & \rho_{7,4} & \rho_{7,5} & \rho_{7,6} & 1 - \sum \text{column} & \rho_{7,8} \\ \rho_{8,1} & \rho_{8,2} & \rho_{8,3} & \rho_{8,4} & \rho_{8,5} & \rho_{8,6} & \rho_{8,7} & 1 - \sum \text{column} \end{pmatrix} \quad (\text{SI.12})$$

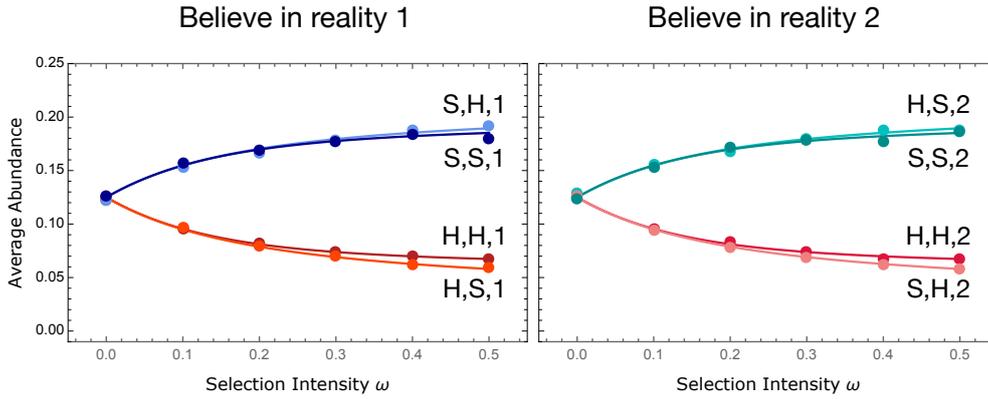
467 The normalised right eigenvector of  $\mathbf{A}$  corresponding to the largest eigenvalue (which  
 468 is 1) provides the stationary distribution of the system [66]. This analytical result is  
 469 plotted as full lines in Figure SI.2 for a given choice of parameters.

## 470 **Alternative decision making rules**

471 We have assumed that the hunting party decides the choice of reality, and hence  
 472 the ensuing actions of the involved individuals via a frequency dependent process  
 473 (Eq. (SI.1)). In this section describe the dynamics and the eventual distribution of the  
 474 strategies when the group uses alternative methods for reality consensus forming.

### 475 **Fixed probability of realising a reality**

476 Instead if the group instead decides the choice of reality with a fixed probability then  
 477 the outcome of such a process is qualitatively different than the one discussed in the  
 478 main text. For a fixed value of 0.5 we show the dynamics for infinitely large populations  
 479 in Fig. SI.4



**Figure SI.2: Average abundance in the long run.** In the long run the strategies in the population stabilise at the proportions which can be calculated analytically (lines) and the results supported by individual based simulations (symbols). For a population of size 16, and a small mutation probability of  $\mu = 10^{-3}$ , the average abundance of the eight different strategies is denoted above for a variety of selection intensities (after  $2 \times 10^9$  time-steps). The fitness of each type  $i$  is given by  $\psi_i = 1 + \omega\pi_i$ , where  $\omega$  is the selection intensity. For  $\omega = 0$  selection is neutral and all strategies exist in equal proportions ( $1/8^{\text{th}} = 0.125$ ). As selection increases, we see the prevalence of the stag hunters in the population, irrespective of their belief. Parameters are  $N = 16$ ,  $G = 5$ ,  $M = 4$ ,  $P_S = 4$  and  $P_H = 1$ .

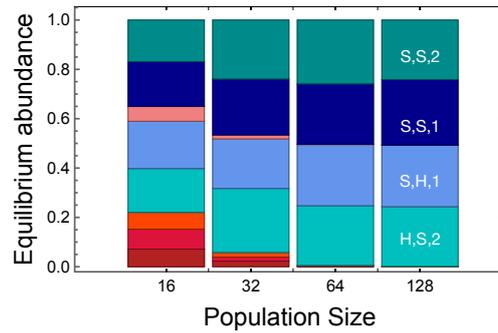
480 **Majority vote**

481 Whereas the frequency dependent nature of decision making introduces a level of  
 482 stochasticity in the system, a majority vote removes the ambiguity. If the number of  
 483 objective reality, 1, believers form a majority, i.e.  $k + \delta_{u^*} > G/2$  then we assume that  
 484 the group decides on the inter-subjective reality to be reality 1 (and 2 otherwise).

