



**HAL**  
open science

# Improving human collective decision-making through animal and artificial intelligence

Christophe Bousquet, Romain Espinosa, Jean-Louis Deneubourg, Cédric Sueur

► **To cite this version:**

Christophe Bousquet, Romain Espinosa, Jean-Louis Deneubourg, Cédric Sueur. Improving human collective decision-making through animal and artificial intelligence. 2021. hal-03299087v1

**HAL Id: hal-03299087**

**<https://hal.science/hal-03299087v1>**

Preprint submitted on 28 Jul 2021 (v1), last revised 30 Aug 2021 (v3)

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Improving human collective decision-making through animal and artificial intelligence**

2 Christophe Bousquet<sup>1,2,\*</sup>, Romain Espinosa<sup>3,4</sup>, Jean-Louis Deneubourg<sup>5</sup>, Cédric Sueur<sup>6,7,\*</sup>

3 <sup>1</sup> Laboratoire Cogitamus, <https://www.cogitamus.fr/>

4 <sup>2</sup> Centre de Recherche en Neurosciences de Lyon, CRNL Inserm U1028 - CNRS UMR5292 -

5 UCBLyon1

6 <sup>3</sup> CNRS, CREM – Université Rennes 1, France

7 <sup>4</sup> Rennes School of Business, France

8 <sup>5</sup> Center for Nonlinear Phenomena and Complex Systems (Cenoli) - CP 231, Université Libre

9 de Bruxelles (ULB), Campus Plaine, Boulevard du Triomphe, Building NO - level 5, B-1050,

10 Bruxelles, Belgium.

11 <sup>6</sup> Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France

12 <sup>7</sup> Institut Universitaire de France, Saint-Michel 103, F-75005 Paris, France

13 \*Correspondence: [cedric.sueur@iphc.cnrs.fr](mailto:cedric.sueur@iphc.cnrs.fr) (C. Sueur); [chr\\_bousquet@protonmail.com](mailto:chr_bousquet@protonmail.com) (C.

14 Bousquet)

15

16 **Abstract**

17 **Whilst fundamental to human societies, voting systems can lead to suboptimal decisions,**

18 **as past climate policies demonstrate. Current systems are harshly criticized for the way**

19 **they consider voters' needs and knowledge. Voting is central in human societies but also**

20 **occurs in animal groups mostly when animals need to choose when and where to move. In**

21 **these societies, animals also consider the needs of the group members and rely on the**

22 **expertise of the most knowledgeable. Recent works in artificial intelligence have sought to**

23 **improve decision-making in human groups, sometimes inspired by animals' decision-**

24 **making systems. We discuss here how our societies could benefit from recent advances in**  
25 **ethology and artificial intelligence to improve our collective decision-making system.**

26 **Keywords: collective decisions, vote, democracy, representativeness, machine learning**

27 **Rethinking current voting systems**

28         The voting system is a pillar of our societies. However, voting may sometimes lead to  
29 suboptimal or non-representative decisions. This was the case with the election of François  
30 Hollande in 2012 <sup>1</sup> and the election of Donald Trump in 2016 <sup>2</sup>. These two instances illustrate  
31 a first issue of our democracies, the Condorcet paradox (Box 1). Besides, society has become  
32 more polarised on many issues, due to the massive use of social networks and influencers <sup>3,4</sup>,  
33 while the political supply has not become more diverse. This combination of high  
34 polarisation and low political diversity results in a decrease in citizens' satisfaction with  
35 democracy <sup>5</sup>. In addition, Western democracies suffer from low turnout rates (only one out  
36 of two European voters took part in the 2019 European elections,  
37 <https://www.europarl.europa.eu/election-results-2019/en/turnout/>), which further  
38 weakens the political systems. It is therefore essential to find solutions that ensure citizens'  
39 acceptance. The issues that may lead to dissatisfaction with elections or referendums can be  
40 summarised in three categories: 1. the **voting systems** (see Glossary), 2. the needs of  
41 citizens, and 3. the knowledge on which electors base their decisions. Each of these  
42 categories could benefit from recent findings in animal and **artificial intelligence (AI)**.

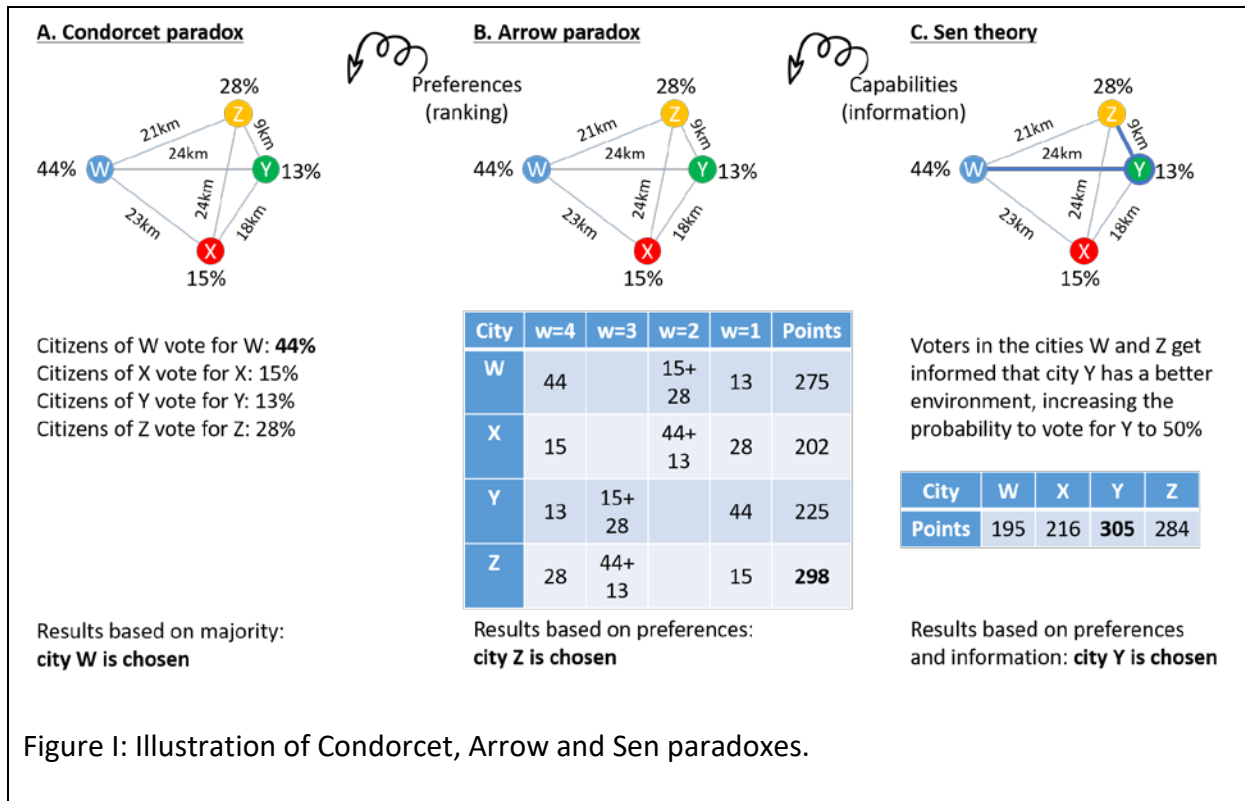
43         Humans are not the only species that use group processes to make important  
44 choices. These concepts also exist in other animal societies, in which voting systems are  
45 readily used, for instance to decide where to go (Box 2). These decisions can be complex  
46 since they involve many (up to thousands) individuals having different needs and  
47 information about a complex environment with high conflicts needing resolution and wrong

48 decisions potentially leading to death. Acquiring information is costly, which is why animals  
49 often rely on their groupmates to get informed <sup>6</sup>. By pooling information and needs within  
50 the group, these social species seem to solve the paradoxes of majority voting (Box 1), and  
51 thus take decisions that ensure group cohesion. Indeed, decision making and rules of  
52 interaction are selected for over generations to improve speed and accuracy of decisions  
53 and therefore biological fitness of those making such decisions. Because of this strong  
54 natural selection increasing the **efficiency** of animal systems, authors call for researches on  
55 animal systems to improve the decision-making process in human societies, especially in link  
56 with AI <sup>7-11</sup>: bioinspiration for AI may conduct to better understand and control AI behaviour  
57 <sup>12</sup>. Nowadays, AI is more and more capable to solve problems of aggregation of individual  
58 preferences. Its implementation in human voting processes is now possible, if not inevitable  
59 (Box 3). Identifying any similarities and continuities between different species and AI should  
60 permit a more unified and informed understanding of group decision-making processes and  
61 outcomes in humans and other animals. Whilst it is difficult to know the optimal outcomes  
62 in real situations, experimental studies on animals and humans allow assessing this <sup>13</sup>. This  
63 paper seeks to show how animal studies can inspire AI devoted to increase voting system's  
64 effectiveness.

