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JEL Codes: D72; C72; C63.

Keywords: Approval voting, Poisson games, Strategic voting, Condorcet consistency, Fictitious play, Expressive voting.



# VOTER COORDINATION IN ELECTIONS: A CASE FOR APPROVAL VOTING\*

FRANÇOIS DURAND<sup>a</sup>, ANTONIN MACÉ<sup>b</sup>, AND MATÍAS NÚÑEZ<sup>c</sup>

**ABSTRACT.** We study how voting rules shape voter coordination in large three-candidate elections. We consider three rules, varying according to the number of candidates that voters can support in their ballot: Plurality (one), Anti-Plurality (two) and Approval Voting (one or two). We show that the Condorcet winner—a normatively desirable candidate—can always be elected at equilibrium under Approval Voting. We then numerically study a dynamic process of political tâtonnement. Monte-Carlo simulations of the process deliver rich insights on election outcomes. The Condorcet winner is virtually always elected under Approval Voting, but not under the other rules. The dominance of Approval Voting is robust to alternative welfare criteria and to the introduction of expressive voters.

**KEYWORDS.** Approval voting, Poisson games, Strategic voting, Condorcet consistency, Fictitious play, Expressive voting.

**JEL CLASSIFICATION.** D72; C72; C63.

## 1. INTRODUCTION

First-past-the-post voting remains one of the most common election methods across the world. Under this rule, also known as Plurality rule (henceforth PL), voters vote for just one candidate, and the candidate with the highest support is elected. In the U.S., where the rule is used in most local elections, recent years have seen a surge in popular initiatives aimed at changing the local election method away from PL. For instance, in the city of St. Louis, Missouri, the Proposition D initiative, which seeks to replace plurality voting by an approval

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<sup>a</sup> NOKIA BELL LABS FRANCE & LINC'S ([www.lincs.fr](http://www.lincs.fr)).

<sup>b</sup> CNRS, PARIS SCHOOL OF ECONOMICS & ÉCOLE NORMALE SUPÉRIEURE, FRANCE.

<sup>c</sup> CREST, ÉCOLE POLYTECHNIQUE & CNRS, FRANCE.

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voting system, obtained the support of 68.15% of the voters in November 2020. Two years earlier, the citizens of Fargo, North Dakota, adopted a similar initiative, and the approval voting system was used there in June 2020.<sup>1</sup> In its simplest form, Approval Voting (henceforth AV) is an extension of PL, whereby voters can vote for (*approve of*) as many candidates as they want, and the candidate with the highest support is elected.<sup>2</sup> Voters thus benefit from an increased flexibility in casting their ballots under AV. Beyond this individual benefit, what are the potential collective gains from changing the election method from PL to AV? Would this improve the quality of preference aggregation?

As a first observation, voting rules shape the identity of the election winner beyond the preferences of the electorate. Voting rules not only differ in how they measure the support for each candidate, they also create different incentives for the voters. For instance, PL features a *wasted vote effect*, whereby voters who prefer a candidate with virtually no chance of winning have the incentive to drop their support and opt instead for a more serious candidate. This effect disappears under AV, as voters may simultaneously approve of a non-viable candidate and a more serious one. Taking voter incentives into account, we can refine our initial questions: which voting rules allow voters to coordinate on a given election outcome? If coordination is possible, which voting rules select the best candidates?

We address these questions by focusing on the simplest setting of a three-candidate election.<sup>3</sup> We consider three main voting rules: AV, PL and Anti-Plurality (henceforth APL), the polar opposite of PL, in which each voter votes for

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<sup>1</sup>Besides Approval Voting, on which we focus in this paper, several localities have adopted a *ranked-choice voting* system, where ballots are counted by the *instant runoff* procedure (IRV). Examples include San Francisco (in 2002), Berkeley (in 2005), Oakland (in 2006) and New York City (in 2019). While we do not study IRV here, the rule seems ill-suited to selecting the Condorcet winner: experimental results indicate that voters tend to report their preferences truthfully due to the complexity of the system, and that the Condorcet winner may well be overlooked as a result [Van der Straeten et al., 2010].

<sup>2</sup>This rule, first proposed by Weber [1977] and Brams and Fishburn [1978], has attracted the interest of scholars in economics and political science. See for instance Brams and Fishburn [2005], Laslier and Sanver [2010], Laslier [2012] and the review of the literature (Section 2).

<sup>3</sup>The case of three candidates is of particular relevance: (i) it constitutes the simplest case of non-trivial multi-candidate elections, and it is thus a central focus in the literature; (ii) a significant share of single-winner elections involve three candidates, notably because barriers to entry prevent other candidates from running; and (iii) informally, if more candidates participate in the election, the insights we draw for three-candidate elections should be relevant to describe voter choices with respect to the three most serious candidates.

two candidates (or equivalently, against one), and the candidate with the highest support is elected.<sup>4</sup> We study voter behavior in large elections basing our analysis on the classical game-theoretical model of Poisson games [Myerson, 2000], where the number of voters is drawn from a Poisson distribution.<sup>5</sup> Voters hold private values and we allow for all possible preference orderings and intensities.

In this setting, the results for PL and APL are clear-cut, and thus serve as benchmarks to evaluate the performance of AV. Under PL, a consequence of the *wasted vote effect* is *Duverger's law* which asserts that any pair of candidates can concentrate all the votes in equilibrium [Duverger, 1951]. Thus, coordination is always possible (an equilibrium exists), but the outcome is indeterminate (the set of equilibrium winners is large). However for APL, we obtain a polar result: coordination is impossible as, generically, no equilibrium exists. This means that, for any belief that the electorate may hold, some voters would prefer to change their vote. Hence, this election method appears unstable. Given this panorama, our question becomes as follows: can AV sustain the coordination of voters, steering away from the instability of APL, while selecting a normatively desirable candidate, and thus avoiding the indeterminacy of PL? Combining equilibrium analysis to numerical simulations, we offer a qualified but broadly positive answer to that question.

We start by describing voter best replies under AV. Voters either vote for their favorite candidate or for their two preferred candidates. The choice between these two strategies is governed by a *utility threshold*: voters approve of their second candidate only if she yields a utility higher than this threshold.<sup>6</sup> In a technical step, we show that this threshold converges when the expected size of the electorate becomes large. This allows us to define *asymptotic best replies* at the limit, and the associated notion of *asymptotic equilibrium*. Moreover, we provide explicit formulas for the limit threshold. These formulas form the core of the Python package “Poisson-Approval”, designed by one member of our team, which

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<sup>4</sup>While we are primarily motivated by the comparison between AV and PL, APL is a natural addition as the three rules form the whole class of binary scoring rules with three candidates (each candidate is either fully supported or not supported at all by any given voter). Scoring rules are important in social choice theory, as they can be (essentially) characterized by the attractive property of *reinforcement* [Myerson, 1995].

<sup>5</sup>Myerson [1998] shows that these games are characterized by two properties: the aggregate actions taken by different types are independent (*independent actions*); and the probabilistic environment assessed by each player is the same as by any external observer (*environmental equivalence*).

<sup>6</sup>The threshold may be degenerate, in which case voters' behavior does not depend on preference intensities.

we extensively use in our numerical analysis.<sup>7</sup>

We use these tools to derive our main analytical result. We show that under AV, whenever the preference profile admits a Condorcet winner,<sup>8</sup> an equilibrium exists by which this candidate wins. Therefore, coordination is possible and may indeed also lead to the election of this normatively appealing candidate. Yet, this first result does not preclude the existence of other equilibria under AV, where the Condorcet winner might not be elected. As a first pass, we provide a preliminary set of results indicating that such “bad equilibria” should be rare, relying on a distinction between *cardinal equilibria*, where preference intensities matter for some voters, and *ordinal equilibria*, where they do not. We show that, if voters’ utility distributions are not biased against the Condorcet winner, then only this candidate can be elected at a cardinal equilibrium. In turn, we show numerically that ordinal equilibria in which the Condorcet winner is not elected only exist for an extremely small region of preference profiles.

In the final section, we introduce a dynamic model of “political tâtonnement”, which can be interpreted as a micro-foundation for the equilibrium analysis.<sup>9</sup> In this adaptive procedure, a poll is released at each stage, and a fraction of voters update their behavior by best replying to a belief incorporating both current and past polls. We use the Python package “Poisson Approval” to simulate the trajectories of the adaptive procedure, and we interpret their long-run behavior as the outcome of the election. We then run Monte-Carlo simulations to obtain relevant statistics on election outcomes under each voting rule. The conclusions we draw from these simulations are broadly consistent with the equilibrium analysis but also offer a number of additional insights.

First, we find that the procedure converges (i.e. that voters coordinate) under AV, provided that a Condorcet winner exists. By contrast, convergence always occurs under PL, whereas it never does under APL. Second, conditioning on the existence of a Condorcet winner, we show that this candidate virtually always

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<sup>7</sup>The Python package, along with instructions and tutorials, is available at the following link: <https://pypi.org/project/poisson-approval>. It has been designed by François Durand. All the commands used to generate the numbers, tables and figures in this article are available at: <https://poisson-approval.readthedocs.io/en/latest/notebooks-article/index.html>.

<sup>8</sup>A Condorcet winner is a candidate preferred to any other candidate by a majority of voters.

<sup>9</sup>Myerson and Weber [1993] write “one might expect that voters will ultimately behave in accordance with a voting equilibrium after observing the series of public reports that accompany an extended campaign. (The campaign is, in part, a political tâtonnement, or equilibrium-seeking, process.)”.

wins under AV, while she often fails to be elected under either PL or APL. We illustrate this dominance of AV over PL on a domain of divided preferences,<sup>10</sup> in which we highlight the fact that it holds for any preference profile. We further show that the superiority of AV over both PL and APL extends to other normative criteria than the selection of the Condorcet winner. AV surpasses both rules not only in terms of utilitarian welfare, but also in terms of Rawlsian (maxmin) and anti-Rawlsian (maxmax) criteria.<sup>11</sup> This is remarkable as these two criteria would respectively be maximized under APL and under PL if voters were not strategic. As a last observation, we note that the winner under AV is almost always the sole candidate receiving the support of a majority of the electorate. This election method thus tends to confer political legitimacy to the winner.

We conclude by considering the robustness of our results to the assumption of strategic voting. Indeed, recent empirical studies suggest that, at least under PL, a significant share of voters behave *expressively* rather than strategically. These *expressive* voters vote for their favorite candidate, independently of her chance of winning. We thus run simulations in which a fixed share of the electorate is expressive. While AV becomes mechanically closer to PL as the share of expressive voters increases, AV still outperforms both PL and APL.

## 2. REVIEW OF THE LITERATURE

Our work closely relates to the literature on multi-candidate elections relying on the model of Poisson games, established in the pioneering papers of Myerson [1998, 2000, 2002]. In this model, voter behavior is driven by the relative probabilities of *pivot events*, which are obtained endogenously. Myerson [2002] provides two illuminating examples of stylized preference profiles for which AV performs better than other scoring rules.<sup>12</sup> Yet, Núñez [2010] and Bouton and Castanheira [2012] exhibit preference profiles admitting an equilibrium where the Condorcet winner is not elected under AV, suggesting that the equilibrium analysis of this

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<sup>10</sup>This domain generalizes the *divided majority*, often analyzed in the literature [Borda, 1781, Myerson and Weber, 1993, Bouton and Castanheira, 2012]. The electorate is polarized, in the sense that one particular candidate is ranked either first or third by all voters. Any preference profile on this domain admits a Condorcet winner.

<sup>11</sup>As we discuss in the text, welfare criteria are applied to normalized von Neumann and Morgenstern utilities, taking values between 0 and 1.

<sup>12</sup>In the first example (*Above the Fray*), one candidate is ranked first by all voters. This candidate is always elected under AV, but may be overlooked under PL. In the second example (*Bad Apple*), one candidate is disliked by all voters. The candidate is never elected under AV but she remains a serious candidate under APL, elected with positive probability.

rule is subtle. Our results contribute to show that, despite these examples, Myerson’s initial insights are particularly robust. The selection of the Condorcet winner under AV is always possible at equilibrium but it also most often occurs in practice for a wide variety of preference configurations, and the dominance of AV over PL and APL extends to several prominent welfare criteria.<sup>13</sup> Technically, we use a notion of *asymptotic equilibrium*, which differs from that of *large equilibrium* in Myerson [2002]. As we argue in Section 4.2 and Section 5.3, our equilibrium concept has the advantage of not relying on vanishingly small details in voter beliefs and is well-suited to our numerical analysis.

Some other studies on Poisson games are also connected to our work. The model has been useful to describe the properties of *runoff elections* [Bouton, 2013, Bouton and Gratton, 2015], which are quite similar to PL, as we discuss in the conclusion. While we do not include these rules in our study, we borrow to Bouton and Gratton [2015] the general setting in which all possible preference ordering and intensities are considered feasible.<sup>14</sup> Our results are thus not driven by a specific domain restriction. Poisson games have also proved tractable to study information aggregation in elections, notably under AV. While Bouton and Castanheira [2012] argue that the presence of common values is essential to generate coordination under AV,<sup>15</sup> our results show that AV facilitates coordination even in a pure preference aggregation setting.

Our work also relates to models of large elections where the probabilities of pivot events are not explicitly computed, but are instead assumed to follow natural restrictions [Myerson and Weber, 1993, Laslier, 2009].<sup>16</sup> When applied to AV,

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<sup>13</sup>Myerson [2002] establishes that all equilibria under AV select the Condorcet winner for the domain of *bipolar elections with corruption*. For three candidates, this domain is one-dimensional, while the results we obtain hold for either the Condorcet domain or the universal domain (both are 5-dimensional).

<sup>14</sup>With three options available, it seems empirically plausible to encounter many different preference orderings. In Eggers [2020], 2019 UK poll data indicate that 5 among 6 possible orderings concern more than 5% of individuals on the options {*Remain*, *Deal*, *No Deal*}. The same paper reports that, in the 2018 mayoral election of San Francisco held under ranked-choice voting, each of the 6 possible orderings among the top three candidates is expressed by more than 5% of voters.

<sup>15</sup>Bouton and Castanheira [2012] focus on the specific domain of a *divided majority*, where a majority group is split between two candidates. On the topic of information aggregation, see also Goertz and Maniquet [2011] and Ahn and Oliveros [2016], who argue that AV performs better than other scoring rules.

<sup>16</sup>The main restriction is the *ordering condition*, stating that, if the expected score of candidate  $j$  is above that of  $k$ , then the pivot event where candidates  $i$  and  $j$  are tied for victory is infinitely more likely than the one where  $i$  and  $k$  are tied for victory.



these models may be interpreted as behavioral, in the sense that voters neglect both the correlation in candidates' scores and pivot events involving more than two candidates. Laslier [2009] proves that if a Condorcet winner exists, there is a unique equilibrium under AV, and it is such that the Condorcet winner is elected.<sup>17</sup> The substantive conclusion thus coincides with our results, although the precise behavior of voters differs. In the equilibrium of Laslier [2009], voters' choices do not depend on preference intensities, whereas they do matter in our model. While we believe that the latter feature seems more behaviorally plausible, we are comforted that the two models reach the same normative conclusion.

Besides large election models, our paper is also connected to the literature that studies AV and other scoring rules in small electorates. Buenrostro et al. [2013] and Courtin and Núñez [2017] show that, in models of strategic reasoning (i.e. iterated dominance), AV tends to select the Condorcet winner whenever the game is dominance solvable. This *Condorcet efficiency* of AV is also supported experimentally. In Van der Straeten et al. [2010], preferences are single-peaked, so that the centrist candidate is the Condorcet winner. This candidate is most often selected by AV, but not by the other voting rules under study. Forsythe et al. [1996] focus on a *divided majority* and show that the Condorcet loser tends to be elected less frequently under AV than under PL. In Bol et al. [2020], when experienced voters face a choice between AV and PL under a veil of ignorance on their preferences, they choose AV more often than PL.

In our last section, we introduce an adaptive procedure as a plausible micro-foundation for the equilibrium analysis. This approach has a long tradition in game theory [Fudenberg and Levine, 1998] and it is also well suited to the study of strategic voting. As mentioned in the concluding remarks of one of the early papers on the topic [Palfrey, 1989], this perspective presents at least two benefits. First, it highlights the importance of pre-election polls to generate the coordination of voters. This role of polls has indeed been put forth experimentally by Forsythe et al. [1993]. Second, the dynamic approach can help resolve indeterminacies when multiple equilibria exist. For instance, Fey [1997] leverages this perspective to underline the instability of an equilibrium for which three candidates receive positive vote shares under PL. Here, we use this approach more generally by applying the same dynamic procedure to several voting rules and for a wide variety of preference profiles. We also see a third benefit: the trajectories of the adaptive procedure can be explicitly computed numerically. In the computer science literature, the convergence of a related iterative voting process under PL has been explored by Meir et al. [2017], who show that it depends on the

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<sup>17</sup>One strength of this result is that it holds true for any number of candidates.

nature of the tie-breaking rule in small electorates. By contrast, we focus on large electorates for which tie-breaking rules are less important but we find significant differences of convergence rates across voting rules.<sup>18</sup>

Our Monte-Carlo simulations bring to mind the literature assessing statistical properties of voting rules. A relevant example is Gehrlein and Lepelley [2015], which measures the probability of the election of the Condorcet winner (when she exists) under the probabilistic model of *impartial anonymous culture*. In that paper, voter behavior under AV is *mechanic* as a fixed randomly drawn share of the electorate casts a vote for two candidates. Here PL is found to select the Condorcet winner more often than AV, which is itself better than APL for that purpose. What we add to that model is that we take into account voter strategic behavior for each given draw of the preference profile. As a result, the ordering of the rules is reversed with AV dominating both PL and APL.