Majority vote is denoted by a modification of the group decision function to:

$$f(k, u^{star}) = \begin{cases} 1, & \text{if } k + \delta_{u^*} > G/2 \\ 0, & \text{otherwise.} \end{cases} \quad (\text{SI.13})$$

485 For a given parameter set the resulting deterministic dynamics between the pure  
 486 states are shown in Fig. SI.5. Interestingly we see a feedback to the all hare states



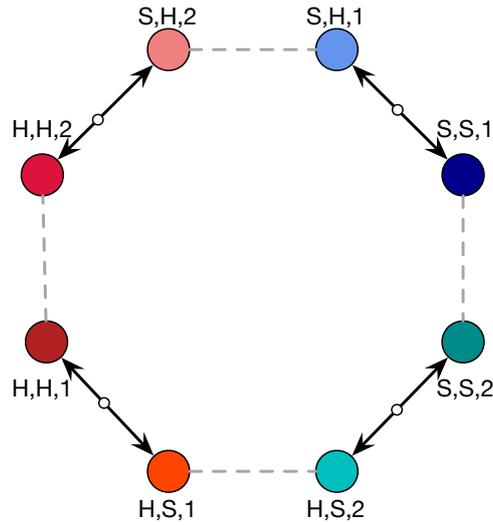
**Figure SI.3: Equilibrium abundance across population sizes.** For increasing population size, the effect of drift gets diluted and the deterministic equilibrium of the system emerges, which is composed of individuals hunting stags. Simulation parameters besides the changing population size are  $\omega = 0.4$ ,  $G = 5$ ,  $M = 4$ ,  $P_S = 4$  and  $P_H = 1$  with  $\mu = 10^{-3}$ . The system status is reported after  $5 \times 10^6$  time-steps.

487 from the jump states of (H,S,1) and (S,H,2). In the long run however, the population  
 488 will escape this cycling and end up in the stag hunting state as seen in Fig. SI.6.

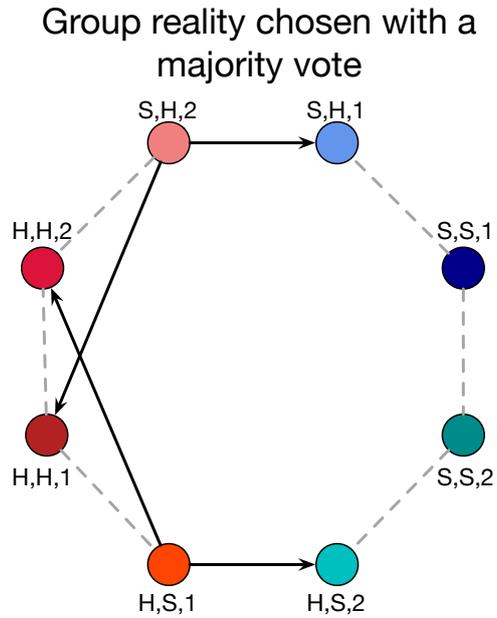
### 489 **Costly beliefs**

490 If the secondary belief, the subjective reality is cognitively costly, the individual who  
 491 prefer 2 would pay a cognitive cost. As the cost increases indeed the alternative  
 492 belief will be harder to fix in the population. However the alternative belief still acts  
 493 as a catalyst Fig. SI.7. It appears in a finite population by chance but spreads as it  
 494 is still better to hunt stags than hares. However when everyone is hunting stags, the  
 495 cognitive cost of maintaining the belief reduces the frequency of the believers. For  
 496 increasing costs clearly the belief declines however the population is left transformed  
 497 in a stag equilibrium.

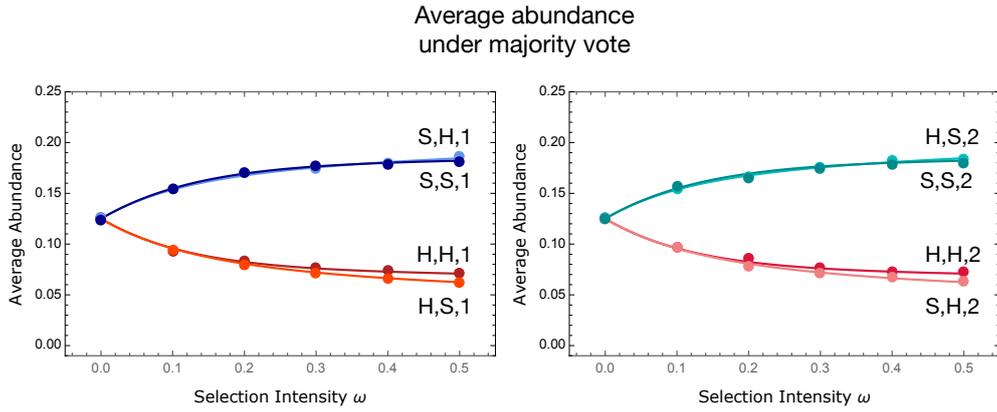
Group reality chosen with a fixed probability 0.5