65 ***Box 1. Condorcet, Arrow and Sen Paradoxes***

66 The Condorcet paradox (Fig. I.A) stipulates that when asking voters to put four proposals W,  
67 Z, X and Y in order of preference, we obtain a cycle (i.e. a majority of participants preferring  
68 W to X, a majority preferring X to Y and a majority preferring Y to W). To illustrate this  
69 concept, imagine that a new school has to be built and the inhabitants have to choose which  
70 of four towns it will be located in (W, X, Y and Z, Fig. I.A). If the referendum has only one  
71 round and each citizen votes for his or her own city, city W would be chosen as the location

72 of the new school with 44% of votes. However, if the referendum has two rounds, city W  
73 and city Z would make it to the second round, and city Z should be chosen with 56% of votes.  
74 If each citizen ranks his or her preferences, we should obtain  $W > Z > X > Y$  for city W,  $X > Y > W > Z$   
75 for city X,  $Y > Z > X > W$  for city Y and  $Z > Y > W > X$  for city Z. So, whilst W would be chosen for the  
76 school in a one-round referendum, Y would be preferred to W three out of four times when  
77 dyads are compared. To solve this issue, Arrow proposed classifying proposals instead of  
78 choosing the majority. This kind of evaluative vote has been shown experimentally to  
79 produce different results from majority voting<sup>1</sup>. Here, the top-ranked city receives 4 points  
80 (weight  $w$  in the table on Fig. I.B), while the second and third-ranked cities receive three and  
81 two points respectively. The lowest-ranked study obtains only one point. This ranking system  
82 shows city Z to be the chosen location for the school, followed by W, Y and lastly X. Sen (Fig.  
83 I.C) considered that although each citizen may have the right to vote, they may not  
84 necessarily be able to do so. Sen distinguished the right to vote from the full capability to  
85 cast this vote<sup>67</sup> (Fig. I.C). In Fig. I.C, we presume that citizens were informed that city Y has a  
86 better environment (trains and less pollution), and 50% of W and Z citizens preferred their  
87 children to go to city Y instead of their own city. In this condition, city Y would be ranked in  
88 first position and thus chosen as the location to build the school.



89

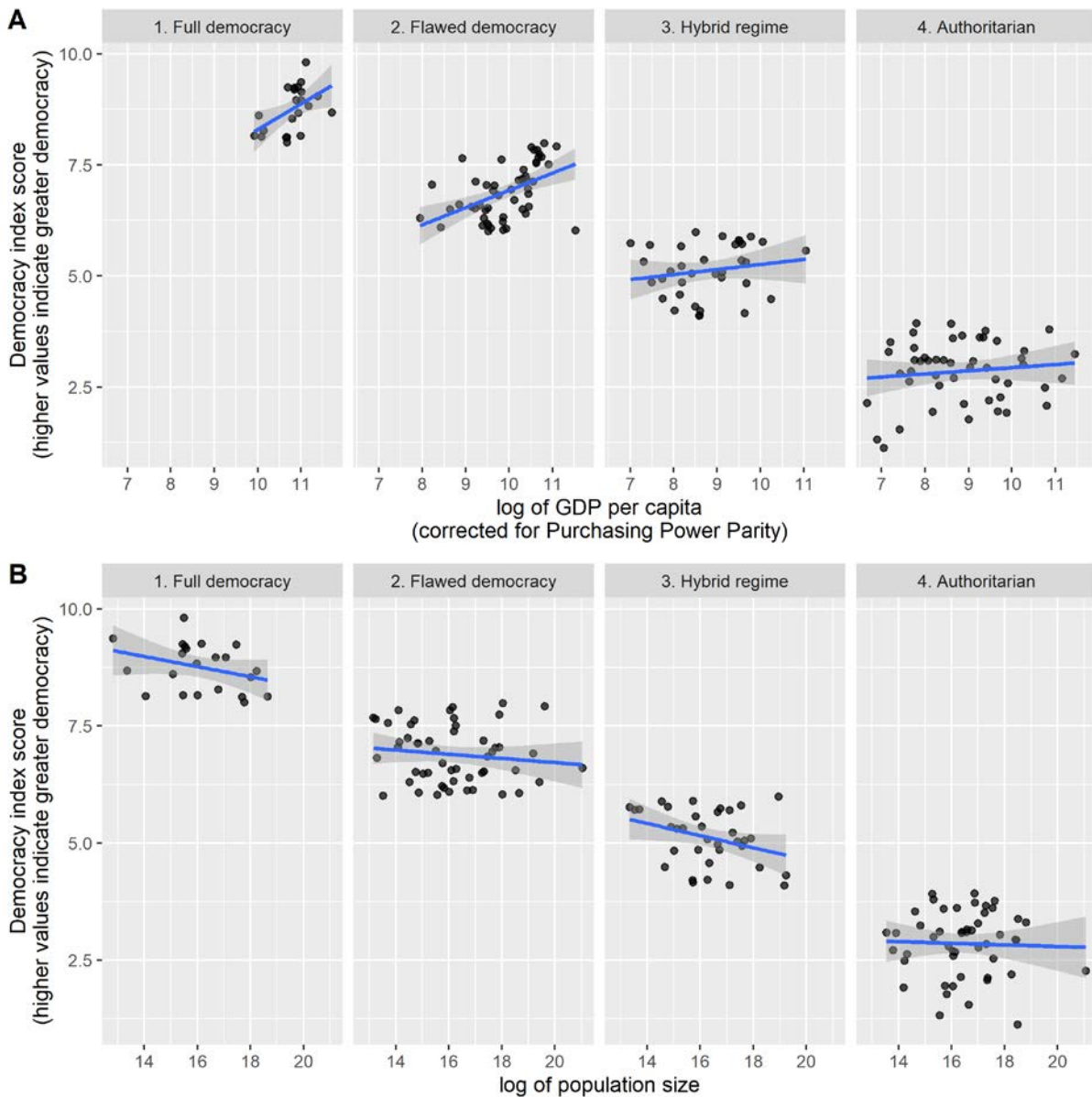
90 Figure I: Illustration of Condorcet, Arrow and Sen paradoxes.