Our final set of results on the robustness to expressive voting is motivated by a recent empirical literature assessing the relevance of the strategic voting model. Kawai and Watanabe [2013] estimate a relaxed version of the model of Myerson and Weber [1993] on data from Japanese general elections, held under PL in multiple districts. They evaluate that 64% to 89% of the electorate can be considered as strategic. Spenkuch [2018] uses rich data from German parliamentary elections, and estimates that, under PL, at least one third of the electorate is not expressive, while around two thirds of voters are not strategic. Pons and Tricaud [2018] study French elections held under PL with quasi-experimental methods, they document voting patterns that are consistent with expressive voting. While not entirely consistent on the share of expressive voters, these works clearly point to the importance of taking expressive voting into account. We thus opt to report our robustness results for any possible fraction of expressive voters.

The paper is structured as follows. Section 3 presents the main setting. Section 4 establishes the key properties of voters' best replies and describes equilibria under AV. Section 5 studies the equilibrium properties of alternative voting rules. Section 6 presents the numerical results obtained with the adaptive procedure. Section 7 concludes. Three appendices complete the paper. Section A contains the proofs of all results, but the convergence of utility thresholds. This last result

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<sup>18</sup>Andonie and Diermeier [2019b] introduce a somewhat less related dynamic model, in which voters update their behavior after receiving individual-specific shocks but not as a function of others' behavior (as in our model). The comparison of voting rules then differs from ours, as AV is found to be typically intermediate between PL and APL [Andonie and Diermeier, 2019a]. As the authors note, the model is problematic under AV since a voter's state describes his propensity to vote for each candidate without taking correlations into account.

is shown in Section B (online), which constitutes the theoretical grounding for the Python package “Poisson Approval”. Section C (online) exposes a number of robustness checks and additional numerical results.

### 3. MODEL

#### 3.1. *Candidates and voters*

We consider an election in which voters elect one candidate into office from a set of candidates  $\mathcal{K} = \{a, b, c\}$ . Generic candidates will be denoted by  $i, j$  or  $k$ . Following the model of Myerson [2002], the number of voters is drawn from a Poisson distribution with mean  $n \in \mathbb{N}$ . Thus, the common knowledge probability that exactly  $\theta$  voters take part in the election equals  $e^{-n} \frac{n^\theta}{\theta!}$ .

A voter’s type  $t$  consists of his von Neumann and Morgenstern preference over lotteries on  $\mathcal{K}$ . It will be convenient to write  $t = (o, u)$  where  $o$  corresponds to the voter’s ordinal preference over candidates in  $\mathcal{K}$ , and  $u$  corresponds to a cardinal representation. Formally, if a voter has preference  $i \succ j \succ k$ , his *ordinal type* is denoted by  $o = ij$ , and we write  $o_1 = i$  and  $o_2 = j$  to respectively denote the most and the second most preferred candidate of an  $o$ -voter. We assume that voters have strict preferences over candidates,<sup>19</sup> so that the set of ordinal types is  $\mathcal{O} = \{ab, ac, ba, bc, ca, cb\}$ . A voter attaches utility 1 (resp. 0) to his preferred (resp. worst) candidate, and we denote by  $u \in (0, 1)$  his utility for his second-best candidate. The set of types can thus be written as  $\mathcal{T} = \mathcal{O} \times (0, 1)$ .

Once the electorate is drawn, voters’ types are drawn independently from a distribution  $\rho$  on  $\mathcal{T}$ , that we call the *preference profile*. We denote by  $r \in \Delta(\mathcal{O})$  its marginal on  $\mathcal{O}$ , that we call the *ordinal profile*, so that  $r_o$  denotes the share of  $o$ -voters in the profile. We denote by  $\Delta^*(\mathcal{O}) = \{r \in \Delta(\mathcal{O}) \mid \forall o \in \mathcal{O}, r_o > 0\}$  the set of ordinal profiles that contain all ordinal types. We denote by  $\rho_o$  the conditional distribution of  $\rho$  on  $(0, 1)$  for each ordinal type  $o \in \mathcal{O}$ , so that  $\rho_o$  is the distribution of utilities for candidate  $o_2$  and ordinal type  $o$ . We assume that each distribution  $\rho_o$  is absolutely continuous with respect to the Lebesgue measure, and we denote by  $F_o$  its cumulative distribution function.

#### 3.2. *Strategies, profiles and pivots*

We focus on simple scoring rules, in which candidates are evaluated on the basis of their aggregate support in the electorate. A rule is then defined by the set of messages (or ballots) available to each voter, denoted by  $\mathcal{M} \subseteq 2^{\mathcal{K}}$ . The plurality

<sup>19</sup>We make this assumption for the clarity of exposition, but it is not substantive. Note that under AV, it is straightforward for a voter with preference  $i \succ j \sim k$  (resp.  $i \sim j \succ k$ ) to vote  $i$  (resp.  $ij$ ).

rule is defined by  $\mathcal{M}^{PL} = \{a, b, c\}$ , the anti-plurality rule is such that  $\mathcal{M}^{APL} = \{ab, ac, bc\}$  and approval voting is defined by  $\mathcal{M}^{AV} = \{\emptyset, a, b, c, ab, ac, bc, abc\}$ . For any ballot  $m \in \mathcal{M}$  and candidate  $k$ , we note  $k \in m$  if  $k$  is approved (or supported) in  $m$ .

A (pure) *strategy* is a measurable function  $\sigma : \mathcal{T} \rightarrow \mathcal{M}$ . For any ballot  $m$  and strategy  $\sigma$ , we denote by  $\tau_m$  the expected share of voters casting the ballot  $m$ :

$$\forall m \in \mathcal{M}, \quad \tau_m = \rho(\{t \in \mathcal{T} \mid \sigma(t) = m\}) = \sum_{o \in \mathcal{O}} r_o \int_0^1 \mathbb{1}_{\{\sigma(o, u) = m\}} dF_o(u).$$

The (ballot) *profile*  $\tau = (\tau_m)_{m \in \mathcal{M}} \in \Delta(\mathcal{M})$  plays a central role in our analysis as it captures all the relevant strategic information contained in the strategy  $\sigma$ . For any candidate  $k$ , we denote by  $\gamma_k$  her (normalized) expected score:  $\gamma_k = \sum_{m \mid k \in m} \tau_m$ .<sup>20</sup> We say that a candidate  $k$  is *elected* under a profile  $\tau$  if  $\gamma_k > \gamma_j$  for any  $j \neq k$ .

The set  $\mathcal{Z} \subseteq \mathbb{N}^{\mathcal{M}}$  describes the possible outcomes of the election, a typical element is a vector  $z = (z_m)_{m \in \mathcal{M}}$  where each component  $z_m$  denotes the number of voters casting ballot  $m$ . The probability of an outcome  $z \in \mathcal{Z}$  is:

$$\mathbb{P}[z \mid n\tau] = \prod_{m \in \mathcal{M}} \left( \frac{e^{-n\tau_m} (n\tau_m)^{z_m}}{z_m!} \right).$$

For each outcome  $z$  and each candidate  $k$ , we denote by  $s_k(z)$  the number of approvals for  $k$  at  $z$  (the score of  $k$ ) and by  $W(z)$  the set of candidates with maximal score at  $z$  (the set of winners):

$$s_k(z) = \sum_{m \mid k \in m} z_m \quad \text{and} \quad W(z) = \arg \max_{k \in \mathcal{K}} s_k(z).$$

The expected utility for a voter of type  $t$  when he casts a ballot  $m$  is given by:

$$U_t[m \mid n\tau] = \sum_{z \in \mathcal{Z}} U_t[m \mid z] \mathbb{P}[z \mid n\tau],$$

where  $U_t[m \mid z]$  denotes the average utility of a  $t$ -voter for candidates in  $W(z + m)$ , with  $z + m$  being the outcome where one ballot  $m$  has been added to  $z$ .<sup>21</sup>

In order to determine voters' best replies, two sorts of events play a crucial role: pivot and tie events, defined as follows. For each subset of candidates  $K \subseteq \mathcal{K}$ , we write

$$\text{piv}_K = \{z \in \mathcal{Z} \mid s_i(z) = s_j(z) > s_k(z), \forall i, j \in K, \forall k \notin K\},$$

<sup>20</sup>The number of ballots  $m$  is a random variable  $Z_m \sim \mathcal{P}(n\tau_m)$ , while the number of approvals for  $k$  is a random variable  $S_k \sim \mathcal{P}(n\gamma_k)$ . Note that: variables  $(Z_m)_{m \in \mathcal{M}}$  are independent by the *independent actions* property; variables  $(S_k)_{k \in \mathcal{K}}$  may be correlated (if  $\tau_{ij} > 0$  for some  $i, j \in \mathcal{K}$ );  $\sum_{m \in \mathcal{M}} \tau_m = 1$  and  $\sum_{k \in \mathcal{K}} \gamma_k \geq 1$ .

<sup>21</sup>Formally, for  $t = (o, u)$ , we write:  $U_t[m \mid z] = \frac{1}{\#W(z + m)} (\mathbb{1}_{\{o_1 \in W(z + m)\}} + u \times \mathbb{1}_{\{o_2 \in W(z + m)\}})$ .

the event where exactly candidates in  $K$  are tied for victory. Such an event is referred to as a *pivot event*, since the ballot cast by an additional voter can affect the outcome in favor of any candidate in  $K$ . Similarly, we define a *tie event* as follows: for each  $K \subseteq \mathcal{K}$ , we let

$$\text{tie}_K = \{z \in \mathcal{Z} \mid s_i(z) = s_j(z), \forall i, j \in K\},$$

stand for the event where all candidates in  $K$  are tied. For any event  $E \subseteq \mathcal{Z}$  and ballot  $m$ , we denote by  $E - m = \{z \in \mathcal{Z} \mid z + m \in E\}$  the event where adding a ballot  $m$  creates an outcome in  $E$ . For each pair  $ij$  of candidates and each ordinal type  $o \in \mathcal{O}$ , we denote by

$$\text{piv}_{ij}^o = (\text{piv}_{ij} - o_1) \cup (\text{piv}_{ij} - o_1 o_2),$$

the event where casting a ballot  $o_1$  or  $o_1 o_2$  can create a pivot between candidates  $i$  and  $j$ , and we denote by

$$\text{tie}_{abc}^{o,1} = \text{tie}_{abc} - o_1 \quad \text{and} \quad \text{tie}_{abc}^{o,2} = \text{tie}_{abc} - o_1 o_2,$$

the events where casting a ballot  $o_1$  or  $o_1 o_2$  (respectively) can create a tie between the three candidates.

#### 4. BEST REPLIES AND ASYMPTOTIC EQUILIBRIA UNDER AV

This section presents the basic tools for the analysis of strategic voting under AV. We describe voters' best replies and introduce the notion of asymptotic equilibria. Although we solely concentrate on AV, which constitutes our primary focus in this paper, all results can be similarly adapted to PL and APL.

##### 4.1. Best Replies

For any profile  $\tau$ , the best reply for a  $t$ -voter in an election of expected size  $n$  is defined by:

$$BR^n(t \mid \tau) = \arg \max_{m \in \mathcal{M}} U_t[m \mid n\tau].$$

We first observe that for each voter with ordinal type  $o$ , any ballot  $m \in \mathcal{M} \setminus \{o_1, o_1 o_2\}$  is strictly dominated by either  $o_1$  or  $o_1 o_2$ . Therefore, all voters will approve of their favorite candidate, while some voters will also approve of their second-best one. More precisely, the following result asserts that the choice between the two undominated ballots,  $o_1$  and  $o_1 o_2$ , monotonically depends on a voter's cardinal utility for his second-best candidate.

**Proposition 1.** *For each ordinal type  $o \in \mathcal{O}$ , each  $n \in \mathbb{N}$  and each profile  $\tau \in \Delta(\mathcal{M})$ , there is a threshold  $u_o^n(\tau) \in [0, 1]$  such that:*

$$\forall u \in (0, 1), \quad BR^n(t = (o, u) \mid \tau) = \begin{cases} o_1 & \text{if } u < u_o^n(\tau) \\ o_1 o_2 & \text{if } u > u_o^n(\tau). \end{cases}$$

In words, when deciding whether to approve his second-best candidate, a voter compares his utility for this candidate to the (endogenous) *utility threshold*  $u_o^n(\tau)$ . If  $u$  is low enough ( $u < u_o^n(\tau)$ ), he only votes for his best candidate whereas when  $u$  is high enough ( $u > u_o^n(\tau)$ ), he approves of his two preferred candidates. While the derivation and the explicit formula of  $u_o^n(\tau)$  is included in the appendix (Proposition 1\*), the underlying intuition can be easily derived from the voter's decision problem. For a voter with type  $t = (o = ij, u)$ , the expected utility difference between his two undominated ballots, i.e.  $o_1 = i$  and  $o_1 o_2 = ij$ , is given by:

$$U_t[i | n\tau] - U_t[ij | n\tau] = \underbrace{\mathbb{P}[\text{piv}_{ij}^o | n\tau] \left( \frac{1-u}{2} \right)}_{\text{pivot } ij} + \underbrace{\mathbb{P}[\text{piv}_{jk}^o | n\tau] \left( -\frac{u}{2} \right)}_{\text{pivot } jk} + \underbrace{\mathbb{P}[\text{tie}_{abc}^{o,1} | n\tau] \left( \frac{1-2u}{3} \right) + \mathbb{P}[\text{tie}_{abc}^{o,2} | n\tau] \left( \frac{1-2u}{6} \right)}_{\text{tie } abc}.$$

The threshold  $u_o^n(\tau)$  essentially depends on the relative probabilities of two events: the event  $\text{piv}_{ij}$  and the event  $\text{piv}_{jk}$ . Informally, if  $\text{piv}_{ij}$  is much more likely than  $\text{piv}_{jk}$ , voters perceive the race between  $i$  and  $j$  as most important, so that most voters with ordinal type  $o = ij$  prefer to cast a ballot  $i$ , and we have  $u_{ij}^n(\tau) \approx 1$ . Similarly, if  $\text{piv}_{jk}$  is much more likely than  $\text{piv}_{ij}$ , the race between  $j$  and  $k$  appears as most serious and we have  $u_{ij}^n(\tau) \approx 0$ . However, if  $\text{piv}_{jk}$  and  $\text{piv}_{ij}$  are of similar magnitudes, best replies of voters with ordinal type  $o = ij$  critically depend on the utility they attach to  $j$ .

#### 4.2. Asymptotic Equilibria

We focus on strategic behavior in a large population. Our analysis relies on the following result.

**Theorem 1.** *For any ordinal type  $o \in \mathcal{O}$ , for any profile  $\tau \in \Delta(\mathcal{M})$ , the sequence  $(u_o^n(\tau))_{n \geq 0}$  converges. We denote by  $u_o^\infty(\tau) \in [0, 1]$  its limit.*

Theorem 1 is important as it allows to focus on an asymptotic version of the game. Its proof is relegated to Section B (online), where we also provide explicit formulas for the *asymptotic utility thresholds*  $u_o^\infty(\tau)$ . These formulas are at the core of the Python package “Poisson-Approval”, which we extensively use in our numerical analysis.

Building on Theorem 1, we define asymptotic best replies by:

$$\forall o \in \mathcal{O}, \forall u \in (0, 1), \quad BR^\infty(t = (o, u) | \tau) = \begin{cases} o_1 & \text{if } u < u_o^\infty(\tau), \\ o_1 o_2 & \text{if } u > u_o^\infty(\tau). \end{cases}$$

This induces an asymptotic best reply function from the set of profiles onto itself,

$\widetilde{BR}^\infty : \Delta(\mathcal{M}) \rightarrow \Delta(\mathcal{M})$ , defined by:

$$\forall \tau \in \Delta(\mathcal{M}), \quad \widetilde{BR}^\infty(\tau) = \left( \rho(\{t \in \mathcal{T} \mid BR^\infty(t \mid \tau) = m\}) \right)_{m \in \mathcal{M}}.$$

We say that a profile  $\tau$  is an *(asymptotic) equilibrium* if  $\tau = \widetilde{BR}^\infty(\tau)$ . In other words,  $\tau$  is an asymptotic equilibrium if, given that voters believe that the aggregate behavior corresponds to  $\tau$ , the profile arising from their best-replies converges to  $\tau$ .<sup>22</sup>

Note that this definition is different from the concept of large equilibrium used by [Myerson, 2002]. Let us define the  $n$ -best reply function by:

$$\forall \tau \in \Delta(\mathcal{M}), \quad \widetilde{BR}^n(\tau) = \left( \rho(\{t \in \mathcal{T} \mid BR^n(t \mid \tau) = m\}) \right)_{m \in \mathcal{M}}.$$

Then, a profile  $\tau$  is a *large equilibrium* if  $\tau = \lim_{n \rightarrow \infty} \tau^n$  with  $\forall n \geq 0, \tau^n = \widetilde{BR}^n(\tau^n)$ . In words,  $\tau$  is a large equilibrium if it is a limit of profiles  $\tau^n$ , in which voters from an electorate of expected size  $n$  believe that the aggregate behavior corresponds to  $\tau^n$  and the profile arising from their best-replies exactly coincides with  $\tau^n$ .

We choose to work with asymptotic equilibria as we believe they are more natural and as, from an algorithmic perspective, it is easier to check if a given profile is an asymptotic equilibrium than if it is a large equilibrium. Contrary to large equilibria, asymptotic equilibria may fail to exist, but we consider them to be a minimal requirement for plausible voter coordination in a large election, as we emphasize later in Section 5.3. In the sequel, we simply refer to *equilibria* for asymptotic equilibria.