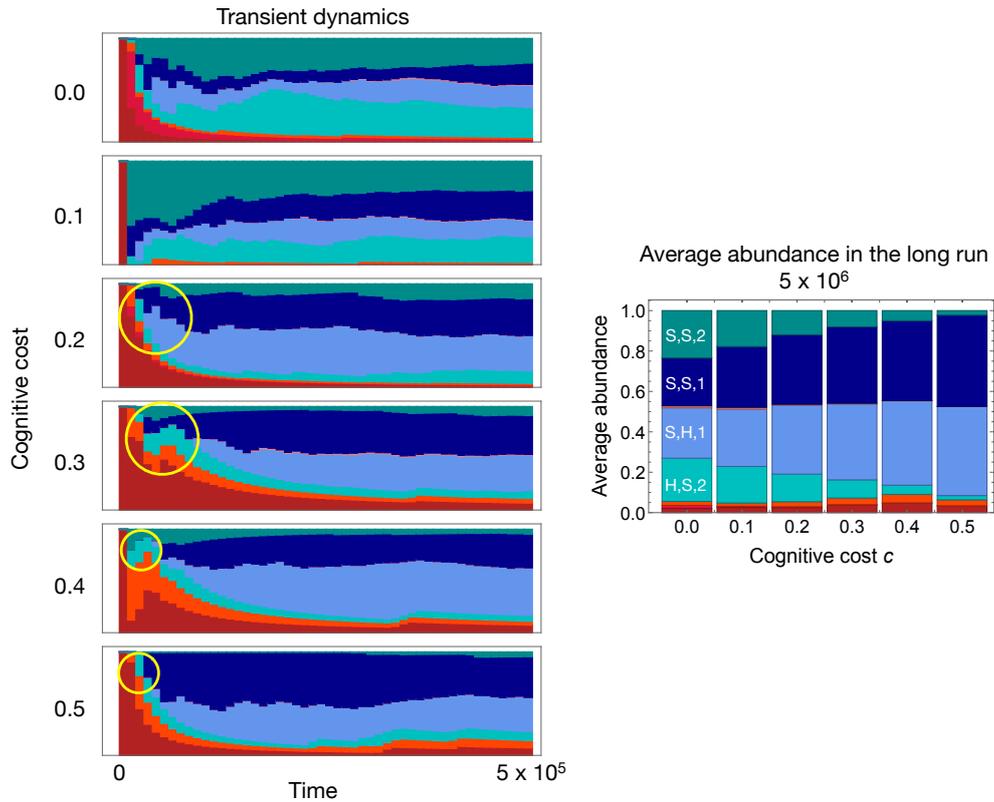
**Figure SI.4: Deterministic dynamics for a fixed group decision.** Instead of a frequency-dependent process as in Eq. (SI.1), if the reality is decided as 1 with probability 0.5 then the eventual outcome is as shown in the figure. We do not show the links in the interior as all of them consist of an unstable equilibrium and are hence impassable. A population starting at (H,H,1) will be stuck in the hare equilibrium (H,H,\*). The appearance of the unstable fixed points along the edges lock the population in pure hare or pure stag states. Parameters used here are,  $G = 5$ ,  $M = 4$ ,  $P_S = 4$  and  $P_H = 1$  with the function  $f(k, u^*) = 0.5$ . Qualitatively similar dynamics are obtained for other fixed values of  $f(k, u^*)$ .



**Figure SI.5: Deterministic dynamics for a majority vote decision.** Instead of a frequency-dependent process as in Eq. (SI.1), the group reality is chosen by a majority vote. The group reality is then the one which more than  $G/2$  members prefer. In this case we see the appearance of a loop where (S,H,2) and (S,H,1) can lead back to the all hare hunters. However, in the long run, stag hunting is the ultimate sink for the dynamics. Parameters used here are,  $G = 5$ ,  $M = 4$ ,  $P_S = 4$  and  $P_H = 1$  with the function  $f(k, u^{star})$  returns the chosen reality if the majority believes in it.



**Figure SI.6: Average abundance in the long run under voting.** In the long run the strategies in the population stabilise at the proportions which can be calculated analytically (lines) and the results supported by individual based simulations (symbols). For a population of size 16, and a small mutation probability of  $\mu = 10^{-3}$ , the average abundance of the eight different strategies is denoted above for a variety of selection intensities (after  $2 \times 10^9$  time-steps). The fitness of each type  $i$  is given by  $\psi_i = 1 + \omega\pi_i$ , where  $\omega$  is the selection intensity. For  $\omega = 0$  selection is neutral and all strategies exist in equal proportions ( $1/8^{\text{th}} = 0.125$ ). As selection increases, we see the prevalence of the stag hunters in the population, irrespective of their belief. Parameters are  $N = 16$ ,  $G = 5$ ,  $M = 4$ ,  $P_S = 4$  and  $P_H = 1$ .



**Figure SI.7: Costly beliefs.** Even if the preference for the alternative belief accrues a cognitive cost, we show that it helps transform the population into a social group where everyone prefers to hunt stags. The alternative belief acts as a stepping stone (highlighted in the transients on the left by the circles), where the belief in 2 enables the spread of stag hunter who believe in 1. Thus acting as a true catalyst, the belief helps transform the population and then disappears. The dynamics of the eight strategies for different levels of cognitive costs is shown for a finite population of size 32, and a small mutation probability of  $\mu = 10^{-3}$ . The equilibrium average abundance of the eight different strategies, which can be calculated analytically is shown in the right panel for a variety of cognitive costs (after  $5 \times 10^6$  time-steps). As selection increases, we see the prevalence of the stag hunters in the population, irrespective of their belief. Parameters are  $N = 16$ ,  $G = 5$ ,  $M = 4$ ,  $P_S = 4$  and  $P_H = 1$ . The selection intensity is set to  $\omega = 0.5$ .