91

92 **The different systems used to aggregate individual preferences**

93 Different systems can be used to aggregate individual preferences, bearing in mind  
 94 that heterogeneous preferences and beliefs hinder conflict resolution. Human political  
 95 systems range from authoritarian regimes to full democracies, depending on the distribution  
 96 of weights for each individual in society (Fig. 1). Authoritarian regimes are more likely to  
 97 emerge and sustain themselves if the despots manage to secure a relative advantage in  
 98 fighting ability<sup>14,15</sup>. In democracies, the most commonly used representation system is the  
 99 voting system with majority voting. For this system to be efficient, members of the majority  
 100 should be competent and benevolent<sup>16</sup>. Furthermore, voters' opinions should be formed  
 101 independently, without influence<sup>16</sup>. However, many voting cases in history have shown that  
 102 these assumptions are not met in practice, leading to suboptimal decisions or ineffective  
 103 leadership for our societies. This is why some political researchers recommend banning  
 104 polls, which lead to a change in voter behaviour known as the "bandwagon effect"<sup>17</sup> and are

105 criticised because they are flawed in many ways<sup>18</sup>. Besides, one may question the validity of  
 106 a vote and the satisfaction of voters when the relative size of the majority is low. The Brexit  
 107 48/52% conundrum is a perfect example<sup>19</sup>. However a strong majority (90/10%) also shows  
 108 a democracy fallacy<sup>20</sup>.  
 109



110  
 111 Figure 1. Relationship of the Democracy Index Score (DIS) (each point represents a country)  
 112 with the logarithm of the country's Growth Domestic Product per capita, corrected for  
 113 purchasing power parity (A) and the logarithm of the country's population size (B). Within  
 114 each regime type, a higher democracy index is more likely when GDP per capita is high  
 115 (LMM:  $0.19 \pm 0.06$ ,  $t = 2.990$ ,  $p < 0.01$ ) (Fig. 1A). There is also a tendency for countries with  
 116 smaller populations to be more democratic (LMM:  $-0.08 \pm 0.05$ ,  $t = -1.692$ ,  $p = 0.09$ ) (Fig. 1B).

117 The analysis takes into account the overall regime type of the country by adding this variable  
118 as a random effect in the model. Data come from the following websites: Democracy Index  
119 (<https://www.eiu.com/topic/democracy-index>), GDP  
120 (<https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD>) and population size  
121 ([https://en.wikipedia.org/wiki/List\\_of\\_countries\\_and\\_dependencies\\_by\\_population](https://en.wikipedia.org/wiki/List_of_countries_and_dependencies_by_population)).  
122 Data and analyses script are available at Zenodo. <http://doi.org/10.5281/zenodo.4703733>  
123

124

125         This model—where one alternative is chosen until it is more popular than another,  
126 however small the difference may be—is called the **Race Model** and was proved to be  
127 suboptimal compared to the **Drift-Diffusion Model** (DDM) <sup>21–24</sup>. The DDM stipulates that the  
128 differences between two alternatives have to reach a threshold and this model, operating in  
129 brain and collective decision processes, is far more efficient than the race model <sup>25,26</sup>. It is  
130 adaptive in urgent situations where decision speed is favoured to accuracy <sup>24,26</sup>. This model  
131 should replace majority voting in order to solve the issue of proportionality. For instance, the  
132 Belgian Parliament chose a two-thirds supermajority quorum <sup>27</sup>. This use of different  
133 quorums could help to generalise the **Condorcet jury theorem** to a wider range of decision  
134 ecologies <sup>28</sup>. In decision ecology, individuals are prone to two different types of errors: false  
135 positives and false negatives. Yet, in its simplest form, the Condorcet theorem assumes that  
136 both errors are identical. When this assumption is relaxed (when the probability of a false  
137 positive differs from the probability of a false negative), it can be shown that majority voting  
138 becomes suboptimal and should be replaced by sub- or supermajority quorums depending  
139 on the conditions <sup>28</sup>. Current voting systems could also be improved by creating independent  
140 small groups of voters and pooling votes within each group, either by majority rule or  
141 another rule. Such settings have proved to provide better and more robust collective  
142 decisions in a variety of contexts <sup>13,29,30</sup>.



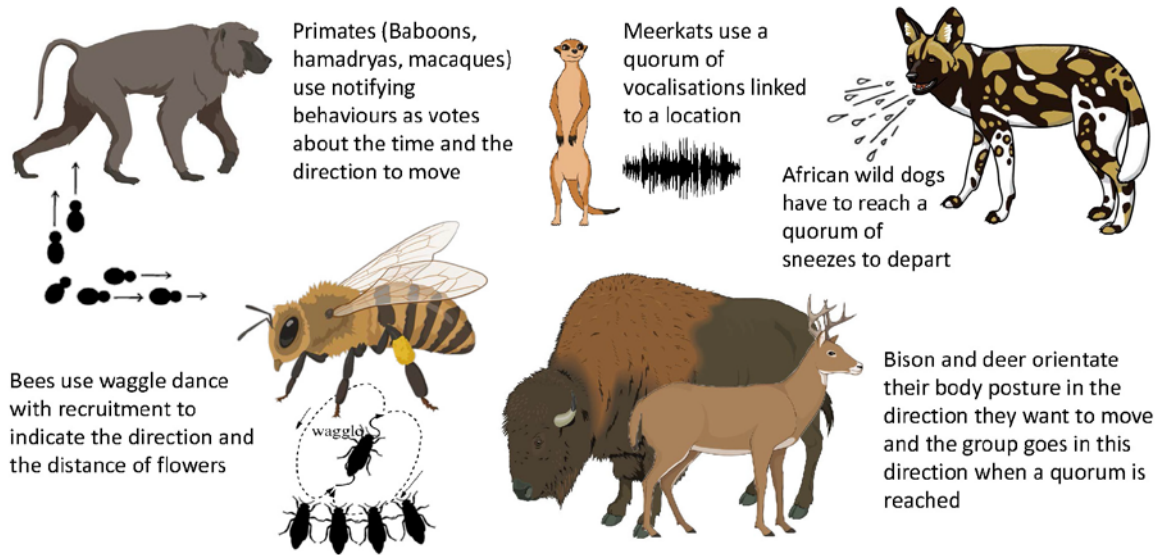
143           In animals, the spectrum of weight distributions for individual preferences is also  
144 quite broad. Animals have different needs according to their physiological status, different  
145 knowledge about their environment and different personality types<sup>31</sup>. These variables may  
146 have synergetic effects to determine which individuals will emerge as a leader<sup>32</sup>. Some  
147 species can be classified as despotic, particularly when there is a large difference in  
148 resource-holding potential within a group<sup>33</sup>. In other species, some group members have a  
149 greater weight in group decisions, especially when these individuals possess a greater  
150 knowledge of the environment that can benefit all group members. Still, mechanisms are at  
151 work to allow most if not all group members to express their preferences. One such  
152 mechanism is to attain a specific number of individuals (a quorum) notifying a preference  
153 (Box 2). Once this quorum is reached, the probability of deciding for the proposed  
154 alternative sharply shifts, leading to a group consensus. However, supermajority quorums  
155 could be used by a minority to maintain the status quo, without aiming at finding a  
156 consensus. Such an attitude could be detected by non-cooperative behaviour detection  
157 algorithms, which could then reduce the weight of this uncooperative minority in the  
158 calculation of consensus degree<sup>34</sup>. Quorum decisions are used to manage competing needs  
159 and information in order to decrease decision errors<sup>28,35</sup>. This solution to a collective  
160 problem can work without needing high cognitive capacities: much of these collective  
161 decisions are the result of relatively simple interaction patterns among group members. In  
162 such 'self-organising systems', multiple individuals following simple rules can produce  
163 complex collective behaviours without requiring high abilities at the individual level<sup>25,36</sup>,  
164 which is of great relevance for AI systems used in voting systems.  
165