#### 4.3. Magnitudes and Discriminatory Equilibria

We now dig into the properties of best replies by analyzing the probabilities of pivot events. Following Myerson [2000], we define the magnitude of an event  $E \subseteq \mathcal{Z}$  as the rate at which its probability tends to 0 when the population becomes large:

$$\mu[E \mid \tau] = \lim_{n \rightarrow \infty} \frac{\log(\mathbb{P}[E \mid n\tau])}{n}.$$

The main property of magnitudes is that, for any events  $E, F \subseteq \mathcal{Z}$ ,  $\mu[E \mid \tau] > \mu[F \mid \tau]$  implies  $\lim_{n \rightarrow \infty} \mathbb{P}[F \mid n\tau] / \mathbb{P}[E \mid n\tau] = 0$ . In words, if two events have different magnitudes, their probabilities diverge in the limit. While the magnitude of an event crucially depends on the profile  $\tau$ , we omit this dependence in the sequel to lighten the notations.

<sup>22</sup>Note that we choose to define an equilibrium as a profile  $\tau$ , as this variable captures the relevant information to compute voters' best replies. Alternatively, one might say that  $\sigma$  is a (strategy-) equilibrium if the associated profile  $\tau$  is an equilibrium.

As previously argued, best replies essentially depend on the relative probabilities of three pivot events ( $\text{piv}_{ab}$ ,  $\text{piv}_{ac}$  and  $\text{piv}_{bc}$ ), and we denote each corresponding *pivot magnitude* by  $\mu_{ab}$ ,  $\mu_{ac}$  and  $\mu_{bc}$ .<sup>23</sup> As a first observation, we note that when two of these magnitudes differ,  $\mu_{ij} \neq \mu_{jk}$ , the best reply of voters for which  $j$  is a second-best candidate does not depend on cardinal utilities.

**Remark 1.** For any profile  $\tau$  with  $\mu_{ij} > \mu_{jk}$ ,  $u_{ij}^\infty(\tau) = 1$  and  $u_{kj}^\infty(\tau) = 0$ .<sup>24</sup>

To illustrate the previous remark, we depict on Figure 1 the asymptotic best replies of a voter with ordinal type  $bc$ . The left panel considers the case where  $\mu_{ac} > \mu_{bc}$ , while the right panel corresponds to  $\mu_{ac} = \mu_{bc}$ . In each panel, the diagram features voters with ordinal types  $bc$ , represented in green, who may choose one of the two (undominated) ballots  $b$  and  $bc$ , represented in red. Best replies are indicated by a curly arrow (from a voter's ordinal type to a ballot), which is dashed when the choice depends on cardinal utilities.<sup>25</sup>

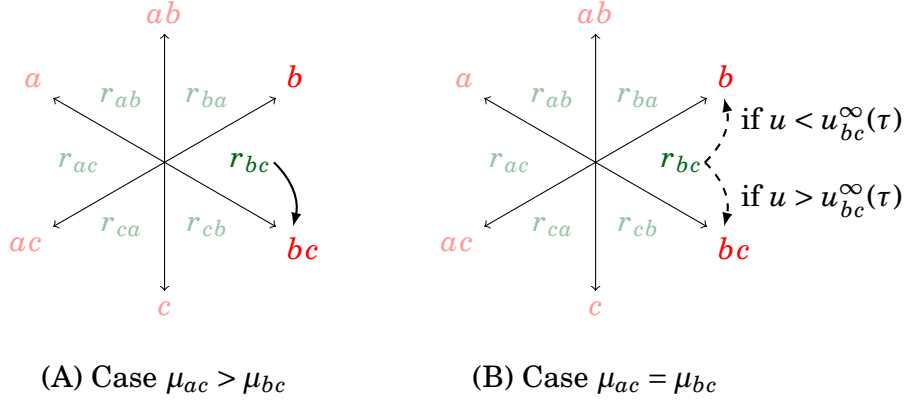


FIGURE 1. Asymptotic best replies for voters with ordinal type  $bc$ .

As pivot magnitudes drive best replies, it is useful to characterize ballot profiles with respect to the magnitude ordering they generate. Following Myerson [2002], we say that a profile  $\tau$  is *discriminatory* if there are two candidates  $i, j \in \mathcal{K}$  such that  $\mu_{ij} > \mu_{ik}, \mu_{jk}$ . Essentially, this means that voters perceive the race between candidates  $i$  and  $j$  as the most serious race in the election. The following result underscores the importance of discriminatory profiles.

<sup>23</sup>The precise definition of the magnitude for the pivot  $ij$  is  $\mu_{ij} = \mu[\text{piv}_{ij} \cup \text{tie}_{abc}]$  (see Section A.2).

<sup>24</sup>Let  $\tau$  be such that  $\mu_{ij} > \mu_{jk}$ . By application of Lemma 1 in the appendix, we have that  $\mu_{ij} > \mu_{jk} \geq \mu[\text{tie}_{abc}]$ . Using the formula for the utility threshold provided in Proposition 1\* in the appendix, we obtain:  $u_{ij}^\infty(\tau) = \lim_{n \rightarrow \infty} u_{ij}^n(\tau) = 1$  and  $u_{kj}^\infty(\tau) = \lim_{n \rightarrow \infty} u_{kj}^n(\tau) = 0$ .

<sup>25</sup>The case in which  $\mu_{bc}$  dominates is not depicted since it is symmetric to the one in



**Proposition 2.** *The set of discriminatory profiles is of (Lebesgue) measure 1.*

Proposition 2 highlights that almost all profiles are discriminatory, so that these profiles constitute a natural benchmark to focus on.<sup>26</sup>

#### 4.4. A typology of discriminatory equilibria

In this section, we describe qualitative features of voters' behavior in discriminatory equilibria, which we use later in Section 5.1. We classify these equilibria in two types: *cardinal equilibria*, for which  $\mu_{ij} > \mu_{ik} = \mu_{jk}$ , and *ordinal equilibria*, for which  $\mu_{ij} > \mu_{ik} > \mu_{jk}$ . We illustrate voters' behavior in these two types of equilibria on Figure 2, with  $i = a$ ,  $j = b$  and  $k = c$ .

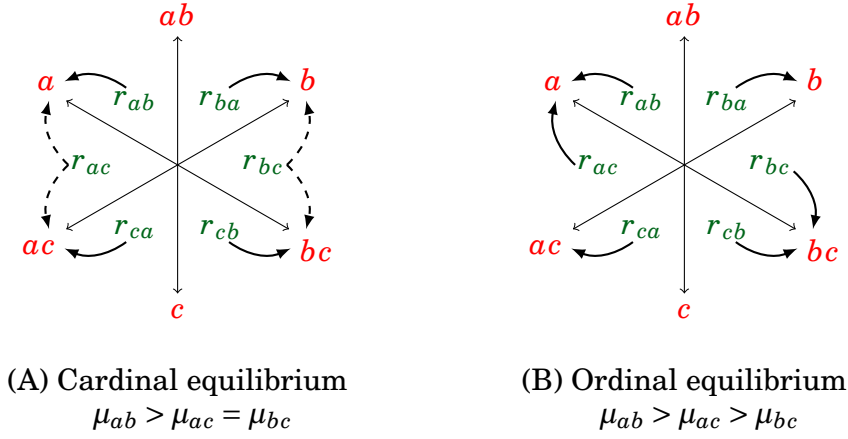


FIGURE 2. Two kinds of discriminatory equilibria.

In Figure 2 (A), we have  $\mu_{ab} > \mu_{ac} = \mu_{bc}$ .<sup>27</sup> Hence, voters perceive that the most serious race occurs between candidates  $a$  and  $b$ . The behavior of voters having either  $a$  or  $b$  as a second candidate is totally determined by this fact: these voters approve of their favorite between  $a$  and  $b$ , as well as  $c$  if it is preferred to both  $a$  and  $b$ . Voters having  $c$  as a second candidate also approve of their favorite between  $a$  and  $b$ , but they only approve of  $c$  if she yields a high enough utility.<sup>28</sup> We therefore refer to such an equilibrium as *cardinal*, in the sense that preference

which  $\mu_{ac}$  dominates:  $bc$ -voters all cast a ballot  $b$  instead of ballot  $bc$ .

<sup>26</sup>A consequence of the fragility of non-discriminatory profiles is that the best-reply function  $\widetilde{BR}^\infty$  is always discontinuous at such profiles. Even if an equilibrium is reached at such profile, it may thus be unstable. By contrast, for a generic discriminatory profile  $\tau$ , the best-reply function  $\widetilde{BR}^\infty$  is continuous at  $\tau$ .

<sup>27</sup>While this case might seem knife-edge at first sight, this is not true: there is a positive measure of profiles  $\tau$  for which this magnitude ordering holds (see Lemma 1 in the appendix).

<sup>28</sup>We provide a formula to compute voters' asymptotic utility thresholds at such an

intensities do matter for some voters, a feature in line with empirical election data [Spenkuch, 2018].

In Figure 2 (B), we have  $\mu_{ab} > \mu_{ac} > \mu_{bc}$ . Hence, voters perceive that the most serious race occurs between candidates  $a$  and  $b$ , and the second most serious race occurs between  $a$  and  $c$ . All voters then follow a version of the *leader rule* [Laslier, 2009]: they compare all candidates to the leader ( $a$ ), and approve of only those candidates preferred to  $a$ , then they approve  $a$  only if they prefer her to her main contender  $b$ .<sup>29</sup> Here, preference intensities play no role, and we refer to such an equilibrium as *ordinal*. A distinctive feature of ordinal equilibria is that all ordinal types of voters vote in block, so that all ordinal equilibria can be easily computed numerically for a given (ordinal) preference profile. We exploit this feature in our subsequent numerical analysis.

## 5. EQUILIBRIUM ANALYSIS OF VOTING RULES

In this section, we focus on equilibrium analysis to tackle the main questions of our paper: which voting rules allow for voter coordination, and whether such coordination selects normatively appealing candidates. We concentrate on the normative criterion of the Condorcet winner. We say that a candidate  $i \in \mathcal{K}$  is an (asymptotic) *Condorcet winner* if the distribution  $r$  ensures that an expected strict majority of voters prefers  $i$  to any other candidate  $j$ :  $\forall j \neq i, r_{ij} + r_{ik} + r_{ki} > 1/2$ .

We first focus on AV, showing that coordination on the election of the Condorcet winner is always feasible. Relying on the dichotomy between cardinal and ordinal equilibria, we argue that selecting a non-Condorcet winner, while possible in some extreme instances, should be a rare phenomenon under AV. Finally, we point to deficiencies of alternative voting rules: the multiplicity of possible equilibrium winners under PL, and the impossibility to coordinate under APL.

### 5.1. Condorcet Consistency of Approval Voting

We start by a general possibility result under AV.

**Theorem 2.** *For any preference profile  $\rho$ , with  $r \in \Delta^*(\mathcal{C})$  and with a Condorcet winner  $i$ , there exists an equilibrium  $\tau$  under AV such that the candidate  $i$  is elected at  $\tau$ .*

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equilibrium in the appendix (Lemma 3).

<sup>29</sup>There is one important difference with Laslier [2009]. Due to the correlations between candidates' scores, the main race always occurs between the candidate with the highest score and the candidate with the lowest score at an ordinal equilibrium. Note that this pattern violates the *ordering condition* at the root of the earlier model of

Theorem 2 establishes two important properties for profiles admitting a Condorcet winner. First, an equilibrium exists, so that coordination is possible under AV in a large election. Second, it is always possible that this coordination results in the election of the Condorcet winner. In the language of implementation theory, we may say that the voting rule AV partially implements the Condorcet winner.

The proof is constructive: we show the existence of a cardinal equilibrium where the Condorcet winner is elected. If  $i$  denotes the Condorcet winner and  $j$  her best contender (losing against  $i$  by a smaller margin than  $k$  does), the main race occurs between  $i$  and  $j$ . Voters with ordinal types  $ik$  and  $jk$  vote on the basis of their preference intensities. We thus note that the result is different from that in Laslier [2009], where an ordinal equilibrium electing the Condorcet winner is constructed.<sup>30</sup>

While we have no guarantee that the equilibrium is unique, it is important to know whether other candidates than the Condorcet winner may be elected at equilibrium under AV. To address this question, we divide our inquiry in two parts, by focusing first on cardinal equilibria, for which we provide a formal result, and then on ordinal equilibria, for which we rely on numerical computations.

To state the first result, we introduce an assumption of *cardinal support for the Condorcet winner (CSCW)*. A preference profile  $\rho$  with a Condorcet winner  $i$  satisfies CSCW if  $\forall \bar{u} \in (0, 1)$ ,  $F_{ji}(\bar{u}) + F_{ki}(1 - \bar{u}) \leq 1$ . In words, for any utility level  $\bar{u}$ , the share of  $ji$ -voters with a utility above  $\bar{u}$  is higher than the share of  $ki$ -voters with a utility below  $1 - \bar{u}$ . There are many instances for which this assumption is satisfied, notably: if  $F_{ji} = F_{ki}$  is a symmetric distribution on  $(0, 1)$ ; if  $F_{ji}$  and  $F_{ki}$  both first-order stochastically dominate a symmetric distribution  $G$  on  $(0, 1)$ ; or if  $F_{ji}$  is uniform on  $[u_1 - \varepsilon, u_1 + \varepsilon]$ ,  $F_{ki}$  is uniform on  $[u_2 - \varepsilon, u_2 + \varepsilon]$ , with  $\varepsilon$  small and  $u_1 + u_2 \geq 1$  (such as  $u_1 = 0.3$  and  $u_2 = 0.8$ ).

**Proposition 3.** *For any preference profile  $\rho$ , with  $r \in \Delta^*(\mathcal{O})$ , with a Condorcet winner  $i$  and satisfying CSCW, for any cardinal equilibrium  $\tau$  under AV, the candidate  $i$  is elected at  $\tau$ .*

Proposition 3 offers a (conditional) reciprocal statement to Theorem 2 but remains silent on the class of ordinal equilibria.<sup>31</sup> In fact, earlier work [Núñez,

Myerson and Weber [1993]. We provide a comprehensive set of relations between candidates' scores and pivot magnitudes in the Poisson model in the appendix (Lemma 2).

<sup>30</sup>Note that the equilibrium constructed by Laslier [2009] does not exist for Poisson games, as any ordinal equilibrium violates the ordering condition (as mentioned in the previous footnote), the basis on which the equilibrium in Laslier [2009] is constructed.

<sup>31</sup>Note that CSCW is a sufficient condition for the result to hold, but it is by no means necessary. For instance, the same result holds if one assumes that the Condorcet winner

2010] shows that ordinal and cardinal equilibria may coexist under AV, and that a non-Condorcet winner may be an ordinal equilibrium outcome. We thus focus in turn on ordinal equilibria, a class than we can exhaustively compute for a given preference profile. We show that while equilibrium multiplicity is frequent under AV, the election of a candidate different from the Condorcet winner at an ordinal equilibrium is extremely rare.

Let  $\mathcal{R}_{CW} \subset \Delta(\mathcal{O})$  be the set of ordinal profiles with a Condorcet winner. We denote by  $\mathcal{R}_{CW}^o \subseteq \mathcal{R}_{CW}$  the set of ordinal profiles with a Condorcet winner and such that an ordinal equilibrium exists. We denote by  $\mathcal{R}_{CW}^{o,*} \subseteq \mathcal{R}_{CW}^o$  the set of ordinal profiles with a Condorcet winner and such that an ordinal equilibrium exists that does not select this candidate.

To quantify the likelihood of these types of profiles, we run Monte-Carlo simulations for each possible number  $T \in \{2, \dots, 6\}$  of ordinal types present in a profile. Specifically, for each  $T$ , we generate 10,000 ordinal profiles, drawn independently from the uniform distribution on  $\Delta_T(\mathcal{O}) := \{r \in \Delta(\mathcal{O}) \mid \#\{o \in \mathcal{O} \mid r_o > 0\} = T\}$ . For each  $T$ , we report on Table 1 the estimated conditional probabilities of  $\mathcal{R}_{CW}^o$  and  $\mathcal{R}_{CW}^{o,*}$  given  $\mathcal{R}_{CW}$ , as well as the absolute probability that a Condorcet winner exists. With 10,000 independent draws, the boundaries of the 95% confidence interval are always within one percentage point of the point estimate, and are typically more narrow when the point estimate approaches 0% or 100%.<sup>32</sup>

$T$	$\mathbb{P}_T[\mathcal{R}_{CW}^o \mid \mathcal{R}_{CW}]$	$\mathbb{P}_T[\mathcal{R}_{CW}^{o,*} \mid \mathcal{R}_{CW}]$	$\mathbb{P}_T[\mathcal{R}_{CW}]$
2	40.8%	0.0%	100.0%
3	24.1%	3.8%	97.2%
4	27.4%	1.8%	94.9%
5	26.9%	0.3%	94.0%
6	29.4%	0.1%	93.7%

TABLE 1. Estimated frequencies of ordinal equilibrium existence ( $\mathcal{R}_{CW}^o$ ) and of the election of a non-Condorcet winner at an ordinal equilibrium ( $\mathcal{R}_{CW}^{o,*}$ ), conditionally on the existence of a Condorcet winner ( $\mathcal{R}_{CW}$ ), for any given number  $T$  of ordinal types.

We first observe that, when a Condorcet winner exists, a non-negligible proportion of ordinal profiles, estimated at 29.4% overall, admit an ordinal equilibrium. This implies that the (cardinal) equilibrium built in Theorem 2 is not generically unique.

is ranked first by at least half of the voters, without imposing any condition on preference intensities (see the proof of Proposition 3).