166 **Box 2: Voting behaviours in animals**

167 Living in groups bring many advantages but animals have to resolve conflict of interests to  
168 maintain their cohesion and these advantages, through collective decisions. These conflicts  
169 of interests might be on needs of individuals as in primate groups or on information about  
170 different sites as in honeybees swarming<sup>89</sup>. Whilst animals do not elect president (but see<sup>90</sup>  
171 to choose the dominant male in an animal society), they use democratic systems in their  
172 everyday life<sup>40,86,91</sup>. Non-human animals do not have the sophisticated language capacity of  
173 humans but this does not mean that they cannot deliberate and negotiate over different  
174 alternatives and vote for them<sup>40,49,91,92</sup>. Group decision-making is common in the animal  
175 kingdom, and occurs in social insects, fish and mammals (Fig. II). Recent empirical studies  
176 have shown that the decision-making of social species happens through the adoption of  
177 symbolic systems for consensus construction (vocalisations, movements of intentions,  
178 notifying behaviours and dances)<sup>45</sup>. In ethology, voting means that “an animal  
179 communicates its individual preference with regard to the decision outcome”<sup>50</sup> and the  
180 decision is a sign of an “ecological rationality” and intention, the effectiveness of which is  
181 assessed over long evolutionary periods. These voting processes are mostly used to decide  
182 about where and when to go for foraging or for resting. Whilst it is difficult to find a  
183 compromise between two proposed directions, it is possible to satisfy the Condorcet winner  
184 criterion with an average of voters about the time to go (i.e. the **mean voter theorem**). Of  
185 course, this does not mean that these species have the same mental states as humans but  
186 their behaviours suggest certain cognitive capabilities as degrees of theory of mind<sup>93,94</sup>.  
187 Quorum decisions, which include the majority vote as a particular case, allow the  
188 maintenance of group cohesion, the enhancement of decision accuracy compared with  
189 single individuals, and improved decision speed<sup>35</sup>. Whilst the quorum number might be

190 quite low (three in capuchin monkeys <sup>95</sup> or meerkats <sup>44</sup>, or about 30% of the group in deer <sup>50</sup>  
191 or macaques <sup>49</sup>), it generally represents the most pressing needs and information for at least  
192 some members of the society.

193



194

195 Figure II: Species showing these different voting behaviours, specifically primates <sup>49,99</sup>,  
196 meerkats <sup>44</sup>, African wild dogs <sup>43</sup>, honeybees <sup>86</sup>, bison <sup>100</sup> and deer <sup>50</sup>.

197

198 Indeed, humans benefit from a number of recent advances in AI to improve voting  
199 systems (Box 3). The first example is an algorithm developed to counter electoral  
200 gerrymandering by creating electoral districts that are representative of the global  
201 population <sup>37</sup>. Another perspective is the integration of principles derived from collective  
202 animal processes into AI algorithms <sup>38</sup>. A third approach that requires a democratic debate  
203 makes it technically possible for citizens to be represented by avatars reflecting the  
204 preferences of each voter rather than by politicians <sup>39</sup>.

205 Overall, many studies confirmed that the DDM with a quorum threshold seems to be  
206 more efficient than simple majority voting. Another difference between collective decisions  
207 in humans and non-human animals is that the latter do not elect representatives like  
208 humans do, but decide together throughout the day, as a **participatory democracy**. Besides,  
209 non-human animals typically take decisions for short-term aims (those that will occur within  
210 minutes or hours after the decision). There are many multilevel animal societies in which  
211 some individuals have more influence than others at different organisation levels.  
212 Importantly, having a greater weight in the decision does not mean that they are the sole  
213 decision makers. This looks like the participatory democracy (or shared consensus) that  
214 many human citizens request today and seems to be more efficient than a monopolised  
215 leadership (unshared consensus), but the consensus type depends on the population  
216 homogeneity in terms of needs and knowledge <sup>40,41</sup>.

217

### 218 **The needs of citizens**

219 Decision makers within a group vary in terms of needs, goals and preferences.  
220 Therefore, choosing an alternative generally only satisfies individuals who vote for this  
221 alternative. Arrow's impossibility theorem stipulates that there is no way to always  
222 aggregate all individual choices within one voting system. However, when within-group  
223 choices become more aligned, as in emergency or wars, more cohesive or coercive systems  
224 may become more acceptable. Previous theoretical studies worked on this homogeneity  
225 concept <sup>40,41</sup>: when animals all have the same needs, a single leader system is more viable as  
226 all individuals are satisfied and the decisions are taken more rapidly than those made using  
227 democratic systems, which require participants to vote. This is an auto-emergent  
228 dictatorship <sup>41</sup>. However, it is clear that this system is not viable when group members differ

229 in their physiological and social needs and preferences. Moreover, models, confirmed by  
230 empirical data<sup>33</sup>, show that the system collapses if the despot disappears, and a wrong  
231 decision taken by the despot may have strong negative consequences for all individuals<sup>40–42</sup>.  
232 Conradt and Roper's model<sup>40</sup> indicate that democratic decisions can evolve when groups  
233 have a heterogeneous composition. The higher the heterogeneity, the harsher the conflicts  
234 and the more unlikely the conflict resolution. From an evolutionary perspective, animal  
235 societies have managed to resolve these conflicts of interest by giving all members the  
236 opportunity to participate in daily decisions but to different extents. Although dominant  
237 individuals can take the role of leader in African wild dogs<sup>43</sup>, meerkats<sup>44</sup> and baboons<sup>33</sup>,  
238 they do not have the exclusive right to decide, but simply a greater weight in the decision<sup>45</sup>.  
239 The alternating of leadership roles among animals can ensure the expression of individual  
240 needs<sup>46</sup>. For a fully functioning democracy, some researchers in political science favour a  
241 switch from participatory democracy to **deliberative democracy**<sup>20,47</sup>. In deliberative human  
242 democracies, it is crucial to allow every citizen to express themselves freely, with a seamless  
243 interface between this public space and the empowered space<sup>48</sup> and to have an equal right  
244 to participate in the public debate, even outside of the electoral process<sup>47</sup>. For instance, the  
245 European Commission regularly launches public consultations to which all stakeholders,  
246 including unions or NGOs, can contribute.

247         A parallel with deliberative democracy can be drawn in animal societies in such a way  
248 that the preferences of almost all members are also taken into account through the  
249 expression of notifying behaviours (Box 2). Choices are not only based on the number of  
250 voters but also on the number of voting behaviours per individual, a cue about motivation  
251<sup>43,45,49</sup>. An individual may show several notifying behaviours as if it could vote several times  
252 or have a vote with a higher weight than other individuals. Through these notifying

253 behaviours, animals negotiate, change their mind and reach a consensus <sup>49</sup>. This type of  
254 decision-making is in accordance with the Borda count, an election method in which voters  
255 rank options in order of preference (Box 1).

256           Another issue with leadership is that it does not safeguard against profiteers  
257 becoming leaders. Humans elect people who propose an electoral platform but who may  
258 want to be leaders for their personal gain and not for the public good. Leaders can be  
259 described as individuals who have a disproportionate level of influence and decision-making  
260 power within their communities, and can distort social relationships to their advantage <sup>50-52</sup>.  
261 Even in non-human animals, leaders shape social dynamics through policing <sup>53</sup> or by  
262 embodying culturally appropriate behaviour <sup>54</sup>. In return, leaders are often rewarded with  
263 privileges <sup>33,53</sup>. Hence, leadership itself is a frequently contested resource that individuals  
264 compete to obtain and/or maintain. This issue may concern humans and some vertebrates  
265 with theory of mind (see a discussion about Machiavellian intelligence in Primates <sup>55</sup>), but is  
266 absent in species such as ants. Machiavellian Intelligence also applies in the context of  
267 strategic votes, which is quite difficult to measure in animals even if studies on private  
268 versus social information may give some cues about decision-making processes <sup>56</sup>. Are  
269 human leaders alpha individuals in a dominance hierarchy <sup>57</sup>? When we look at our  
270 presidents or monarchs, this appears to be quite plausible. Work in psychology showed that  
271 dominant appearance traits are chosen by voters in absence of more political information  
272 <sup>58,59</sup>. Current knowledge in animal and artificial decision-making can help our societies  
273 improve their public decision-making systems and can provide insight about institutional and  
274 electoral design to select the most appropriate candidates for the offices.

275

## 276 **The knowledge on which citizens base their decisions**

277 Knowledge is important to decide which alternative to vote for. Whilst there is a huge  
278 work on this domain in political science<sup>60,61</sup>, only a few scholars grasped the potential  
279 contribution of animal studies to this field.<sup>62,63</sup> Humans and non-human animals have two  
280 ways to access information: learning by themselves and/or learning from others<sup>6,56</sup>. The  
281 most obvious constraint on majority rules for questions having a correct answer is that the  
282 majority of informants the group relies on need to be right<sup>16,28</sup>. In eusocial insects, groups  
283 seem to identify the best information: while very few individuals actually possess relevant  
284 information regarding the decision at hand, decisions are still efficient with a mix between  
285 private and social information<sup>56</sup>. In many cases, individuals check and compare their private  
286 and social information before making a decision. Yet we currently observe in human  
287 societies many fake news voluntarily spread to influence votes for representatives<sup>3,4</sup>. Fake  
288 news is a clear threat to private and social learning as they drive the majority towards a  
289 suboptimal decision that is beneficial to the group of manipulators. Many AI algorithms try  
290 to identify fake news, particularly during election periods<sup>2,64,65</sup>.

291 To comply with the Condorcet theorem, votes should be independent from each  
292 other. However, the heavy reliance on social information in humans is at odds with this  
293 assumption. Therefore, trusting others may have consequences at the individual level<sup>66</sup>, but  
294 also at the group level. At the individual level, this is what Sen called the ‘capability to vote’  
295 (Box 1): although it is nice to vote, it is better when you have the knowledge to vote well<sup>67</sup>.  
296 At the group level, the sum of knowledge leads to the emergence of the ‘wisdom of crowds’  
297 for humans and ‘swarm intelligence’ for non-human animals<sup>62,68</sup>, both of which sometimes  
298 fail<sup>66,69,70</sup>. As already mentioned, several vote-pooling mechanisms can efficiently improve  
299 outcome accuracy, both when voters cannot communicate<sup>13,30</sup> and when communication is

300 allowed <sup>29</sup>. Theoretical and empirical works suggest that collective decisions can be more  
301 accurate than individual decisions (although homogeneity of individual traits may lead to  
302 suboptimal decisions <sup>71</sup>). In fish, social insects, birds and humans, two or more individuals  
303 independently collect information that is processed through social interactions, providing a  
304 solution to a cognitive problem that is not available to single individuals <sup>62</sup>. Different studies  
305 have attempted to identify who should be trusted and which decision is the best when faced  
306 with the choice between one expert and ten non-experts. Collective decisions are almost  
307 always preferred to individual ones <sup>72,73</sup>. However, it is not necessary to know who has the  
308 best information as the combination of individual behaviours and social interactions lead to  
309 the emergence of effective systems <sup>36</sup>.

310         Importantly, two phenomena may prevent individuals or algorithms from correctly  
311 assessing a situation: misinformation (or lack of information) and biases. In order to fight  
312 against misinformation, AI algorithms should be developed to produce consistent, unbiased  
313 and privacy-protecting publicly available data <sup>74</sup>. Currently, fake news appears to be on the  
314 rise and poses a threat to democracy, particularly when elected politicians and activist  
315 groups interact to relay such news <sup>75</sup>. This type of misinformation could be mitigated by  
316 providing citizens with a better understanding of how to differentiate between fake and real  
317 news. However, sometimes, fake news can also convince well-informed people through  
318 other cognitive mechanisms (confirmation bias, desirability bias <sup>76</sup>). In such cases, algorithms  
319 relying on advanced AI can detect fake news from real information in social media posts <sup>77</sup> or  
320 in video speeches <sup>78</sup>. This better identification also comes from research on animal and  
321 human communication, particularly facial expressions <sup>79,80</sup>.

322         Specific connections in social networks may lead information that is considered  
323 untrue by the majority to be excessively over-trusted by voters who only have access to



324 these connections. This social effect, called the ‘majority illusion’, is derived from the  
325 ‘friendship paradox’. It leads individuals to systematically overestimate the prevalence of a  
326 piece of information, manipulating evidences in the DDM, which may accelerate the spread  
327 of fake news and the ultimate choice of an unsuitable alternative<sup>81,82</sup>. Such so-called ‘small  
328 world’ networks<sup>83</sup> lead to partial views of the world. To our knowledge, only one study has  
329 shown this effect in non-human animals<sup>84</sup>. This is maybe the most difficult issue to control  
330 when trying to take individual and collective decisions.

331 ***Box 3: AI and voting systems***

332 AI can help shaping human voting systems in several ways, from the establishment of fair  
333 voting conditions to the integration of artificial voting agents. For instance, by using an  
334 algorithm following a divide-and-conquer approach, it is possible to produce electoral  
335 districts’ maps that maximise compactness (to ensure geographical continuity) and minimise  
336 population deviation (to ensure representativeness)<sup>37</sup>. By following these two goals, the  
337 algorithm avoids gerrymandering, thus providing fairer voting conditions.

338 Representativeness in redistricting and publicly available datasets can also be enhanced by  
339 more advanced techniques, such as Natural Language Processing (NLP) and mining of Big  
340 Data, to produce consistent, unbiased and privacy-protecting data<sup>74</sup>.

341 When faced with electoral choices, voters sometimes find it difficult to distinguish or rank  
342 the positions of different political offers on various issues. Analyses by NLP make it easier to  
343 compare the contents of political programmes<sup>96</sup>. This tool provides a more quantitative  
344 representation of political programmes, or an easier means to trace the evolution of a  
345 party’s positions on a specific topic over time. This leverage could be used to improve the  
346 trade-offs among parties between rounds or in combination with evaluative voting<sup>1</sup>.

347 Technically, it will soon be possible to create intelligent e-democracy bots that can infer the  
348 political preferences of their associated human voter. Such bots could then be allowed to  
349 participate in voting processes on the voter's behalf <sup>39</sup>. For example, these bots could use  
350 NLP to copy the opinion expressed by the politician deemed closest to the voter's position.  
351 This controversial topic could allow citizens to express themselves on a wide range of issues.  
352 Yet this same technique could reinforce vote manipulation or the abandonment of political  
353 life by voters by delegating the expression of their opinions to a bot.  
354 By combining human and AI, the Artificial Swarm Intelligence algorithm <sup>38</sup> offers promising  
355 results: it performs better than humans-only and machine-only setups on a variety of tasks.  
356 The resulting increase in accuracy and acceptance of the collective decision is attributable to  
357 the direct involvement of humans in the decision process.  
358 This last point underlines the importance of the acceptability of AI by the public. While AI is  
359 generally viewed positively by the media <sup>97</sup>, significant concerns about data protection <sup>74</sup> and  
360 human employment have recently emerged. Thus, resistance to AI is stronger among those  
361 least inclined to innovation and most sensitive to data privacy <sup>98</sup>.

362

363

## 364 **Concluding remarks and future perspectives**

365 Numerous instances, such as policies on climate change, show that majority voting  
366 fall short and frequently lead to suboptimal collective decisions. We identified several  
367 research frameworks enhancing human voting system effectiveness (see Outstanding  
368 Questions):

369 1. Animal studies have shown that collective rules evolve to achieve efficient  
370 decisions. Many of these results inspired AI to help reach better democratic decisions.

371 Continuing to think about a diffusion model with an appropriate difference threshold  
372 between alternatives and with an appropriate quorum <sup>21,25</sup> would increase effectiveness of  
373 human systems. We have to create systems in which minorities can attempt different  
374 strategies that search through the solution space. We need to “rethink democracy” not as an  
375 all-or-nothing system <sup>85</sup>, with always opposite alternatives where one wins and one loses but  
376 to build integrative solutions leading to unified societies as defined in deliberative  
377 democracy. As Seeley says in Honeybee Democracy <sup>86</sup>, “It often pays a group to *argue* things  
378 carefully through to find the best solution to a tough problem” (p. 2). This is where applying  
379 the DDM might be useful to balance between accuracy and speed of the collective decision.

380         2. A second aim would be to increase participatory and deliberative democracy and  
381 AI helping it. The frequencies and the weights of decisions of each member in non-human  
382 animal groups are much higher than those observed in human societies, as animal decisions  
383 are on a daily basis: non-human animals appear to hold referendums every day. A more  
384 participatory democracy resembling those we observe in animal societies could result in  
385 greater satisfaction of citizens but also more efficient decisions due to a greater  
386 accumulation of knowledge <sup>56,72</sup>.