<sup>32</sup>To lighten notations, we do not report the (asymmetric) confidence intervals in the tables, but we provide the boundaries of the 95% confidence interval attached to all possible point estimates in Section C.9 (online).

Second, we observe that the overall prevalence of “bad” ordinal equilibria, where the Condorcet winner is not elected, is extremely rare, as they appear for only 0.1% of ordinal profiles admitting a Condorcet winner.<sup>33</sup> We note however that these rare cases appear to be slightly more likely with few ordinal types, as they occur in 1.8% of the simulations when  $T = 4$  and in 3.8% when  $T = 3$ .

To better understand the circumstances under which such examples can be found, we compute  $\mathbb{P}_O[\mathcal{R}_{CW}^{O,*} \mid \mathcal{R}_{CW}]$ , the conditional probability of a “bad” ordinal equilibrium, for each possible subset of ordinal types  $O \subseteq \mathcal{O}$ , with Monte-Carlo simulations performed for a sample of 10,000 draws.<sup>34</sup> We obtain that, perhaps surprisingly, the only domain where the conditional probability is above 5% is the single-peaked domain.<sup>35</sup> Indeed, an ordinal equilibrium where the Condorcet winner is not elected exists in 5.9% of all single-peaked profiles and in 13.0% of single-peaked profiles with three ordinal types such that each of them has a different candidate ranked first.<sup>36</sup> We return to the domain of single-peaked profiles when we present the simulations of the adaptive procedure in Section 6.

The conclusion we draw from this section is rather positive for AV: the rule partially implements the Condorcet winner, and we have reasons to believe that the election of a candidate different from the Condorcet winner is unlikely. In the sequel, we address the same questions for PL and APL, as these alternative rules offer a benchmark to which we can compare the performance of AV.

## 5.2. Duverger’s law under Plurality Voting

In this section, we recall Duverger’s law for PL. For any pair of candidates  $i, j \in \mathcal{K}$ , the belief that all voters vote for either  $i$  or  $j$  is self-fulfilling. Hence there is an equilibrium where one of these two candidates is elected: the one preferred by a majority in the race between  $i$  and  $j$ .

**Proposition 4.** (*Duverger, 1951; Myerson, 2002*) *Under PL, for a generic ordinal profile  $r$ , for any candidates  $i$  and  $j$ , there is an equilibrium  $\tau$  with  $\gamma_i, \gamma_j > \gamma_k = 0$ . For any such profile  $r$ , at least two candidates can be elected at equilibrium.*

<sup>33</sup>In that case, the elected candidate is always the non-Condorcet loser.

<sup>34</sup>Ordinal profiles  $r$  are drawn from the uniform distribution over the simplex  $\Delta(O)$ .

<sup>35</sup>The single-peaked domain is defined as  $\mathcal{D}_{SP} = \{r \in \Delta(\mathcal{O}) \mid \exists i, j \in \mathcal{K}, r_{ij} + r_{ji} = 0\}$ . Informally, one candidate ( $k$ ) is never ranked last. On this domain, a Condorcet winner always exists.

<sup>36</sup>We can show that, on the single-peaked domain, only the central candidate (say  $b$ ) can be elected at an ordinal equilibrium. The region of parameter values for which this equilibrium exists but  $b$  is not the Condorcet winner is (i) convex, (ii) contiguous to the region where  $b$  is the Condorcet winner and (iii) such that at least  $\frac{3-\sqrt{5}}{2} \approx 38\%$  of voters prefer  $b$  to the Condorcet winner.

We observe that PL always admits an equilibrium where the Condorcet winner is elected, exactly as for AV. However, contrary to AV, there always is a multiplicity of equilibrium winners.

### 5.3. Coordination failure under Anti-Plurality Voting

In this section, we show that coordination is generally impossible under APL.

**Proposition 5.** *Under APL, for any utility distributions  $(\rho_o)_{o \in \mathcal{O}}$ , the set of ordinal profiles  $r$  for which an equilibrium exists is of measure 0.*

The result implies that coordination failures are pervasive under APL. Proposition 5 falls in line with the non-existence of discriminatory large equilibria proven by Myerson [2002]. The intuition is simple: if two candidates  $i$  and  $j$  were expected to form the most serious race of the election, all voters would vote against their most disliked candidate between  $i$  and  $j$ , thus pushing the score of the third candidate,  $k$ , above both  $i$  and  $j$ 's scores, a contradiction. What we add to this intuition is the observation that other, non-discriminatory equilibria cannot generically exist.

Note the stark contrast between Proposition 5, establishing the generic non-existence of *asymptotic equilibria*, and the general existence of *large equilibria* under APL [Myerson, 2002]. Generically, there is no asymptotically self-fulfilling belief  $\tau$ , but there always exists a converging sequence of beliefs  $(\tau^n)_{n \geq 0}$ , each  $\tau^n$  being self-fulfilling for an electorate of expected size  $n$ . Thus, the construction of large equilibria hinges on extremely small details in beliefs, vanishing at the limit, a behavioral assumption that seems rather implausible. Therefore, we see large equilibria as a very relevant theoretical tool, whose existence is guaranteed, but as a rather artificial construction for meaningful coordination in practice. In the particular case of APL, the existence of large equilibria may hide serious difficulties of coordination under this rule.<sup>37</sup>

## 6. A MODEL OF POLITICAL TÂTONNEMENT

To gain more insights on strategic behavior in large elections, we consider a dynamic process from which equilibria may plausibly arise: an adaptive procedure of “political tâtonnement”. The procedure simulates a repeated sequence of polls,<sup>38</sup> in which a fraction of voters updates its behavior after the publication of each poll, and we focus on long-run outcomes. The virtues of this alternative

<sup>37</sup>See the discussion in Section C.4.2 (online), where we apply the adaptive procedure from Section 6 to the *Bad Apple* example of Myerson [2002] under APL.

<sup>38</sup>We refer to a ballot profile  $\tau$  as a poll for illustrative purposes here. Note that  $\tau$

modeling device are twofold. First, we avoid the difficulties associated with equilibrium multiplicity or non-existence. Indeed, if multiple equilibria exist, any converging trajectory selects one particular equilibrium. If no equilibrium exists, the long-run outcome of a trajectory may provide relevant information on voters' behavior. Second, the trajectories of the procedure can be numerically computed. We thus perform Monte-Carlo simulations to describe various features of voter behavior in large elections and to assess the robustness of the results to the presence of expressive voters.

### 6.1. Adaptive procedure

The procedure is based on the concept of *fictitious play* [Brown, 1951]. Formally, we consider a sequence of profiles  $(\tau^p)_{p \geq 0}$ , with initial profile  $\tau^0$  drawn from the uniform distribution on  $\Delta(\mathcal{M})$ , and whose dynamic is described by the following equations:

$$\begin{cases} \hat{\tau}^1 = \tau^0 \\ \tau^1 = \widehat{BR}^\infty(\tau^0) \end{cases} \quad \text{and} \quad \forall p > 1, \quad \begin{cases} \hat{\tau}^p = (1 - \alpha^p)\hat{\tau}^{p-1} + \alpha^p \tau^{p-1} \\ \tau^p = (1 - \beta^p)\tau^{p-1} + \beta^p \widehat{BR}^\infty(\hat{\tau}^p), \end{cases}$$

where  $\alpha^p = \beta^p = \frac{1}{\log(p+1)}$ .

This set of equations can be read as follows. The profile  $\hat{\tau}^p$  corresponds to the *perceived profile* at period  $p$ . At  $p = 1$ , the perceived profile coincides with the initial profile  $\tau^0$ . At later periods, the perceived profile  $\hat{\tau}^p$  is a weighted average of the perceived profile at  $p - 1$  and of the *actual profile* being played at  $p - 1$ ,  $\alpha^p$  being the weight attached to that latter term. The actual profile  $\tau^p$  initially corresponds to the best reply to  $\tau^0$ . At later periods, a share  $\beta^p$  of the electorate updates its behavior and plays a best reply to the perceived profile  $\hat{\tau}^p$ . We choose  $\alpha^p = \beta^p = \frac{1}{\log(p+1)}$  to optimize (numerically) the convergence rate of the procedure. In terms of beliefs, the procedure is thus intermediate between the best-reply dynamic ( $\alpha^p = 1$ ) and the classical fictitious play ( $\alpha^p = \frac{1}{p+1}$ ).<sup>39</sup> Intuitively, all previous periods are taken into account, but later ones get a disproportionate weight.<sup>40</sup>

We choose to focus on a uniform draw of the initial poll  $\tau^0$ , as this assumption provides a transparent account of all the possible outcomes that may happen under a certain voting rule at a given preference profile. In practice, there are many reasons why polls at the beginning of an election campaign may be only remotely related to preferences: preferences might evolve during the campaign corresponds to an idealized poll, as there is no randomness arising from sample selection.

<sup>39</sup>See for instance Fudenberg and Levine [1998].

<sup>40</sup>More precisely, for any fraction  $f \in (0, 1)$ , the total weight assigned to the fraction  $f$  of latest periods converges to one when the total number of periods diverges to infinity.

as information and debates unfold, polls may be strategically used to favor certain candidates, primaries might first occur in localities whose preferences are at odds with those of the electorate at large, etc. We discuss in Section C.3 (online) alternative specifications for the distribution of  $\tau^0$ .

We note that the steady states of the procedure coincide with the (asymptotic) equilibria analyzed in Section 5:

**Remark 2.**  $(\hat{\tau}, \tau)$  is a steady state of the adaptive procedure if and only if  $\hat{\tau} = \tau$  is an equilibrium.

In the sequel, we report the results of Monte-Carlo simulations of the adaptive procedure. Each observation consists of two independent draws, one for the ordinal preference profile  $r$  and the other for the initial poll  $\tau^0$ . The profile  $r$  is drawn from the uniform distribution on the simplex  $\Delta(\mathcal{C})$ , unless otherwise specified. Moreover, we assume that for each ordinal type  $o$ , the distribution of utilities for the second candidate,  $\rho_o$ , is uniform on  $(0, 1)$ .<sup>41</sup> All simulations reported below rely on a number of 10,000 draws, so that the remark on confidence intervals made in Section 5.1 also applies to these simulations.

## 6.2. Comparisons of voting rules

**6.2.1. Convergence.** We consider that the sequence  $(\tau^p)_{p \geq 0}$  converges (numerically) if there is a period  $p$  such that the two following conditions are satisfied:  $\|\tau^p - \widetilde{BR}^\infty(\hat{\tau}^p)\|_\infty \leq 10^{-9}$  and  $\|\hat{\tau}^p - \widetilde{BR}^\infty(\hat{\tau}^p)\|_\infty \leq 10^{-9}$ .<sup>42</sup>

We report in Table 2 the convergence rate of the procedure in the Monte-Carlo simulations, for each voting rule and with a maximum of  $P = 1,000$  iterations. We decompose this rate for profiles with and without a Condorcet winner.

	PL	APL	AV
general	100.0%	0.0%	95.2%
$\exists$ CW			99.97%
$\nexists$ CW			19.3%

TABLE 2. Percentage of observations for which the procedure converges.

We observe that the procedure always converges under PL, but that it never does under APL, in line with the theoretical results of Section 5: coordination always occurs under PL but never arises under APL. Convergence is very frequent

<sup>41</sup>Note that utilities are not drawn. Instead, for each ordinal type  $o$ , we compute the share of voters casting a ballot  $o_1$  (resp.  $o_1 o_2$ ) by explicitly computing the asymptotic utility threshold  $u_o^\infty(\tau)$ .

<sup>42</sup>These conditions jointly imply that  $\|\tau^{p+1} - \tau^p\|_\infty \leq 10^{-9} \beta^{p+1}$  and  $\|\hat{\tau}^{p+1} - \hat{\tau}^p\|_\infty \leq 2 \times 10^{-9} \alpha^{p+1}$ .



under AV in general, but appears to be rare in the absence of a Condorcet winner.

When the sequence  $(\tau^p)_{p \geq 1}$  converges at a period  $p^*$ , we consider that  $\tau^{p^*}$  is the outcome of the adaptive procedure. When this is not the case, we use in the sequel the following definition of the outcome of the trajectory, which corresponds to its average long-run behavior, computed for  $P = 1,000$ . For any outcome function  $w : \Delta(\mathcal{M}) \rightarrow X$  (candidates' scores, identity of the winner, etc.), we define inductively  $w^P \in \Delta(X)$ , the (average, long-run) outcome of the sequence  $(\tau^p)_{1 \leq p \leq P}$ , by:

$$w^1 = w(\tau^1) \quad \text{and} \quad \forall p > 1, \quad w^p = (1 - \lambda^p)w^{p-1} + \lambda^p w(\tau^p),$$

where  $\lambda^p = \frac{1}{\log(p+1)}$ , so that all periods are accounted for but later ones get a disproportionate weight.

Note that, since the definition of the outcome of the procedure may be probabilistic, the percentages we report in the sequel corresponds to averages taken over three non-deterministic elements: the draw of the ordinal preference profile  $r$ , the draw of the initial profile  $\tau^0$  and the outcome  $w^P$  (only if the trajectory does not converge).

**6.2.2. Condorcet Consistency.** In this section, we focus on preference profiles with a Condorcet winner. We report in the table below the frequency with which the Condorcet winner is elected for each voting rule. As we observed in Section 5 that single-peaked profiles were more likely than others to admit an ordinal equilibrium electing a non-Condorcet winner under AV, we also report frequencies computed over this particular domain.

	PL	APL	AV
$\exists$ CW	66.1%	49.5%	99.96%
Single-Peaked	66.1%	74.7%	99.2%

TABLE 3. Percentage of observations for which the Condorcet winner is elected.

The main result of Table 3 is that AV almost always implements the Condorcet winner, whereas PL and APL often elect a non-Condorcet winner. For PL, the equilibrium multiplicity of Duverger's law (Proposition 4) translates in a significant chance to miss the Condorcet winner, which occurs if voters coordinate on the “wrong equilibrium” where the Condorcet winner is not a serious contender. For APL, the generic nonexistence of equilibrium (Proposition 5) hinders voters to coordinate to elect the Condorcet winner.

We observe that the main conclusion remains valid on the domain of single-peaked profiles. Although AV may admit some equilibria on this domain for which the Condorcet winner is not elected, these are almost never reached by the adaptive procedure, as the Condorcet winner is elected in 99.2% of the simulations.

**6.2.3. Illustration: Divided preferences.** In this section, we illustrate the comparison between AV and PL on the domain of *divided preferences*, defined by:

$$\mathcal{R}_{DP} = \{r \in \Delta(\mathcal{O}) \mid \exists k \in \mathcal{K} \text{ such that } r_{ik} + r_{jk} = 0\}.$$

On this domain, there is a candidate that is never ranked second, we let this candidate be  $c$ . The election thus displays the confrontation of two sides: those who rank  $c$  first and those who rank  $c$  last.<sup>43</sup> Any preference profile on this domain admits a Condorcet winner.

We perform Monte-Carlo simulations for fixed preference profiles on the domain, so that the main source of uncertainty pertains to the draw of the initial ballot profile  $\tau^0$ , and we conduct 1,000 draws per profile. We consider profiles on a finite grid, assuming that  $r_{cb} = 0.2$ , so that a fixed share of 20% of voters prefer  $c$  to  $b$  to  $a$ . Profiles vary along two parameters:<sup>44</sup> the share of voters who rank  $a$  first and the share of voters who rank  $b$  first. Remaining voters prefer  $c$  to  $a$  to  $b$ , and these three groups form a total of 80% of the electorate. We report on Figure 3 the winning frequencies of each candidate as a function of the ordinal preference profile  $r$ .

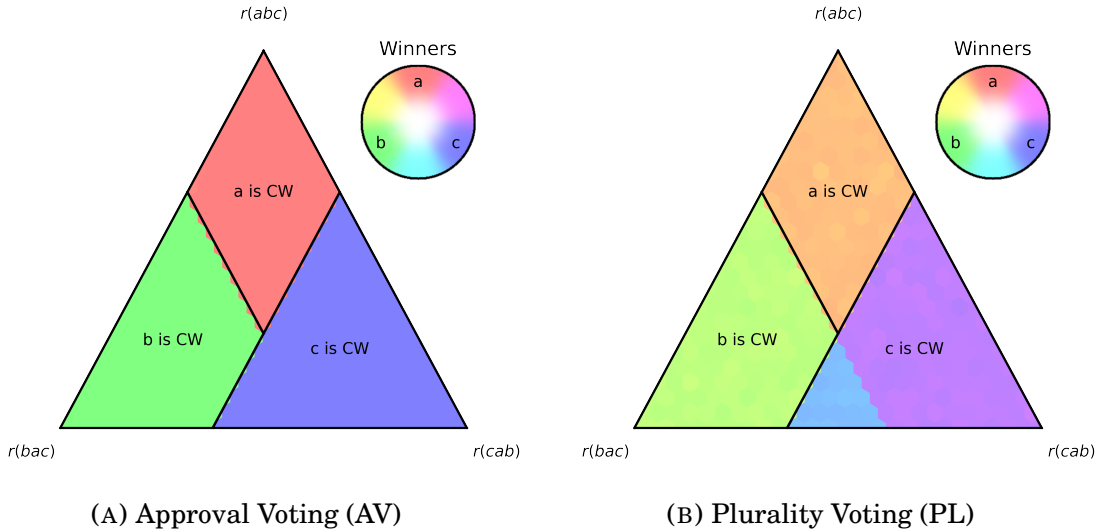


FIGURE 3. Candidates' long-run winning frequencies with divided preferences and a fixed share  $r_{cb} = 20\%$  of voters.