387         3. Third, we need to better understand how our connections affect the quality of  
388 information we get and as a consequence the efficiency of our decisions. We can gain a  
389 better picture of how our individual or collective decisions are constructed through the study  
390 of the real or imaginative links we make between the information provided by TV, social  
391 networks, social media and influential people <sup>69</sup>. As humans we tend to think that we have  
392 control over our decisions and knowledge, but recent events in elections have shown this to  
393 be untrue. Many voting processes are self-organized in the animal kingdom and we should  
394 admit that this is also the case in humans <sup>35,69</sup>.

395 Identifying these animals collective solutions shaped by selection over millions of  
396 years and implementing them into AI algorithms devoted to democracy is likely to increase  
397 the stability of our political systems in achieving larger consensus and reducing polarization.  
398 More research on efficient collective decisions in algorithms and animals has to be done  
399 focusing on the outcomes and their effectiveness. Indeed, humans are limited by their  
400 cognitive capacities, some biases and their mental dimensions, leading to higher polarization  
401 of societies and mental block to think about new voting systems. As animals do not think as  
402 we do, behavioural experiments on multiple species and modelling can help to get out of  
403 these human dimensions, and to find new ones <sup>87,88</sup>. This could improve humanity and yield  
404 novel bioinspired technologies.

405

406 **Twitter accounts:** @cedrisueur, @EspinosaRomain, @KrisAnathema

407

#### 408 **Acknowledgements**

409 We thank Herrade Igersheim, Julien Navarro and José Kobielski for their help about concepts  
410 detailed in this paper.

411

#### 412 **Conflicts of interest**

413 The authors declare no competing interests

414

#### 415 **Authors contribution**

416 CS and CB wrote a first version of the paper. RE and JLD reviewed, commented and  
417 enhanced the different versions. All authors read and agreed with the final version.

418

419 **References**

- 420 1. Baujard, A., Igersheim, H., Lebon, I., Gavrel, F. & Laslier, J.-F. Who's favored by evaluative  
421 voting? An experiment conducted during the 2012 French presidential election. *Elect. Stud.* **34**,  
422 131–145 (2014).
- 423 2. Gunther, R., Beck, P. A. & Nisbet, E. C. "Fake news" and the defection of 2012 Obama voters in  
424 the 2016 presidential election. *Elect. Stud.* **61**, 102030 (2019).
- 425 3. Kurvers, R. *et al.* How to sway voters. (2020).
- 426 4. Golub, B. & Jackson, M. O. Naive learning in social networks and the wisdom of crowds. *Am.*  
427 *Econ. J. Microecon.* **2**, 112–49 (2010).
- 428 5. Hoerner, J. M. & Hobolt, S. B. Unity in diversity? Polarization, issue diversity and satisfaction  
429 with democracy. *J. Eur. Public Policy* 1–20 (2019) doi:10.1080/13501763.2019.1699592.
- 430 6. Duboscq, J., Romano, V., MacIntosh, A. & Sueur, C. Social Information Transmission in Animals:  
431 Lessons from Studies of Diffusion. *Front. Psychol.* **7**, (2016).
- 432 7. Dorigo, M., Theraulaz, G. & Trianni, V. Reflections on the future of swarm robotics. *Sci. Robot.*  
433 **5**, eabe4385 (2020).
- 434 8. Hassabis, D., Kumaran, D., Summerfield, C. & Botvinick, M. Neuroscience-Inspired Artificial  
435 Intelligence. *Neuron* **95**, 245–258 (2017).
- 436 9. Zador, A. M. A critique of pure learning and what artificial neural networks can learn from  
437 animal brains. *Nat. Commun.* **10**, 3770 (2019).
- 438 10. Aral, S. & Eckles, D. Protecting elections from social media manipulation. *Science* **365**, 858–861  
439 (2019).
- 440 11. Mezza-Garcia, N. Bio-inspired Political Systems: Opening a Field. in *Proceedings of the European*  
441 *Conference on Complex Systems 2012* (eds. Gilbert, T., Kirkilionis, M. & Nicolis, G.) 785–812  
442 (Springer International Publishing, 2013). doi:10.1007/978-3-319-00395-5\_97.
- 443 12. Rahwan, I. *et al.* Machine behaviour. *Nature* **568**, 477–486 (2019).

- 444 13. Almaatouq, A. *et al.* Adaptive social networks promote the wisdom of crowds. *Proc. Natl. Acad.*  
445 *Sci. U. S. A.* **117**, 11379–113686 (2020).
- 446 14. Summers, K. The evolutionary ecology of despotism. *Evol. Hum. Behav.* **26**, 106–135 (2005).
- 447 15. Hemelrijk, C. K. An individual-orientated model of the emergence of despotic and egalitarian  
448 societies. *Proc. R. Soc. Lond. B* **266**, 361–369 (1999).
- 449 16. Mercier, H. & Morin, O. Majority rules: how good are we at aggregating convergent opinions?  
450 *Evol. Hum. Sci.* **1**, e6 (2019).
- 451 17. Rothschild, D. & Malhotra, N. Are public opinion polls self-fulfilling prophecies? *Res. Polit.* **1**,  
452 2053168014547667 (2014).
- 453 18. Kenett, R. S., Pfeffermann, D. & Steinberg, D. M. Election polls—A survey, a critique, and  
454 proposals. *Annu. Rev. Stat. Its Appl.* **5**, 1–24 (2018).
- 455 19. Hobolt, S. B. The Brexit vote: a divided nation, a divided continent. *J. Eur. Public Policy* **23**,  
456 1259–1277 (2016).
- 457 20. Dryzek, J. S. *et al.* The crisis of democracy and the science of deliberation. *Science* **363**, 1144–  
458 1146 (2019).
- 459 21. Bogacz, R. Optimal decision-making theories: linking neurobiology with behaviour. *Trends Cogn.*  
460 *Sci.* **11**, 118–125 (2007).
- 461 22. Ratcliff, R., Smith, P. L., Brown, S. D. & McKoon, G. Diffusion decision model: current issues and  
462 history. *Trends Cogn. Sci.* **20**, 260–281 (2016).
- 463 23. Tavares, G., Perona, P. & Rangel, A. The Attentional Drift Diffusion Model of Simple Perceptual  
464 Decision-Making. *Front. Neurosci.* **11**, (2017).
- 465 24. Pirrone, A., Stafford, T. & Marshall, J. A. When natural selection should optimize speed-  
466 accuracy trade-offs. *Front. Neurosci.* **8**, 73 (2014).
- 467 25. Marshall, J. A. *et al.* On optimal decision-making in brains and social insect colonies. *J. R. Soc.*  
468 *Interface* **6**, 1065–1074 (2009).

- 469 26. Pelé, M. & Sueur, C. Decision-making theories: linking the disparate research areas of individual  
470 and collective cognition. *Anim. Cogn.* **16**, 543–556 (2013).
- 471 27. Deschouwer, K. Kingdom of Belgium. *Const. Orig. Struct. Change Fed. Ctries.* **1**, 48–75 (2005).
- 472 28. Marshall, J. A., Kurvers, R. H., Krause, J. & Wolf, M. Quorums enable optimal pooling of  
473 independent judgements in biological systems. *eLife* **8**, e40368 (2019).
- 474 29. Navajas, J., Niella, T., Garbulsy, G., Bahrami, B. & Sigman, M. Aggregated knowledge from a  
475 small number of debates outperforms the wisdom of large crowds. *Nat. Hum. Behav.* **2**, 126–  
476 132 (2018).
- 477 30. Kurvers, R., Herzog, S., Hertwig, R., Krause, J. & Wolf, M. Towards more reliable and fairer  
478 decision-making systems: pooling decisions decreases variation in accuracy and response bias.  
479 *PsyArXiv Prepr.* (2020) doi:10.31234/osf.io/sv84r.
- 480 31. Wolf, M. & Weissing, F. J. Animal personalities: consequences for ecology and evolution. *Trends*  
481 *Ecol. Evol.* **27**, 452–461 (2012).
- 482 32. Bousquet, C. A. H., Ahr, N., Sueur, C. & Petit, O. Determinants of leadership in groups of female  
483 mallards. *Behaviour* **154**, 467–507 (2017).
- 484 33. King, A. J., Douglas, C. M. S., Huchard, É., Isaac, N. J. B. & Cowlshaw, G. Dominance and  
485 affiliation mediate despotism in a social primate. *Curr. Biol.* **18**, 1833–1838 (2008).
- 486 34. Ding, R.-X. *et al.* Large-scale decision-making: characterization, taxonomy, challenges and  
487 future directions from an artificial intelligence and applications perspective. *Inf. Fusion* **59**, 84–  
488 102 (2020).
- 489 35. Sumpter, D. J. T. & Pratt, S. C. Quorum responses and consensus decision making. *Philos. Trans.*  
490 *R. Soc. B Biol. Sci.* **364**, 743–753 (2009).
- 491 36. Couzin, I. D., Krause, J., Franks, N. R. & Levin, S. A. Effective leadership and decision-making in  
492 animal groups on the move. *Nature* **433**, 513–516 (2005).
- 493 37. Levin, H. A. & Friedler, S. A. Automated congressional redistricting. *J. Exp. Algorithmics* **24**, 1–24  
494 (2019).

- 495 38. Metcalf, L., Askay, D. A. & Rosenberg, L. B. Keeping humans in the loop: pooling knowledge  
496 through artificial swarm intelligence to improve business decision making. *Calif. Manage. Rev.*  
497 **61**, 84–109 (2019).
- 498 39. Perez, O. Collaborative e-rulemaking, democratic bots, and the future of digital democracy.  
499 *Digit. Gov. Res. Pract.* **1**, 1–13 (2020).
- 500 40. Conradt, L. & Roper, T. J. Group decision-making in animals. *Nature* **421**, 155–158 (2003).
- 501 41. Sueur, C. Viability of decision-making systems in human and animal groups. *J. Theor. Biol.* **306**,  
502 93–103 (2012).
- 503 42. Hooper, P. L., Kaplan, H. S. & Boone, J. L. A theory of leadership in human cooperative groups. *J.*  
504 *Theor. Biol.* **265**, 633–646 (2010).
- 505 43. Walker, R. H., King, A. J., McNutt, J. W. & Jordan, N. R. Sneeze to leave: African wild dogs  
506 (*Lycaon pictus*) use variable quorum thresholds facilitated by sneezes in collective decisions.  
507 *Proc. R. Soc. Lond. B* **284**, 20170347 (2017).
- 508 44. Bousquet, C. A. H., Sumpter, D. J. T. & Manser, M. B. Moving calls: a vocal mechanism  
509 underlying quorum decisions in cohesive groups. *Proc. R. Soc. Lond. B* **278**, 1482–1488 (2011).
- 510 45. King, A. J. & Sueur, C. Where next? Group coordination and collective decision making by  
511 primates. *Int. J. Primatol.* **32**, 1245–1267 (2011).
- 512 46. Bousquet, C. A. H. & Manser, M. B. Resolution of experimentally induced symmetrical conflicts  
513 of interest in meerkats. *Anim. Behav.* **81**, 1101–1107 (2011).
- 514 47. Landemore, H. *Open democracy: reinventing popular rule for the twenty-first century.*  
515 (Princeton University Press, 2020).
- 516 48. Dryzek, J. S. & Stevenson, H. Global democracy and earth system governance. *Ecol. Econ.* **70**,  
517 1865–1874 (2011).
- 518 49. Sueur, C., Deneubourg, J.-L. & Petit, O. From the first intention movement to the last joiner:  
519 macaques combine mimetic rules to optimize their collective decisions. *Proc. R. Soc. Lond. B*  
520 **278**, 1697–1704 (2011).



- 521 50. Conradt, L. & Roper, T. J. Consensus decision making in animals. *Trends Ecol. Evol.* **20**, 449–456  
522 (2005).
- 523 51. King, A. J. Follow me! I'm a leader if you do; I'm a failed initiator if you don't? *Behav. Processes*  
524 **84**, 671–674 (2010).
- 525 52. Bourjade, M. & Sueur, C. Shared or unshared consensus for collective movement? Towards  
526 methodological concerns. *Behav. Processes* **84**, 648–652 (2010).
- 527 53. Flack, J. C., Girvan, M., De Waal, F. B. & Krakauer, D. C. Policing stabilizes construction of social  
528 niches in primates. *Nature* **439**, 426–429 (2006).
- 529 54. Canteloup, C., Hoppitt, W. & van de Waal, E. Wild primates copy higher-ranked individuals in a  
530 social transmission experiment. *Nat. Commun.* **11**, 1–10 (2020).
- 531 55. Whiten, A. & Byrne, R. W. *Machiavellian intelligence II - Extensions and evaluations*. vol. 2  
532 (Cambridge University Press, 1997).
- 533 56. Czaczkes, T. J., Grüter, C., Jones, S. M. & Ratnieks, F. L. Synergy between social and private  
534 information increases foraging efficiency in ants. *Biol. Lett.* **7**, 521–524 (2011).
- 535 57. Smith, J. E. *et al.* Leadership in mammalian societies: emergence, distribution, power, and  
536 payoff. *Trends Ecol. Evol.* **31**, 54–66 (2016).
- 537 58. Olivola, C. Y. & Todorov, A. Elected in 100 milliseconds: Appearance-Based Trait Inferences and  
538 Voting. *J. Nonverbal Behav.* **34**, 83–110 (2010).
- 539 59. Alexander, D. & Andersen, K. Gender as a Factor in the Attribution of Leadership Traits. *Polit.*  
540 *Res. Q.* **46**, 527–545 (1993).
- 541 60. Brown, M. B. *Science in democracy: Expertise, institutions, and representation*. (MIT Press,  
542 2009).
- 543 61. Collins, H., Evans, R., Durant, D. & Weinel, M. Introduction: Pluralist Democracy, Populism and  
544 Expertise. in *Experts and the Will of the People* 1–9 (Springer, 2020).
- 545 62. Krause, J., Ruxton, G. D. & Krause, S. Swarm intelligence in animals and humans. *Trends Ecol.*  
546 *Evol.* **25**, 28–34 (2010).

- 547 63. Conradt, L. & List, C. Group decisions in humans and animals: a survey. *Philos. Trans. R. Soc. B*  
548 *Biol. Sci.* **364**, 719–742 (2009).
- 549 64. Ozbay, F. A. & Alatas, B. Fake news detection within online social media using supervised  
550 artificial intelligence algorithms. *Phys. Stat. Mech. Its Appl.* **540**, 123174 (2020).
- 551 65. KAPLAN, A. Artificial intelligence, social media, and fake news: Is this the end of democracy?  
552 *MEDIA Soc.* 149 (2020).
- 553 66. Giraldeau, L., Valone, T. J. & Templeton, J. J. Potential disadvantages of using socially acquired  
554 information. *Philos. Trans. R. Soc. B Biol. Sci.* **357**, 1559–1566 (2002).
- 555 67. Sen, A. K. *The idea of justice*. (Harvard University Press, 2009).
- 556 68. Nagy, M. *et al.* Synergistic Benefits of Group Search in Rats. *Curr. Biol.* **0**, (2020).
- 557 69. Kao, A. B. & Couzin, I. D. Decision accuracy in complex environments is often maximized by  
558 small group sizes. *Proc. R. Soc. Lond. B* **281**, 20133305 (2014).
- 559 70. Chamley, C. Rational herds. *Camb. Univ. Press Camb.* **3**, 20 (2004).
- 560 71. Jolles, J. W., King, A. J. & Killen, S. S. The role of individual heterogeneity in collective animal  
561 behaviour. *Trends Ecol. Evol.* **35**, 278–291 (2020).
- 562 72. Katsikopoulos, K. V. & King, A. J. Swarm intelligence in animal groups: when can a collective  
563 out-perform an expert? *PLoS ONE* **5**, e15505 (2010).
- 564 73. Kurvers, R. H. *et al.* Boosting medical diagnostics by pooling independent judgments. *Proc. Natl.*  
565 *Acad. Sci. U. S. A.* **113**, 8777–8782 (2016).
- 566 74. Lane, J. *Democratizing our data: a manifesto*. (MIT Press, 2020).
- 567 75. Tollefson, J. Tracking QAnon: how Trump turned conspiracy-theory research upside down.  
568 *Nature* (2021) doi:10.1038/d41586-021-00257-y.
- 569 76. Lazer, D. M. *et al.* The science of fake news. *Science* **359**, 1094–1096 (2018).
- 570 77. Ozbay, F. A. & Alatas, B. Fake news detection within online social media using supervised  
571 artificial intelligence algorithms. *Phys. Stat. Mech. Its Appl.* **540**, 123174 (2020).