On the left panel, we observe that AV almost always selects the Condorcet winner. The only exception, barely noticeable on the figure, arises on the left side of

<sup>43</sup>The domain often appears in the literature as a *divided majority*, with the feature that supporters of  $c$  form a minority and are indifferent between  $a$  and  $b$  [Borda, 1781, Myerson and Weber, 1993, Bouton and Castanheira, 2012].

<sup>44</sup>Numerically, Figure 3 is drawn on a grid where each parameter can take any of 26 equally spaced values from 0 to 1.

the upper left area where  $a$  is the Condorcet winner. Under this profile, a narrow majority of the electorate prefers  $a$  to  $b$ . The probability to elect  $a$  under this profile is large, but there is a small chance, estimated at 4%, that  $b$  gets elected.<sup>45</sup>

On the right panel, we observe the results for PL. For all preference profiles, there are two possible winners (the Condorcet loser never wins), and the Condorcet winner is elected with probability  $2/3$ .<sup>46</sup> The explanation is simple: for a random draw of the initial poll  $\tau^0$ , there is generically a unique pivot with the highest magnitude, and by symmetry, there is a chance of  $2/3$  that this pivot contains the Condorcet winner. In subsequent periods, updating voters only vote for the two candidates appearing in the pivot, so that this pivot always remains the one with the highest magnitude, and the majority-preferred candidate in the pivot gets elected. Hence, the Condorcet winner fails to be elected when she does not appear in the main pivot at the first period, this situation arises with a significant probability of  $1/3$ . We report in Section C.4 (online) the (less encouraging) results obtained under APL.

**6.2.4. Welfare comparisons.** To complement the analysis of the previous sections, we compare voting rules according to other normative criteria than the selection of the Condorcet winner. We start with the notion of utilitarian welfare. As (von Neumann and Morgenstern) utilities have been normalized to lie between 0 and 1 for each voter, this welfare criterion corresponds to *relative utilitarianism*, which has a solid theoretical foundation [Dhillon and Mertens, 1999, Borgers and Choo, 2017].

We report on Figure 4 the cumulative distribution function of utilitarian welfare losses (with respect to the welfare maximizing candidate) under the three voting rules.<sup>47</sup> For this figure as for subsequent ones, the grey area around each line corresponds to a width of 2 percentage points, which contains the 95% confidence interval associated to each reported estimate (see Section C.9, online).

<sup>45</sup>For instance, a profile in this region that admits two equilibria is as follows:  $r_{ab} = 55\%$ ,  $r_{ba} = 25\%$  and  $r_{cb} = 20\%$ , so that  $a$  is the Condorcet winner. There is a cardinal equilibrium, with  $\mu_{ab} > \mu_{ac} = \mu_{bc}$ , where players' strategies are:  $ab \rightarrow a$ ,  $ba \rightarrow b$  and  $cb \rightarrow bc$ , so that  $a$  is elected. There is also an ordinal equilibrium, with  $\mu_{bc} > \mu_{ab} > \mu_{ac}$ , where players' strategies are:  $ab \rightarrow ab$ ,  $ba \rightarrow b$  and  $cb \rightarrow c$ . In this last equilibrium,  $b$  is elected.

<sup>46</sup>Note that the right region where  $c$  is the Condorcet winner is divided between a light blue sub-region on the left, on which  $b$  is not the Condorcet loser and thus sometimes wins, and a larger violet sub-region on the right, on which  $a$  is not the Condorcet loser and thus sometimes wins.

<sup>47</sup>Formally, the welfare loss associated to the election of a candidate  $k^*$  is  $(\max_{i \in \mathcal{K}} W(i)) - W(k^*)$ , where the utilitarian welfare function is defined by:  $W(i) = r_{ik} + r_{ij} + r_{ki} \int_0^1 u dF_{ki}(u) + r_{ji} \int_0^1 u dF_{ji}(u)$ .

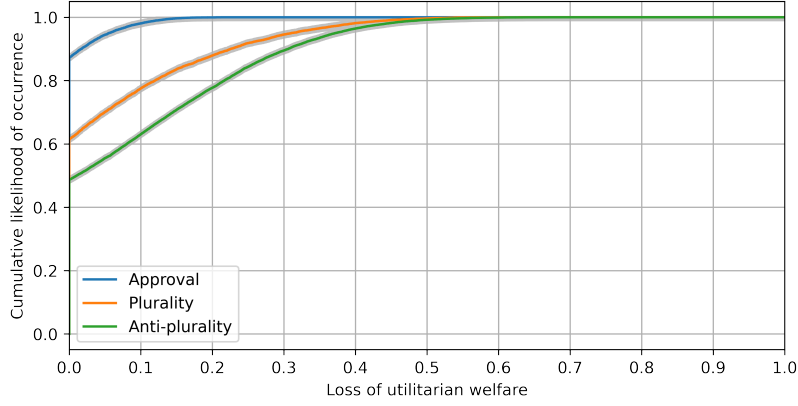


FIGURE 4. Cumulative distribution of utilitarian welfare losses under each voting rule.

We observe a clear ordering of the three voting rules, in the sense of first-order stochastic dominance, which matches the results on Condorcet consistency. Welfare losses are significantly lower under AV than under the other rules, and are smaller under PL compared to APL.<sup>48</sup>

We then consider two other criteria:  $W_{PL}$  measures the share of voters having their first choice elected, while  $W_{APL}$  measures the share of voters having either their first choice or their second choice elected.<sup>49</sup> In our setting, these two criteria are arguably less normatively appealing than utilitarian welfare.<sup>50</sup> Yet, they are of particular interest with respect to the rules we consider:  $W_{PL}$  would be maximized under PL if all voters voted expressively (for their first choice), and  $W_{APL}$  would be maximized under APL if all voters voted expressively (against their last choice). What happens when voters are strategic?

We report on Figure 5 the cumulative distribution functions of welfare losses under the three voting rules, computed for  $W_{PL}$  in the left-panel and for  $W_{APL}$  in the right panel.

Remarkably, AV still dominates both PL and APL in the sense of first-order stochastic dominance, for both welfare criteria. Overall, Figure 4 and Figure 5 give us confidence that the dominance of AV over the other voting rules is robust, and not sensitive to the retained normative criterion.

<sup>48</sup>We note a difference between preference profiles with and without a Condorcet winner. When conditioning on the existence of a Condorcet winner, we obtain a figure broadly similar to the previous one. However, the three rules become virtually indistinguishable when we condition on the non-existence of a Condorcet winner. See Section C.5 (online).

<sup>49</sup>Formally:  $W_{PL}(i) = r_{ij} + r_{ik}$  and  $W_{APL}(i) = 1 - r_{jk} - r_{kj}$ .

<sup>50</sup>Note that  $W_{APL}$  may be interpreted as Rawlsian welfare (maxmin), while  $W_{PL}$  may be interpreted as anti-Rawlsian welfare (maxmax).

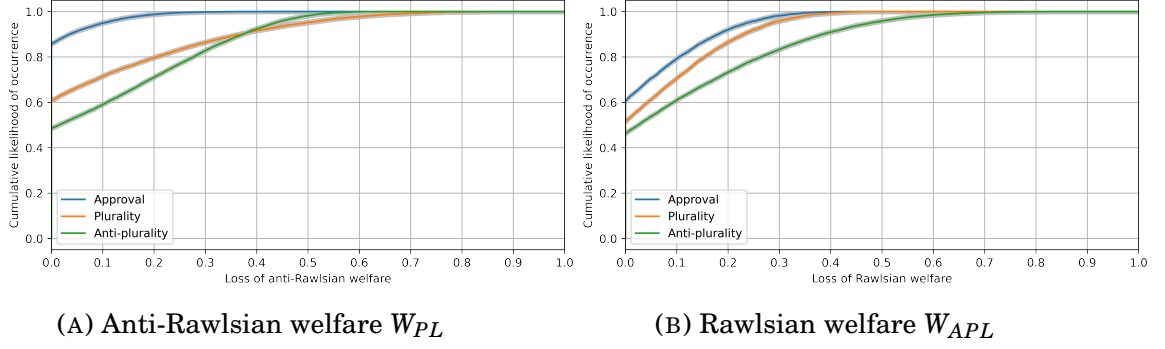


FIGURE 5. Cumulative distributions of welfare losses under each voting rule.

### 6.3. Features of voter behavior and election outcomes under AV

We report statistics on voter behavior and election outcomes under AV in the simulations.

As emphasized in Section 4, the main parameter governing the choice of a voter is his asymptotic utility threshold. Averaging over all simulations and types, we find that 47.2% of voters have a utility threshold of 1, and thus always vote for their favorite candidate only, while 18.5% of voters have a threshold of 0, and thus always vote for their two favorite candidates. The remaining share of 34.3% of voters vote for their two favorite candidates only if they have a high enough utility for the second candidate. This confirms that utility-dependent voting is a robust phenomenon in Poisson games, and that the approximate Condorcet consistency of AV is not driven by the same behavior as in Laslier [2009], where preference intensities do not play any role. As a result of this threshold distribution, we obtain that, over all simulations, 31.9% of voters approve of two candidates, while 68.1% of voters only vote for one candidate.<sup>51</sup> Hence, the positive welfare results under AV are obtained despite a majority of voters do not use the possibility to vote for multiple candidates.

In relation to Condorcet consistency and welfare comparisons, an arguably important criterion for the acceptability of election results concerns majoritarian legitimacy. While it is important that the election winner be approved by a majority of the electorate, this might not be sufficient to ensure legitimacy of the winner, as more than one candidate may receive majoritarian support under AV. The legitimacy of the winner would be stronger if this candidate was the only one to be approved by a majority. It turns out that this is what happens in almost all

<sup>51</sup>We depict in Section C.7 (online) the empirical cumulative distribution function of the utility thresholds, from which these numbers are obtained.

simulations under AV.<sup>52</sup> We report on Figure 6 the empirical cumulative distribution of the score of each candidate as a function of her rank in the election.

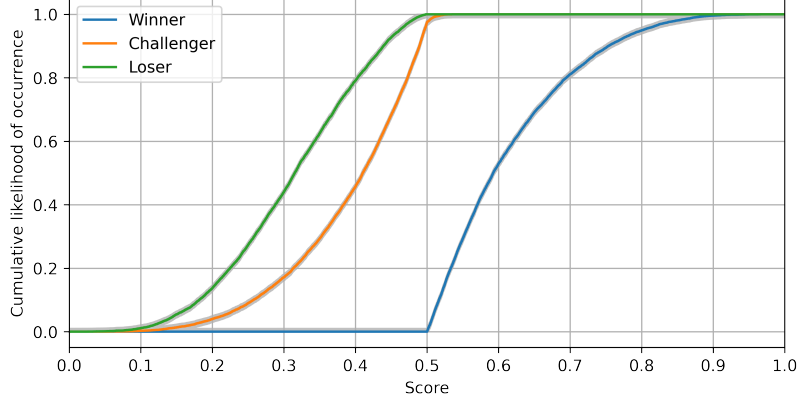


FIGURE 6. Cumulative distribution of candidates' scores under AV.

We observe that the winner always gets above 50% of approvals, while both the challenger (ranked second) and the loser (ranked third) are almost always approved by a minority of the electorate.<sup>53</sup> Hence, not only AV performs well with respect to the Condorcet and welfare criteria, but it also provides a form of majoritarian legitimacy to the election winner, at least in a strategic electorate.

#### 6.4. Robustness to expressive voting

We assumed in the analysis above that all voters were strategic. This is an arguably strong assumption that has been disputed in the empirical literature. While strategic voting models do capture features of behavior observed in experimental and empirical data, there is ample evidence that some voters vote expressively, casting a ballot for the candidate they prefer, independently of her chance of winning. We consider in this section simulations where only a fraction of the electorate is strategic, while remaining voters are expressive.

While expressiveness (or sincerity) is easy to define under PL and APL, it may be polysemic under AV [Merill and Nagel, 1987]. We start by adopting the view, both empirically plausible and well-defined theoretically, that an expressive voter

<sup>52</sup>In that case, the elected candidate may be deemed legitimate, as her election is both *internally* and *externally* consistent with a principle of majoritarian support (see Patty and Penn [2011]).

<sup>53</sup>While running the simulations, we found rare exceptions, where the challenger was approved by a majority of the electorate. One such example is described in Section C.8 (online).

votes as if he were the only voter in the electorate.<sup>54</sup> Hence, we first assume that a (model 1-) expressive voter simply approves of his favorite candidate under AV. We report on Figure 7 the frequency of the election of the Condorcet winner when she exists, as a function of the fraction of (model 1-) expressive voters, under each voting rule.<sup>55</sup>

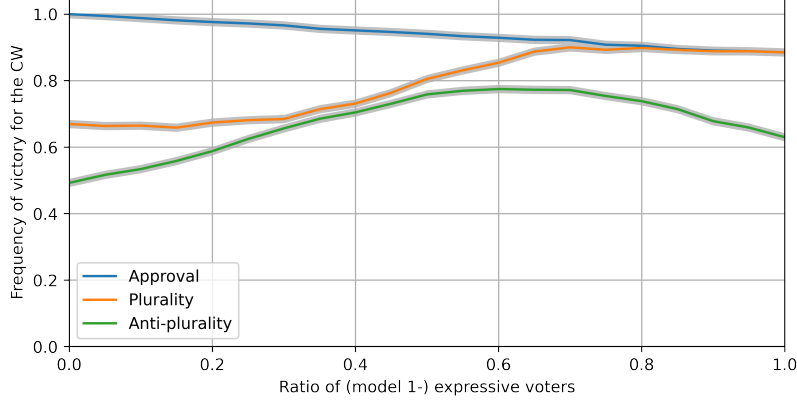


FIGURE 7. Winning frequency of the Condorcet winner as a function of the fraction of (model 1-) expressive voters.

We observe that the superiority of AV over PL and APL is robust to the introduction of expressive voters. Even if half of the electorate behaves expressively, AV still clearly dominates the two alternative rules.

We emphasize that this comparison is conservative as we implicitly assumed that the share of expressive voters is independent of the voting rule. However, moving from expressive to strategic behavior is plausibly more costly under PL than under AV. Indeed, when expressive and strategic behaviors differ under PL, a strategic voter should give up voting for his favorite candidate, which might be difficult to accept. On the other hand, when expressive and strategic behaviors differ under AV, a strategic voter should just approve of his second candidate in addition to his favorite one, which appears a milder departure from expressive behavior.

We thus consider a second model of expressive voting. We now assume that a (model 2-) expressive voter is restricted to cast a *weakly sincere* ballot, i.e. to not support a candidate deemed worse than another non-supported candidate. Yet, we allow such voter to (optimally) choose his ballot if several ballots are

<sup>54</sup>Formally, for any rule  $R \in \{AV, PL, APL\}$ , for any  $t$ ,  $\sigma_t^{R,E1} \in \arg\max_{m \in \mathcal{M}^R} U_t[m \mid n = 0]$ . For  $t = (o, u)$ , we obtain  $\sigma_t^{AV,E1} = \sigma_t^{PL,E1} = o_1$  and  $\sigma_t^{APL,E1} = o_1 o_2$ .

<sup>55</sup>We implicitly assume that whether a voter is expressive or not is independent of his preferences.

weakly sincere.<sup>56</sup> This second model of expressive voting is not different from the first one under PL or APL. However, the constraint of weak sincerity is moot under AV, as the (unconstrained) optimal ballot is always weakly sincere, so that the expressive model 2 coincides with the strategic one. As a result, we obtain a stronger argument for AV. In the figure, the upper blue line on Figure 7 becomes flat, starting with the same point at the origin, so that AV clearly dominates both PL and APL for *any fraction* of (model 2-) expressive voters in the electorate.

## 7. CONCLUDING REMARKS

This work underlines the potential of AV as a promising alternative voting method to PL for large elections. The flexibility that voters have to cast their ballots under AV translates to significant gains in the quality of the collective decision. When a Condorcet winner exists, our analytical and numerical results converge to show that voters will profitably coordinate to elect this candidate. Thus, AV can alleviate coordination problems in electoral settings. Yet, we wish to stress that the voting rule alone is not sufficient to generate coordination, and that the social context in which the election takes place is also important. Along this line, we have shown that a positive fraction of strategic voters (possibly lower than 1), and the existence of frequent and reliable polls are two (jointly) sufficient conditions under which the superiority of AV can be established.

Besides AV, another usual idea to ease coordination is to add a runoff to a first-stage election held under PL. In its most common version which is used in many democracies, the runoff is only held if no candidate obtains the support of a majority in the first round. Alas, as shown in Bouton [2013] and Bouton and Gratton [2015], this rule creates the same Duvergerian equilibria as under PL, and the coordination problem remains.<sup>57</sup> Another possibility, put forth by Tsakas and Xefteris [2021] in a context of information aggregation, would be to *always* conduct a runoff between the top-two candidates, even if a candidate is supported by a majority in the first round. Interestingly, the strategic situation of the first round becomes similar to that of APL.<sup>58</sup> Hence, we conjecture that it would lead to the same instability. Finally, while we have shown that AV tends to confer legitimacy

<sup>56</sup>Formally, for any  $t = (o, u)$ , let  $\mathcal{M}_t^{ws} = \{o_1, o_1 o_2, abc\}$  be the set of *weakly sincere* ballots for type  $t$ . For any rule  $R \in \{AV, PL, APL\}$ , for any profile  $\tau$ , for any  $t$ , a (model-2) expressive voter casts a ballot  $\sigma_t^{R,E2} \in \arg\max_{m \in \mathcal{M}_t^R \cap \mathcal{M}_t^{ws}} U_t[m \mid n \rightarrow +\infty, \tau]$ . For  $t = (o, u)$ , we obtain  $\sigma_t^{AV,E2} = \widetilde{BR}^\infty(t \mid \tau)$ ,  $\sigma_t^{PL,E2} = o_1$  and  $\sigma_t^{APL,E2} = o_1 o_2$ .

<sup>57</sup>Bouton and Gratton [2015] identify another equilibrium where three candidates obtain positive vote shares. Yet, even in this equilibrium, the Condorcet winner may not be selected to the second round.

<sup>58</sup>Under this rule, each voter vote for one candidate in the first round, and two out



to the elected candidate when voters are strategic, there is no guarantee that this will always occur in practice. Combining AV with a runoff would provide such a guarantee.<sup>59</sup> Understanding the effect of strategic behavior under this rule is outside the scope of the current paper but indeed seems a promising direction for future research.

## APPENDIX A. TECHNICAL APPENDIX: PROOFS

This appendix contains the proofs to all results from the article, except the convergence of utility thresholds (Theorem 1), relegated to Section B (online).

### A.1. Proof of Proposition 1

We prove a stronger version of Proposition 1 in which a formula for the utility thresholds is explicitly provided.

**Proposition 1\*.** *For each ordinal type  $o \in \mathcal{O}$ , each  $n \in \mathbb{N}$  and each profile  $\tau \in \Delta(\mathcal{M})$ , best replies are such that:*

$$\forall u \in (0, 1), \quad BR^n(t = (o, u) \mid \tau) = \begin{cases} o_1 & \text{if } u < u_o^n(\tau) \\ o_1 o_2 & \text{if } u > u_o^n(\tau), \end{cases}$$

where the utility threshold  $u_o^n(\tau) \in [0, 1]$  is given by:

$$u_o^n(\tau) = \frac{3\mathbb{P}[\text{piv}_{o_1 o_2}^o \mid n\tau] + 2\mathbb{P}[\text{tie}_{abc}^{o,1} \mid n\tau] + \mathbb{P}[\text{tie}_{abc}^{o,2} \mid n\tau]}{3\mathbb{P}[\text{piv}_{o_1 o_2}^o \mid n\tau] + 3\mathbb{P}[\text{piv}_{o_2 o_3}^o \mid n\tau] + 4\mathbb{P}[\text{tie}_{abc}^{o,1} \mid n\tau] + 2\mathbb{P}[\text{tie}_{abc}^{o,2} \mid n\tau]}. \quad (1)$$

*Proof.* We study in-depth the decision problem of a voter with ordinal type  $o = ij$ .

We first note that any ballot  $m \in \mathcal{M} \setminus \{i, ij\}$  is strictly dominated by either  $i$  or  $ij$ . Indeed,  $\emptyset$ ,  $k$  and  $ik$  are weakly dominated by the ballot  $i$  for any outcome  $z \in \mathcal{Z}$ ,<sup>60</sup> while  $j$ ,  $jk$  and  $ijk$  are weakly dominated by the ballot  $ij$  for any outcome  $z \in \mathcal{Z}$ . Moreover, each of these dominance relations become strict for the outcome  $z = 0$ , which arises with probability  $e^{-n} > 0$ . We may thus restrict our attention to ballots  $i$  and  $ij$ .

Writing  $\mathbb{P}[z]$  for  $\mathbb{P}[z \mid n\tau]$  for each  $z \in \mathcal{Z}$  for ease of notation, the expected utility

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of three are selected. Symmetrically, each voter vote for two candidates under APL (or equivalently, against the third one) and one is selected (two are eliminated).

<sup>59</sup>Note that the voting rule adopted in St. Louis, Missouri in November 2020 precisely corresponds to AV with an *automatic* runoff, held between the two candidates obtaining the highest support in the first round.

<sup>60</sup>We say that  $m$  is weakly dominated by  $m'$  for an outcome  $z$  if  $U_t[m \mid z] \geq U_t[m' \mid z]$ .

of a voter with type  $t = (o, u)$  from casting a ballot  $i$  equals:

$$\begin{aligned}
 U_t[i \mid n\tau] = & \overbrace{\mathbb{P}[\text{piv}_i - i] \cdot 1 + \mathbb{P}[\text{piv}_j - i] \cdot u + \mathbb{P}[\text{piv}_k - i] \cdot 0}^{\text{Single-winner events}} \\
 & + \overbrace{\mathbb{P}[\text{piv}_{ij} - i] \left(\frac{1+u}{2}\right) + \mathbb{P}[\text{piv}_{ik} - i] \left(\frac{1}{2}\right) + \mathbb{P}[\text{piv}_{jk} - i] \left(\frac{u}{2}\right)}^{\text{Two-way pivots}} \\
 & + \overbrace{\mathbb{P}[\text{tie}_{abc} - i] \left(\frac{1+u}{3}\right)}^{\text{Three-way tie}}.
 \end{aligned}$$

The expected utility of a voter with type  $t = (o, u)$  from casting a ballot  $ij$  equals:

$$\begin{aligned}
 U_t[ij \mid n\tau] = & \overbrace{\mathbb{P}[\text{piv}_i - ij] \cdot 1 + \mathbb{P}[\text{piv}_j - ij] \cdot u + \mathbb{P}[\text{piv}_k - ij] \cdot 0}^{\text{Single-winner events}} \\
 & + \overbrace{\mathbb{P}[\text{piv}_{ij} - ij] \left(\frac{1+u}{2}\right) + \mathbb{P}[\text{piv}_{ik} - ij] \left(\frac{1}{2}\right) + \mathbb{P}[\text{piv}_{jk} - ij] \left(\frac{u}{2}\right)}^{\text{Two-way pivots}} \\
 & + \overbrace{\mathbb{P}[\text{tie}_{abc} - ij] \left(\frac{1+u}{3}\right)}^{\text{Three-way tie}}.
 \end{aligned}$$

Thus, the difference  $\Delta_t(n, \tau) := U_t[i \mid n\tau] - U_t[ij \mid n\tau]$  equals:

$$\begin{aligned}
 & \left( \mathbb{P}[\text{piv}_i - i] + \mathbb{P}[\text{piv}_j - i]u + \mathbb{P}[\text{piv}_{ij} - i] \frac{1+u}{2} + \mathbb{P}[\text{piv}_{ik} - i] \frac{1}{2} + \mathbb{P}[\text{piv}_{jk} - i] \frac{u}{2} + \mathbb{P}[\text{tie}_{abc} - i] \frac{1+u}{3} \right) - \\
 & \left( \mathbb{P}[\text{piv}_i - ij] + \mathbb{P}[\text{piv}_j - ij]u + \mathbb{P}[\text{piv}_{ij} - ij] \frac{1+u}{2} + \mathbb{P}[\text{piv}_{ik} - ij] \frac{1}{2} + \mathbb{P}[\text{piv}_{jk} - ij] \frac{u}{2} + \mathbb{P}[\text{tie}_{abc} - ij] \frac{1+u}{3} \right).
 \end{aligned}$$

The previous expression can be simplified due to the three following observations.

Note first that  $(\text{piv}_i - i) = (\text{piv}_i - ij) \uplus (\text{piv}_{ij} - ij)$ , where the symbol  $\uplus$  expresses a union with an empty intersection. Hence,

$$\mathbb{P}[\text{piv}_i - i] - \mathbb{P}[\text{piv}_i - ij] - \mathbb{P}[\text{piv}_{ij} - ij] \frac{1+u}{2} = \mathbb{P}[\text{piv}_{ij} - ij] \frac{1-u}{2}.$$

Second, observe that  $(\text{piv}_j - ij) = (\text{piv}_j - i) \uplus (\text{piv}_{ij} - i) \uplus (\text{piv}_{jk} - i) \uplus (\text{tie}_{abc} - i)$ . Thus,

$$\begin{aligned}
 & \mathbb{P}[\text{piv}_j - i]u + \mathbb{P}[\text{piv}_{ij} - i] \frac{1+u}{2} + \mathbb{P}[\text{piv}_{jk} - i] \frac{u}{2} + \mathbb{P}[\text{tie}_{abc} - i] \frac{1+u}{3} - \mathbb{P}[\text{piv}_j - ij]u \\
 & = \mathbb{P}[\text{piv}_{ij} - i] \frac{1-u}{2} + \mathbb{P}[\text{piv}_{jk} - i] \left(-\frac{u}{2}\right) + \mathbb{P}[\text{tie}_{abc} - i] \frac{1-2u}{3}.
 \end{aligned}$$

Third, observe that  $(\text{piv}_{ik} - i) = (\text{piv}_{ik} - ij) \uplus (\text{tie}_{abc} - ij)$ . Therefore,

$$\begin{aligned}
 & \mathbb{P}[\text{piv}_{ik} - i] \frac{1}{2} - \mathbb{P}[\text{piv}_{ik} - ij] \frac{1}{2} - \mathbb{P}[\text{tie}_{abc} - ij] \frac{1+u}{3} = \mathbb{P}[\text{tie}_{abc} - ij] \left(\frac{1}{2} - \frac{1+u}{3}\right) \\
 & = \mathbb{P}[\text{tie}_{abc} - ij] \frac{1-2u}{6}.
 \end{aligned}$$

Combining the three observations, the difference  $\Delta_t(n, \tau)$  can be rewritten as :

$$\begin{aligned} & \left( \mathbb{P}[\text{piv}_{ij} - i] + \mathbb{P}[\text{piv}_{ij} - ij] \right) \frac{1-u}{2} + \left( \mathbb{P}[\text{piv}_{jk} - i] + \mathbb{P}[\text{piv}_{jk} - ij] \right) \left( -\frac{u}{2} \right) \\ & \quad + \mathbb{P}[\text{tie}_{abc} - i] \frac{1-2u}{3} + \mathbb{P}[\text{tie}_{abc} - ij] \frac{1-2u}{6}. \end{aligned}$$

Finally, observing that  $\text{piv}_{ij}^o = (\text{piv}_{ij} - i) \uplus (\text{piv}_{ij} - ij)$ ,  $\text{piv}_{jk}^o = (\text{piv}_{jk} - i) \uplus (\text{piv}_{jk} - ij)$ ,  $\text{tie}_{abc}^{o,1} = (\text{tie}_{abc} - i)$  and  $\text{tie}_{abc}^{o,2} = (\text{tie}_{abc} - ij)$ , we may write:

$$\Delta_t(n, \tau) = \mathbb{P}[\text{piv}_{ij}^o] \left( \frac{1-u}{2} \right) + \mathbb{P}[\text{piv}_{jk}^o] \left( -\frac{u}{2} \right) + \mathbb{P}[\text{tie}_{abc}^{o,1}] \left( \frac{1-2u}{3} \right) + \mathbb{P}[\text{tie}_{abc}^{o,2}] \left( \frac{1-2u}{6} \right).$$

We thus obtain the desired formulas for the best replies and the utility threshold.  $\square$

### A.2. Two lemmata on pivot magnitudes

In the sequel, we use the notion of *weak pivot events*, defined for  $i, j, k \in \mathcal{K}$  by

$$\widetilde{\text{piv}_{ij}} = \{z \in \mathcal{Z} \mid s_i(z) = s_j(z) \geq s_k(z)\} = \text{piv}_{ij} \uplus \text{tie}_{abc}.$$

The magnitudes of these events and of the three-candidate tie will be used throughout the appendix, we denote them by  $\mu_{ij} := \mu[\widetilde{\text{piv}_{ij}}]$  and  $\mu_{abc} := \mu[\text{tie}_{abc}]$ . Moreover, we extensively use the notion of *offset ratios*, which is important to derive these magnitudes. The offset-ratio  $\phi_m$  of a ballot  $m$  at an event  $E$  corresponds to the most likely number of ballots  $m$  when  $E$  occurs, divided by its expected value  $n\tau_m$ . For instance, the offset ration of ballot  $m$  in the event  $\{z\}$  is simply  $\frac{z_m}{n\tau_m}$ . The notion of offset ratios is introduced by Myerson [2000, 2002], who applies *large deviations* techniques to show that the probability of a cone event  $E$  is concentrated in outcomes for which the proportion of either ballot is (approximately) fixed. The offset ratios can then be obtained as solutions of a constrained minimization program, whose value corresponds to the magnitude of the event  $E$  (*Dual Magnitude Theorem* in Myerson [2002]). By application of these techniques, we obtain the following result.

**Lemma 1.** *Let  $\tau$  be a profile such that  $\tau_i + \tau_{ij} > 0$  for all  $i, j \in \mathcal{K}$ . For each ordinal type  $o$ , for any pair  $(i, j)$ , pivot magnitudes are such that:*

$$\bullet \mu_{ij} = \mu[\text{piv}_{ij}^o] = \begin{cases} \mu[\text{tie}_{ij}] & \text{if } \delta_{ij}(\tau) > 0, \\ \mu[\text{tie}_{abc}] & \text{if } \delta_{ij}(\tau) \leq 0, \end{cases} \quad \text{with:}$$

$$\delta_{ij}(\tau) = \tau_i \sqrt{\frac{\tau_j + \tau_{jk}}{\tau_i + \tau_{ik}}} + \tau_{ij} - \tau_{jk} \sqrt{\frac{\tau_i + \tau_{ik}}{\tau_j + \tau_{jk}}} - \tau_k,$$

$$\bullet \mu_{abc} = \mu[\text{tie}_{abc}^{o,1}] = \mu[\text{tie}_{abc}^{o,2}].$$

Lemma 1 establishes two important properties: (i) the magnitudes of pivot

events do not depend on types (superscript  $o$ ); and (ii) the magnitude of a pivot  $ij$  equals either the magnitude of  $\text{tie}_{ij}$  or that of  $\text{tie}_{abc}$ . The intuition for the second point stems from the interpretation of the threshold  $\delta_{ij}(\tau)$  as the difference between the expected score of  $i$  (which coincides with that of  $j$ ) and that of  $k$ , conditionally on  $\text{tie}_{ij}$ . For  $E = \text{tie}_{ij}$ , it is easy to see that the offset-ratios satisfy  $\phi_k = \phi_{ij} = 1$  (ballots  $ij$  and  $k$  do not influence the relative scores of  $i$  and  $j$ ), while  $\phi_i = 1/\phi_{jk} = \sqrt{(\tau_j + \tau_{jk})/(\tau_i + \tau_{ik})}$ . Therefore, the most likely score difference between  $i$  and  $k$  in the event  $\text{tie}_{ij}$  can be written as  $\delta_{ij}(\tau) = \tau_i\phi_i + \tau_{ij}\phi_{ij} - \tau_{jk}\phi_{jk} + \tau_k\phi_k$ . If conditionally on  $\text{tie}_{ij}$ , the expected score of  $k$  is below that of  $i$  (i.e.  $\delta_{ij}(\tau) > 0$ ), then a typical realization of  $\text{tie}_{ij}$  is actually also in  $\text{piv}_{ij}$ . This explains why the two events have the same magnitude. On the other hand, if conditionally on  $\text{tie}_{ij}$ , the expected score of  $k$  is above that of  $i$  (i.e.  $\delta_{ij}(\tau) \leq 0$ ), then  $\text{piv}_{ij}$  becomes much less likely than  $\text{tie}_{ij}$ , and in fact,  $\text{piv}_{ij}$  has the same magnitude as  $\text{tie}_{abc}$ .

*Proof.* Let  $\tau$  be a profile such that  $\tau_i + \tau_{ij} > 0$  for all  $i, j \in \mathcal{K}$ . As a direct application of the *Magnitude Equivalence Theorem* by Núñez [2010], we have that for any ordinal type  $o$ , any profile  $\tau$ , and any pair  $ij$  of candidates:

$$\mu[\text{piv}_{ij}^o] = \mu[\widetilde{\text{piv}_{ij}}] = \mu_{ij} \quad \text{and} \quad \mu[\text{tie}_{abc}^{o,1}] = \mu[\text{tie}_{abc}^{o,2}] = \mu[\text{tie}_{abc}] = \mu_{abc}.$$

Applying the *Dual Magnitude Theorem* [Myerson, 2002], we can write:

$$\mu_{abc} = \min_{x,y \in \mathbb{R}} F(x,y), \quad \mu_{ij} = \min_{x \in \mathbb{R}, y \geq 0} F(x,y), \quad \mu[\text{tie}_{ij}] = \min_{x \in \mathbb{R}, y=0} F(x,y)$$

where

$$F(x,y) = \tau_i e^{x+y} + \tau_{ik} e^x + \tau_j e^{-x} + \tau_{jk} e^{-(x+y)} + \tau_k e^{-y} + \tau_{ij} e^y - 1.$$

The function  $F$  is strictly convex as  $\frac{\partial^2 F}{\partial x^2} = e^x(\tau_i e^y + \tau_{ik}) + e^{-x}(\tau_j + \tau_{jk} e^{-y}) > 0$  and

$\Delta := \frac{\partial^2 F}{\partial x^2} \times \frac{\partial^2 F}{\partial y^2} - \left( \frac{\partial^2 F}{\partial x \partial y} \right)^2$  is such that:

$$\begin{aligned} \Delta &= [e^x(\tau_i e^y + \tau_{ik}) + e^{-x}(\tau_j + \tau_{jk} e^{-y})] \times \\ &\quad [e^y(\tau_i e^x + \tau_{ij}) + e^{-y}(\tau_k + \tau_{jk} e^{-x})] - (\tau_i e^{x+y} + \tau_{jk} e^{-(x+y)})^2 \\ &= e^{x+y}(\tau_i \tau_{ik} e^x + \tau_i \tau_{ij} e^y + \tau_{ij} \tau_{ik}) + e^{y-x}(\tau_i \tau_j e^x + \tau_j \tau_{ij} + \tau_{ij} \tau_{jk} e^{-y}) \\ &\quad + e^{x-y}(\tau_i \tau_k e^y + \tau_k \tau_{ik} + \tau_{ik} \tau_{jk} e^{-x}) + e^{-x-y}(\tau_j \tau_{jk} e^{-x} + \tau_j \tau_k + \tau_k \tau_{jk} e^{-y}) > 0. \end{aligned}$$

Since  $\tau_i + \tau_{ij} > 0$  for all  $i, j \in \mathcal{K}$ , it can be checked that  $|F(x,y)|$  tends to infinity when either  $|x|$  or  $|y|$  tends to infinity.<sup>61</sup> Therefore, the strictly convex function  $F$  admits a unique critical point  $(x^{**}, y^{**}) \in \mathbb{R}^2$ . The value  $y^{**}$  solves for

<sup>61</sup>We obtained this by considering in turn the five possible cases: (i)  $\tau_i \tau_j \tau_k > 0$ ; (ii)  $\tau_{ij} \tau_{ik} \tau_{jk} > 0$ ; (iii)  $\tau_i \tau_j \tau_{ik} \tau_{jk} > 0$ ; (iv)  $\tau_i \tau_k \tau_{ij} \tau_{jk} > 0$  and (v)  $\tau_j \tau_k \tau_{ij} \tau_{ik} > 0$ .