- 572 78. Kaur, S., Kumar, P. & Kumaraguru, P. Deepfakes: temporal sequential analysis to detect face-  
573 swapped video clips using convolutional long short-term memory. *J. Electron. Imaging* **29**,  
574 033013 (2020).
- 575 79. Crivelli, C. & Fridlund, A. J. Facial displays are tools for social influence. *Trends Cogn. Sci.* **22**,  
576 388–399 (2018).
- 577 80. Lisetti, C. L. & Schiano, D. J. Automatic facial expression interpretation: Where human-  
578 computer interaction, artificial intelligence and cognitive science intersect. *Pragmat. Cogn.* **8**,  
579 185–235 (2000).
- 580 81. Jackson, M. O. The friendship paradox and systematic biases in perceptions and social norms. *J.*  
581 *Polit. Econ.* **127**, 777–818 (2019).
- 582 82. Lerman, K., Yan, X. & Wu, X.-Z. The ‘majority illusion’ in social networks. *PLoS ONE* **11**,  
583 e0147617 (2016).
- 584 83. Milgram, S. The small world problem. *Psychol. Today* **1**, 60–67 (1967).
- 585 84. Pasquaretta, C. *et al.* How social network structure affects decision-making in *Drosophila*  
586 *melanogaster*. *Proc. R. Soc. Lond. B* **283**, 20152954 (2016).
- 587 85. Bollen, K. A. & Jackman, R. W. Democracy, stability, and dichotomies. *Am. Sociol. Rev.* 612–621  
588 (1989).
- 589 86. Seeley, T. D. *Honeybee democracy*. (Princeton University Press, 2010).
- 590 87. De Waal, F. *Are we smart enough to know how smart animals are?* (WW Norton & Company,  
591 2016).
- 592 88. Meijer, E. *When Animals Speak: Toward an Interspecies Democracy*. (NYU Press, 2019).
- 593 89. Marshall, J. A. Optimal voting in groups with convergent interests. in (2011).
- 594 90. Waal, F. de. *Chimpanzee Politics: Power and Sex Among Apes*. (JHU Press, 2007).
- 595 91. List, C. Democracy in animal groups: a political science perspective. *Trends Ecol. Evol. Pers. Ed.*  
596 **19**, 168–169 (2004).

- 597 92. Pennisi, A. & Giallongo, L. Animal biopolitics: how animals vote. *Int. J. Semiot. Law - Rev. Int.*  
598 *Sémiot. Jurid.* **31**, 491–499 (2018).
- 599 93. Boureau, Y.-L., Sokol-Hessner, P. & Daw, N. D. Deciding How To Decide: Self-Control and Meta-  
600 Decision Making. *Trends Cogn. Sci.* **19**, 700–710 (2015).
- 601 94. Bayne, T. *et al.* What is cognition? *Curr. Biol.* **29**, R608–R615 (2019).
- 602 95. Petit, O., Gautrais, J., Leca, J.-B., Theraulaz, G. & Deneubourg, J.-L. Collective decision-making in  
603 white-faced capuchin monkeys. *Proc. R. Soc. Lond. B* **276**, 3495–3503 (2009).
- 604 96. Merz, N., Regel, S. & Lewandowski, J. The Manifesto Corpus: a new resource for research on  
605 political parties and quantitative text analysis. *Res. Polit.* **3**, 2053168016643346 (2016).
- 606 97. Fast, E. & Horvitz, E. Long-term trends in the public perception of artificial intelligence. *ArXiv*  
607 *Prepr.* arXiv:1609.04904 (2016).
- 608 98. Lobera, J., Fernández Rodríguez, C. J. & Torres-Albero, C. Privacy, values and machines:  
609 predicting opposition to artificial intelligence. *Commun. Stud.* **71**, 448–465 (2020).
- 610 99. Strandburg-Peshkin, A., Farine, D. R., Couzin, I. D. & Crofoot, M. C. Shared decision-making  
611 drives collective movement in wild baboons. *Science* **348**, 1358–1361 (2015).
- 612 100. Ramos, A., Petit, O., Longour, P., Pasquaretta, C. & Sueur, C. Collective decision making during  
613 group movements in European bison, *Bison bonasus*. *Anim. Behav.* **109**, 149–160 (2015).
- 614

615 **Glossary**

616 **Artificial intelligence:** Set of algorithms and processes enabling artificial agents to perceive  
617 their environment or to process data in order to respond in an optimised way to a given  
618 problem.

619 **Condorcet's jury theorem:** The Condorcet Jury Theorem implies that the choice made by a  
620 group using the majority voting rule will be better than the individual choices of the  
621 members of that group, provided that the members of the group have more than a 1 in 2  
622 chance of being correct. One of its postulates is that individuals can only make one type of  
623 mistake, which is not always true.

624 **Condorcet winner criterion:** The Condorcet criterion for a voting system is that it chooses  
625 the beats-all winner when one exists

626 **Deliberative democracy:** Form of democracy in which deliberation and negotiation are  
627 central to decision-making. It adopts elements of both consensus decision-making and  
628 majority rule.

629 **Drift-Diffusion Model:** The DDM stipulates that a choice should be made as soon as the  
630 difference between the evidence (information) supporting the winning alternative (drift 1)  
631 and the evidence supporting the losing alternative (drift 2) exceeds a threshold. The DDM  
632 implements a test called the sequential probability ratio test which optimizes the speed of  
633 decision-making for a required accuracy.

634 **Efficiency:** In the context of voting, optimality relies on a decision that maximizes the  
635 difference between the benefits and the costs.

636 **Evaluative voting:** Each alternative open to voting can be evaluated independently by each  
637 voter. The scale for evaluating alternatives may vary.

638 **Majority voting:** A decision is taken as soon as a number of votes equals to  $(N/2) + 1$  of the  $N$   
639 votes cast.

640 **Mean voter theorem:** proposition relating to direct ranked preference voting put forward by  
641 Duncan Black. It states that if opinions are distributed along a one-dimensional spectrum,  
642 then any voting method which satisfies the **Condorcet winner criterion** will produce a  
643 winner close to the median voter.

644 **Participatory democracy:** Participatory democracy tends to advocate more involved forms  
645 of citizen participation and greater political representation than representative democracy.

646 **Quorum:** Minimum number of group members necessary to observe a drastic change in  
647 group behaviour or to validate a group decision. Majority voting is a special case of quorum.  
648 50% for a quorum makes sense when only two alternatives are proposed, which is rare in animal  
649 societies as researchers count all animals even those which do not have opinions. 50% majority is  
650 present in humans but removing individuals with no opinion. If we consider individuals who do not  
651 vote or do white vote, the majority does not reach 50%. For instance, if only 60% of the population  
652 vote, then the real quorum is 30% ( $60\% \times 50\%$ ).

653 **Race Model:** The Race Model stipulates that a choice should be made as soon as the  
654 evidence supporting the winning alternative exceeds a threshold.

655 **Voting system:** Mechanism by which individual preferences are pooled together in order to  
656 reach a group decision.