$\min_{y \in \mathbb{R}} F(x^*(y), y)$ , where  $x^*(y) = \operatorname{argmin}_{x \in \mathbb{R}} F(x, y)$  is uniquely defined. We consider two cases:

- Either  $\frac{\partial F}{\partial y}(x^*(0), 0) > 0$ . In that case,  $y^{**} < 0$ , and we obtain that  $\mu_{ij} > \mu_{abc}$  and  $\mu[\text{tie}_{ij}] > \mu_{abc}$ . Moreover, we have:

$$\mu_{ij} = \min_{x \in \mathbb{R}, y \geq 0} F(x, y) = \min_{y \geq 0} F(x^*(y), y) = F(x^*(0), 0) = \min_{x \in \mathbb{R}, y=0} F(x, y) = \mu[\text{tie}_{ij}].$$

- Or  $\frac{\partial F}{\partial y}(x^*(0), 0) \leq 0$ . In that case,  $y^{**} \geq 0$ , and we obtain that  $\mu_{ij} = \mu_{abc}$ .

To conclude, the value  $x^*(0)$  is obtained by setting

$$0 = \frac{\partial F}{\partial x}(x^*(0), 0) = e^{x^*(0)}(\tau_i + \tau_{ik}) - e^{-x^*(0)}(\tau_j + \tau_{jk}),$$

and we get  $e^{x^*(0)} = \sqrt{\frac{\tau_j + \tau_{jk}}{\tau_i + \tau_{ik}}}$ . Finally, we write

$$\frac{\partial F}{\partial y}(x^*(0), 0) = \tau_i e^{x^*(0)} + \tau_{ij} - \tau_k - \tau_{jk} e^{-x^*(0)} = \delta_{ij}(\tau).$$

As desired, we have shown that  $\mu_{ij}$  is equal to  $\mu[\text{tie}_{ij}]$  when  $\delta_{ij}(\tau) > 0$  or to  $\mu_{abc}$  otherwise.  $\square$

We now state a second lemma, relating candidates' expected scores to pivot magnitudes, which can be viewed as a corollary of Lemma 1.

**Lemma 2.** *Let  $\tau$  be a profile such that  $\tau_i + \tau_{ij} > 0$  for all  $i, j \in \mathcal{K}$ . The expected scores  $\gamma = (\gamma_k)_{k \in \mathcal{K}}$  are such that:*

- (i) *If  $\gamma_a, \gamma_b > \gamma_c$ , then  $\mu_{ab} > \mu_{abc}$ ,*
- (ii) *If  $\gamma_a \geq \gamma_b, \gamma_c$ , then  $\mu_{bc} = \mu_{abc}$ .*

*Proof.* In order to prove (i), let us assume w.l.o.g. that  $\gamma_b \geq \gamma_a$ , so that  $\tau_b + \tau_{bc} \geq \tau_a + \tau_{ac}$ . Building on Lemma 1, we write:

$$\delta_{ab}(\tau) = \tau_a \sqrt{\frac{\tau_b + \tau_{bc}}{\tau_a + \tau_{ac}}} + \tau_{ab} - \tau_{bc} \sqrt{\frac{\tau_a + \tau_{ac}}{\tau_b + \tau_{bc}}} - \tau_c \geq \tau_a + \tau_{ab} - \tau_{bc} - \tau_c = \gamma_a - \gamma_c > 0.$$

Hence,  $\mu_{ab} > \mu_{abc}$ , as desired.

For (ii), let us assume w.l.o.g. that  $\gamma_c \leq \gamma_b$ . We obtain similarly that  $\delta_{bc}(\tau) \leq \gamma_b - \gamma_a \leq 0$ . Hence,  $\mu_{bc} = \mu_{abc}$ , as desired.  $\square$

### A.3. Proof of Proposition 2

**Proposition 2.** *The set of discriminatory profiles is of (Lebesgue) measure 1.*

*Proof.* The set of profiles  $\tau$  such that there exist  $i, j \in \mathcal{K}$  for which  $\tau_i + \tau_{ij} = 0$  is of measure 0. We may thus focus on profiles  $\tau$  for which  $\tau_i + \tau_{ij} > 0$  for all  $i, j \in \mathcal{K}$ .

Let  $\tau$  be a non-discriminatory profile. If the magnitude ordering is of the form  $\mu_{ij} = \mu_{ik} > \mu_{jk}$ , then we know from Lemma 1 that  $\mu_{ij} = \mu[\text{tie}_{ij}]$  and  $\mu_{ik} = \mu[\text{tie}_{ik}]$ . Denoting by  $Z_m$  the random variable counting the number of ballots  $m$  cast in the election, we have  $\text{tie}_{ij} = \{Z_i + Z_{ik} = Z_j + Z_{jk}\}$ , where  $Z_i + Z_{ik} \sim \mathcal{P}((\tau_i + \tau_{ik})n)$  and  $Z_j + Z_{jk} \sim \mathcal{P}((\tau_j + \tau_{jk})n)$  are independent. A symmetric formula applies for  $\text{tie}_{ik}$ . It is well-known that the magnitude of the event that two independent Poisson variables of respective parameters  $\lambda n$  and  $\lambda' n$  are equal has magnitude  $-(\lambda - \lambda')^2$ .<sup>62</sup> Thus,  $\mu_{ij} = \mu_{ik}$  implies:

$$-(\tau_i + \tau_{ik} - \tau_j - \tau_{jk})^2 = -(\tau_i + \tau_{ij} - \tau_k - \tau_{jk})^2.$$

In any small neighborhood of  $\tau$ , the inequalities  $\delta_{ij}(\tau) > 0$  and  $\delta_{ik}(\tau) > 0$  are preserved, so that the formulas for  $\mu_{ij}$  and  $\mu_{ik}$  remain valid. As the previous equality is generically violated in such a neighborhood, we conclude that the set of profiles  $\tau$  with pivot ordering  $\mu_{ij} = \mu_{ik} > \mu_{jk}$  is of (Lebesgue) measure 0.

If the pivot ordering is of the form  $\mu_{ij} = \mu_{ik} = \mu_{jk}$ , then this magnitude is equal to  $\mu_{abc}$ , by application of Lemma 1 and Lemma 2 (ii). By Lemma 2, (i), there is not a unique candidate with the lowest expected score, so it must be that  $\gamma_i \geq \gamma_j = \gamma_k$ . In any neighborhood of  $\tau$ , there generically exists a unique candidate with the lowest expected score, so that, by application of Lemma 2, (i), one pivot magnitude is strictly higher than  $\mu_{abc}$ . Hence, the set of profiles  $\tau$  with pivot ordering  $\mu_{ij} = \mu_{ik} = \mu_{jk}$  is of (Lebesgue) measure 0.  $\square$

#### A.4. One lemma on discriminatory profiles

We now focus on the class of profiles  $\tau$  for which  $\tau_{ij} = \tau_k = 0$ . These profiles are the only relevant candidates for discriminatory equilibria under which  $\mu_{ij} > \mu_{ik}, \mu_{jk}$ . Intuitively, if the most serious race occurs between candidates  $i$  and  $j$ , all voters want to bear on this race, so that no one casts a ballot  $ij$  or a ballot  $k$  (this is a direct application of Remark 1). The next lemma provides explicit formulas for the pivot magnitudes and asymptotic utility thresholds at such profiles. The formulas for the asymptotic utility thresholds are provided for offsets  $\phi_m \neq 1$ , but they remain true at the limit when some offsets are equal to 1.

**Lemma 3.** *For any profile  $\tau$  with  $\tau_{ab} = \tau_c = 0$  and  $\tau_a, \tau_b, \tau_{ac}, \tau_{bc} > 0$ ,*

(i) *Pivot magnitudes are such that:*

$$\begin{cases} \mu_{ab} > \mu_{abc} & \Leftrightarrow & \tau_a \tau_b > \tau_{ac} \tau_{bc}, \\ \mu_{ac} > \mu_{abc} & \Leftrightarrow & \tau_{ac} > \tau_b, \\ \mu_{bc} > \mu_{abc} & \Leftrightarrow & \tau_{bc} > \tau_a. \end{cases}$$

<sup>62</sup>See for instance Lemma 4, (iii) in Section B (online).

In particular,  $\mu_{abc} = \min(\mu_{ab}, \mu_{ac}, \mu_{bc})$ .

(ii) If  $\mu_{ab} > \mu_{ac} = \mu_{bc}$ , then, noting  $\phi_a = \sqrt{\frac{\tau_{bc}}{\tau_a}}$ ,  $\phi_b = \sqrt{\frac{\tau_{ac}}{\tau_b}}$ ,  $\phi_{ac} = \frac{1}{\phi_b}$  and  $\phi_{bc} = \frac{1}{\phi_a}$ , we have that for any ordinal type  $o \in \{ac, bc\}$ :

$$u_o^\infty(\tau) = \frac{g_o(\phi_{o_1 o_2})}{g_o(\phi_{o_1 o_2}) + g_o(1/\phi_{o_1})} \quad \text{with} \quad g_o(y) = \phi_{o_1} + (\phi_{o_1} + \phi_{o_1 o_2}) \left(1 + \frac{3}{y-1}\right).$$

*Proof.* The proof of (i) is a direct application of Lemma 1.

Let  $\tau$  be a profile such that  $\tau_{ab} = \tau_c = 0$ ,  $\tau_a, \tau_b, \tau_{ac}, \tau_{bc} > 0$  and  $\mu_{ab} > \mu_{ac} = \mu_{bc}$ . By application of (i), it is impossible to have simultaneously  $\mu_{ab}, \mu_{ac}, \mu_{bc} > \mu_{abc}$ . Thus, we have  $\mu_{ac} = \mu_{bc} = \mu_{abc}$ . By (i), it follows that  $\tau_a \geq \tau_{bc}$  and  $\tau_b \geq \tau_{ac}$ .

To determine the best replies of ordinal types  $ac$  and  $bc$ , we compute the relative probabilities of pivots  $ac$ ,  $bc$  and  $\text{tie}_{abc}$ . As shown in the sequel, the offset ratios in the event  $\text{tie}_{abc}$  constitute sufficient statistics to compute the relative likelihood of any relevant pivot event with respect to  $\text{tie}_{abc}$ . The offset ratios are obtained as follows. Applying the *Dual Magnitude Theorem* [Myerson, 2002], the magnitude  $\mu[\text{tie}_{abc}]$  equals the optimal value of

$$\min_{x, y \in \mathbb{R}} \tau_a e^{x+y} + \tau_{ac} e^x + \tau_b e^{-x} + \tau_{bc} e^{-(x+y)} - 1.$$

Moreover, denoting by  $(x^*, y^*)$  the values of  $(x, y)$  at the optimum, the offset ratios are given by:

$$\phi_a = e^{x^*+y^*} = \sqrt{\frac{\tau_{bc}}{\tau_a}}, \quad \phi_b = e^{-x^*} = \sqrt{\frac{\tau_{ac}}{\tau_b}}, \quad \phi_{ac} = 1/\phi_b \quad \text{and} \quad \phi_{bc} = 1/\phi_a.$$

**Claim:** The offset ratios are identical in the events  $\text{piv}_{ac}$ ,  $\text{piv}_{bc}$  and  $\text{tie}_{abc}$ .

We prove the claim for  $\text{piv}_{ac}$  and  $\text{tie}_{abc}$ , a similar argument can be made for  $\text{piv}_{bc}$ . We write  $\text{piv}_{ac} = \{z \in \mathcal{Z} \mid z_a = z_{bc}\} \cap \{z \mid z_{ac} > z_b\}$  and  $\text{tie}_{abc} = \{z \in \mathcal{Z} \mid z_a = z_{bc}\} \cap \{z \in \mathcal{Z} \mid z_{ac} = z_b\}$ . We first observe that the offset ratios of ballots  $a$  and  $bc$  will be the same for the two events: both are equal to the corresponding offset ratio in the event  $\{z \in \mathcal{Z} \mid z_a = z_{bc}\}$ . Moreover, as  $\tau_b \geq \tau_{ac}$ , we have that for any  $n$ , the most likely outcome in the event  $\{z \in \mathcal{Z} \mid z_{ac} > z_b\}$  belongs to the event  $\{z \in \mathcal{Z} \mid z_{ac} = z_b + 1\}$ , which implies that the two events admit the same offset ratios. In turn, the offset ratios of ballots  $ac$  and  $b$  are the same for events  $\{z \in \mathcal{Z} \mid z_{ac} = z_b + 1\}$  and  $\{z \in \mathcal{Z} \mid z_{ac} = z_b\}$ , which proves the claim.

From now on, we can thus write  $\phi_m$  for the offset ratio of ballot  $m$ . Since  $\tau_a, \tau_b, \tau_{ac}, \tau_{bc} > 0$ , we have  $\phi_m > 0$  for any  $m \in \{a, b, ac, bc\}$ . The *Offset Theorem*

[Myerson, 2000] implies that:

$$\lim_{n \rightarrow \infty} \frac{\mathbb{P}[\text{piv}_{abc}^{o,1} | n\tau]}{\mathbb{P}[\text{tie}_{abc} | n\tau]} = \phi_{o_1} \quad \text{and} \quad \lim_{n \rightarrow \infty} \frac{\mathbb{P}[\text{piv}_{abc}^{o,2} | n\tau]}{\mathbb{P}[\text{tie}_{abc} | n\tau]} = \phi_{o_1 o_2}.$$

For the pivots with two candidates, we focus on pivot  $ac$ . We have:

$$\lim_{n \rightarrow \infty} \frac{\mathbb{P}[\text{piv}_{ac}^o | n\tau]}{\mathbb{P}[\text{piv}_{ac} | n\tau]} = \lim_{n \rightarrow \infty} \left( \frac{\mathbb{P}[\text{piv}_{ac} - o_1 | n\tau]}{\mathbb{P}[\text{piv}_{ac} | n\tau]} + \frac{\mathbb{P}[\text{piv}_{ac} - o_1 o_2 | n\tau]}{\mathbb{P}[\text{piv}_{ac} | n\tau]} \right) = \phi_{o_1} + \phi_{o_1 o_2}.$$

What remains to be done is to compare the likelihood of events  $\text{piv}_{ac}$  and  $\text{tie}_{abc}$ . We rely on two observations: first,  $\text{piv}_{ac} = (\text{piv}_{ac} \uplus \text{tie}_{abc}) - b$ , as  $\{z \in \mathcal{Z} \mid z_{ac} > z_b\} = \{z \in \mathcal{Z} \mid z_{ac} \geq z_b\} - b$ . Second,  $\phi_b$  is the same in  $\text{piv}_{ac}$  and in  $\text{tie}_{abc}$ : hence,  $\phi_b$  is the the offset ratio of ballot  $b$  in  $\text{piv}_{ac} \uplus \text{tie}_{abc}$ . Applying the offset theorem, we can write:

$$\lim_{n \rightarrow \infty} \frac{\mathbb{P}[\text{piv}_{ac} | n\tau]}{\mathbb{P}[\text{piv}_{ac} | n\tau] + \mathbb{P}[\text{tie}_{abc} | n\tau]} = \lim_{n \rightarrow \infty} \frac{\mathbb{P}[(\text{piv}_{ac} \uplus \text{tie}_{abc}) - b | n\tau]}{\mathbb{P}[\text{piv}_{ac} \uplus \text{tie}_{abc} | n\tau]} = \phi_b.$$

From this we obtain that  $\lim_{n \rightarrow \infty} \frac{\mathbb{P}[\text{piv}_{ac} | n\tau]}{\mathbb{P}[\text{tie}_{abc} | n\tau]} = \frac{\phi_b}{1 - \phi_b}$ ,<sup>63</sup> and we conclude that

$$\lim_{n \rightarrow \infty} \frac{\mathbb{P}[\text{piv}_{ac}^o | n\tau]}{\mathbb{P}[\text{tie}_{abc} | n\tau]} = \frac{\phi_b}{1 - \phi_b} (\phi_{o_1} + \phi_{o_1 o_2}) = \frac{1}{\phi_{ac} - 1} (\phi_{o_1} + \phi_{o_1 o_2}).$$

By symmetry, we also have:

$$\lim_{n \rightarrow \infty} \frac{\mathbb{P}[\text{piv}_{bc}^o | n\tau]}{\mathbb{P}[\text{tie}_{abc} | n\tau]} = \frac{\phi_a}{1 - \phi_a} (\phi_{o_1} + \phi_{o_1 o_2}) = \frac{1}{1/\phi_a - 1} (\phi_{o_1} + \phi_{o_1 o_2}).$$

Applying expression (1) from Proposition 1\*, we obtain at the limit the desired formula:

$$u_o^\infty(\tau) = \frac{3 \frac{1}{\phi_{o_1 o_2} - 1} (\phi_{o_1} + \phi_{o_1 o_2}) + 2\phi_{o_1} + \phi_{o_1 o_2}}{3 \frac{1}{\phi_{o_1 o_2} - 1} (\phi_{o_1} + \phi_{o_1 o_2}) + 3 \frac{1}{1/\phi_{o_1} - 1} (\phi_{o_1} + \phi_{o_1 o_2}) + 4\phi_{o_1} + 2\phi_{o_1 o_2}}. \quad (2)$$

□

#### A.5. Proof of Theorem 2

**Theorem 2.** *For any preference profile  $\rho$ , with  $r \in \Delta^*(\mathcal{C})$  and with a Condorcet winner  $i$ , there exists an equilibrium  $\tau$  under AV such that the candidate  $i$  is elected at  $\tau$ .*

*Proof.* Let  $r$  be an ordinal profile admitting a Condorcet winner denoted by  $a$ . Let  $b$  be such that  $r_{ba} \geq r_{ca}$ , that is,  $b$  is the *best contender* to  $a$  as she loses her duel against  $a$  with the lowest margin. We construct an equilibrium  $\tau$  for which  $\mu_{ab} > \mu_{ac} = \mu_{bc}$ .

<sup>63</sup>Note that, if  $\phi_b = 1$ , the formula holds true at the limit.



We denote by  $\alpha \in (0, 1)$  the share of voters with ordinal type  $ac$  casting a ballot  $a$ , and by  $\beta \in (0, 1)$  the share of voters with ordinal type  $bc$  casting a ballot  $b$ . This is, we consider a profile  $\tau = \tau(\alpha, \beta)$  of the form  $\tau_{ab} = \tau_c = 0$  and:

$$\tau_a = r_{ab} + \alpha r_{ac}, \quad \tau_b = r_{ba} + \beta r_{bc}, \quad \tau_{ac} = r_{ca} + (1 - \alpha)r_{ac}, \quad \tau_{bc} = r_{cb} + (1 - \beta)r_{bc}.$$

We are interested in the set  $\mathcal{D}_r \subseteq [0, 1]^2$  of couples  $(\alpha, \beta)$  that are consistent with the pivot ordering  $\mu_{ab} > \mu_{ac} = \mu_{bc}$ . As  $r \in \Delta^*(\mathcal{C})$ , we have  $\tau_a, \tau_b, \tau_{ac}, \tau_{bc} > 0$ . We may thus apply Lemma 3 and write:

$$\mathcal{D}_r = \{(\alpha, \beta) \in [0, 1]^2 \mid \tau_a \geq \tau_{bc}, \tau_b \geq \tau_{ac}, \tau_a \tau_b > \tau_{ac} \tau_{bc}\}.$$

We have<sup>64</sup>

$$\tau_a \geq \tau_{bc} \quad \Leftrightarrow \quad \alpha r_{ac} + \beta r_{bc} \geq r_{-a} - r_{ab}$$

and

$$\tau_b \geq \tau_{ac} \quad \Leftrightarrow \quad \alpha r_{ac} + \beta r_{bc} \geq r_{-b} - r_{ba}.$$

Since  $a$  is the Condorcet winner, there is a strict majority of voters preferring  $a$  to  $b$ , so that  $r_{-b} - r_{ba} > r_{-a} - r_{ab}$ . Hence,  $\tau_b \geq \tau_{ac} \Rightarrow \tau_a > \tau_{bc}$ , which leads to

$$\mathcal{D}_r = \{(\alpha, \beta) \in [0, 1]^2 \mid \tau_b \geq \tau_{ac}\} = \{(\alpha, \beta) \in [0, 1]^2 \mid \alpha r_{ac} + \beta r_{bc} \geq r_{-b} - r_{ba}\}.$$

By assumption, we have  $r_{ba} \geq r_{ca}$ , and it follows that  $r_{ac} \geq r_{-b} - r_{ba}$ , hence we obtain that  $(1, 0) \in \mathcal{D}_r$ .

We define an asymptotic best-reply function from the set of couples  $(\alpha, \beta)$  to itself by:

$$\text{br} : \begin{cases} \mathcal{D}_r & \rightarrow [0, 1]^2 \\ (\alpha, \beta) & \mapsto \text{br}(\alpha, \beta) = (F_{ac}(u_{ac}^\infty(\tau(\alpha, \beta))), F_{bc}(u_{bc}^\infty(\tau(\alpha, \beta)))) \end{cases}$$

We will show that  $\text{br}$  admits a fixed point  $(\alpha^*, \beta^*)$  on the set  $\mathcal{D}_r$ , which will imply the existence of an equilibrium  $\tau(\alpha^*, \beta^*)$  with pivot ordering  $\mu_{ab} > \mu_{ac} = \mu_{bc}$ . For that, we define  $h(\alpha, \beta) = \text{br}(\alpha, \beta) - (\alpha, \beta)$ . Let us show that there exists  $(\alpha^*, \beta^*) \in \mathcal{D}_r$  for which  $h(\alpha^*, \beta^*) = 0$ .

First, we observe that the function  $h$  is continuous, as each function  $F_o$  is continuous (by assumption) and each function  $u_o^\infty(\cdot)$  is continuous (from expression (2) in Lemma 3).

Second, we compute the value of  $h$  along the (possibly empty) segment  $\mathcal{S}_r = \{(\alpha, \beta) \in [0, 1]^2 \mid \alpha r_{ac} + \beta r_{bc} \geq r_{-b} - r_{ba}\}$ , on the boundary of  $\mathcal{D}_r$ . On this segment, we have that  $\tau_b = \tau_{ac}$  and  $\tau_a > \tau_{bc}$ . We thus have  $\phi_a < 1$  (hence  $\phi_{bc} > 1$ ) while  $\phi_b = 1$  (hence  $\phi_{ac} = 1$ ). By application of (2) in Lemma 3, we obtain  $u_{ac}^\infty(\tau) = 1$  and

<sup>64</sup>For simplicity, we denote the expected share of voters with worst candidate  $i$  by  $r_{-i} := r_{jk} + r_{kj}$ .

$u_{bc}^\infty(\tau) = 0$ . Thus, we have that  $\forall(\alpha, \beta) \in \mathcal{S}_r, \text{br}(\alpha, \beta) = (1, 0)$ . It follows that for any  $(\alpha, \beta) \in \mathcal{S}_r, h_1(\alpha, \beta) \geq 0$  and  $h_2(\alpha, \beta) \leq 0$ .

We draw on Figure 8 the two possible forms that the domain  $\mathcal{D}_r$  can take, using the fact that  $(1, 0) \in \mathcal{D}_r$ . We observe that, by definition of the function  $h$ , the sign of at least one function  $h_i$  is known at any point on the boundaries of  $\mathcal{D}_r$ .

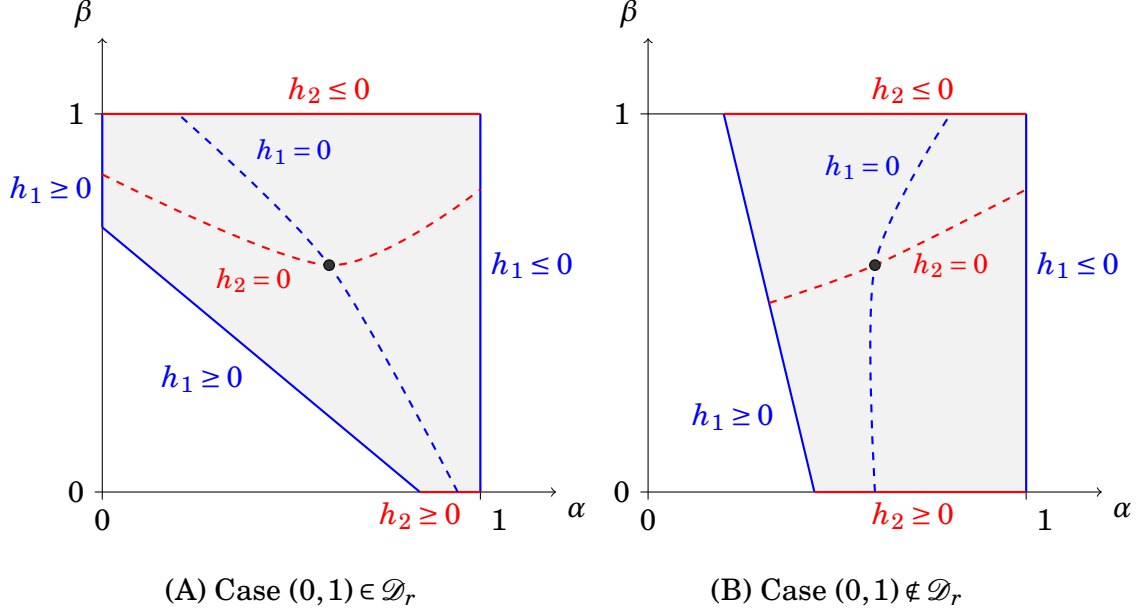


FIGURE 8. Application of the Poincaré-Miranda theorem.

These conditions on the sign of  $h_1$  and  $h_2$  allow us to apply the Poincaré-Miranda theorem [Kulpa, 1997]. There exists a  $(\alpha^*, \beta^*) \in \mathcal{D}_r$  such that  $h(\alpha^*, \beta^*) = 0$ , it is represented by a black point on Figure 8. Hence, we have constructed an equilibrium with  $\mu_{ab} > \mu_{ac} = \mu_{bc}$ .

Since  $a$  is the Condorcet winner and  $\mu_{ab} > \mu_{ac}, \mu_{bc}$ , we have that  $\gamma_a > \gamma_b$ . We observe that it cannot be that  $\gamma_c > \gamma_a > \gamma_b$ , otherwise we would have  $\mu_{ab} = \mu_{abc}$  by application of Lemma 2, (ii). Moreover, it cannot be that  $\gamma_c = \gamma_a > \gamma_b$ , otherwise we would have  $\mu_{ac} > \mu_{ab} = \mu_{abc}$  by application of Lemma 2, (i) and (ii). Thus it must be that  $\gamma_a > \gamma_b, \gamma_c$ . This means that  $a$  is elected under the constructed equilibrium, as desired.  $\square$

#### A.6. Proof of Proposition 3

**Proposition 3.** *For any preference profile  $\rho$ , with  $r \in \Delta^*(\mathcal{O})$ , with a Condorcet winner  $i$  and satisfying CSCW, for any cardinal equilibrium  $\tau$  under AV, the candidate  $i$  is elected at  $\tau$ .*

*Proof.* Let  $\rho$  be a preference profile with  $r \in \Delta^*(\mathcal{O})$ , with a Condorcet winner, say candidate  $a$ , and assume that it satisfies CSCW. Let  $\tau$  be a cardinal equilibrium,

with magnitude ordering  $\mu_{ij} > \mu_{ik} = \mu_{jk}$ . If  $i = a$  or  $j = a$ , we can apply the same reasoning as in the last paragraph of the proof of Theorem 2 to obtain that  $\gamma_a > \gamma_b, \gamma_c$ , in which case  $a$  is elected under  $\tau$ .

We thus consider the remaining case where  $\mu_{bc} > \mu_{ab} = \mu_{ac}$ . As each voter votes for his favorite candidate between  $b$  and  $c$ , we must have  $\gamma_b + \gamma_c = 1$ , and we may assume without loss of generality that  $\gamma_c \leq 1/2$ . Let  $\alpha \in [0, 1]$  be the fraction of voters with ordinal type  $o = ca$  voting for  $c$  and let  $\beta \in [0, 1]$  be the fraction of voters with ordinal type  $o = ba$  voting for  $b$ . As  $\tau$  is an equilibrium, we have  $\alpha = F_{ca}(u_{ca}^\infty(\tau))$  and  $\beta = F_{ba}(u_{ba}^\infty(\tau))$ .

To relate  $\alpha$  and  $\beta$ , we apply Lemma 3 (note that we must have  $\tau_{bc} = \tau_a = 0$  and  $\tau_b, \tau_c, \tau_{ab}, \tau_{ac} > 0$ , so that the lemma can be applied). Since  $\tau$  is a cardinal equilibrium, we have for any  $o \in \{ca, ba\}$ ,  $u_o^\infty(\tau) = \frac{g_o(1/\phi_{o_3})}{g_o(1/\phi_{o_3}) + g_{-o}(1/\phi_{o_1})}$ , where  $g_o(y) = \phi_{o_1} + (\phi_{o_1} + 1/\phi_{o_3})(1 + \frac{3}{y-1})$ . Denoting by  $-o$  the ordinal type having the reversed order from  $o$ , we may write:

$$g_{-o}(y) = \phi_{o_3} + (\phi_{o_3} + 1/\phi_{o_1})(1 + \frac{3}{y-1}) = \frac{\phi_{o_3}}{\phi_{o_1}} g_o(y).$$

We obtain, for any  $o \in \{ca, ba\}$ ,

$$\begin{aligned} u_o^\infty(\tau) &= \frac{g_o(1/\phi_{o_3})}{g_o(1/\phi_{o_3}) + g_{-o}(1/\phi_{o_1})} = \frac{g_{-o}(1/\phi_{o_3})}{g_{-o}(1/\phi_{o_3}) + g_{-o}(1/\phi_{o_1})} \\ &= 1 - \frac{g_{-o}(1/\phi_{o_1})}{g_{-o}(1/\phi_{o_1}) + g_{-o}(1/\phi_{o_3})} = 1 - u_{-o}^\infty(\tau). \end{aligned}$$

By application of the property CSCW, we obtain that:

$$\alpha + \beta = F_{ca}(u_{ca}^\infty(\tau)) + F_{ba}(1 - u_{ca}^\infty(\tau)) \leq 1.$$

Now, we may write the score of candidate  $a$  as:

$$\begin{aligned} \gamma_a &= r_a + (1 - \alpha)r_{ca} + (1 - \beta)r_{ba} \geq r_a + \beta r_{ca} + (1 - \beta)r_{ba} \\ &\geq \beta(r_a + r_{ca}) + (1 - \beta)(r_a + r_{ba}) > 1/2, \end{aligned}$$

where we use the fact that  $a$  is the Condorcet winner, and thus  $r_a + r_{ca} > 1/2$  and  $r_a + r_{ba} > 1/2$ . Hence, we have that  $\gamma_a > 1/2 \geq \gamma_c$ .

If  $\gamma_b > 1/2$ , we have  $\gamma_a, \gamma_b > \gamma_c$ , and by application of Lemma 2 (i), we get  $\mu_{ab} > \mu_{abc}$ , a contradiction.

If  $\gamma_b = 1/2$ , we have  $\gamma_a > \gamma_b = \gamma_c$ , and by application of Lemma 2 (ii), we get  $\mu_{bc} = \mu_{abc}$ , a contradiction.

We conclude that there can be no cardinal equilibrium with  $\mu_{bc} > \mu_{ab} = \mu_{ac}$ . Hence, any cardinal equilibrium must elect the Condorcet winner  $a$ .  $\square$

## A.7. Proof of Proposition 4

**Proposition 4.** *Under PL, for a generic ordinal profile  $r$ , for any candidates  $i$  and  $j$ , there is an equilibrium  $\tau$  with  $\gamma_i, \gamma_j > \gamma_k = 0$ . For any such profile  $r$ , at least two candidates can be elected at equilibrium.*

We show how to adapt this well-known result [Myerson, 2002] to our setting.

*Proof.* Let  $r$  be such that the share of voters preferring a given candidate to another is strictly positive and different from  $1/2$  (this assumption only eliminates a set of ordinal profiles  $r$  of measure 0, i.e. this assumption holds for a generic  $r$ ). Let  $i$  and  $j$  be two candidates, and consider the ballot profile  $\tau$  defined by  $\tau_i = r_{ij} + r_{ik} + r_{ki}$  and  $\tau_j = 1 - \tau_i$ . As  $\tau_i, \tau_j > 0$ , we have that  $\mu_{ij} > \mu_{ik} = \mu_{kj} = \mu_{abc}$ . Hence, voters' asymptotic best replies lead to the profile  $\tau$ , which is thus an equilibrium.

To conclude, either there is a Condorcet loser  $i$ , in which case both the Condorcet winner  $j$  (if she runs against  $i$  or  $k$ ) and the other candidate  $k$  (if she runs against  $i$ ) can be elected at an equilibrium. Or there is a Condorcet cycle, in which case any candidate can be elected at an equilibrium.  $\square$

## A.8. Proof of Proposition 5

**Proposition 5.** *Under Anti-Plurality Voting, for any utility distributions  $(\rho_o)_{o \in \mathcal{O}}$ , the set of ordinal profiles  $r$  for which an equilibrium exists is of measure 0.*

*Proof.* Let  $\tau$  be an asymptotic equilibrium under APL. If there are  $i, j$  such that  $\tau_{ij} = 0$ , we have then  $\tau_{ik} + \tau_{jk} = 1$ . In that case, it can be checked that voters with ordinal type  $ji$  weakly prefer the ballot  $ij$  to the ballot  $jk$  for any outcome that can occur. Moreover, these voters strictly prefer  $ij$  to  $jk$  in the outcome  $z_{ik} = z_{jk} = 0$ , which occurs with positive probability. Hence, the best reply for voters with ordinal type  $ji$  is the ballot  $ij$ . As  $\tau$  is an equilibrium with  $\tau_{ij} = 0$ , it must be that  $r_{ji} = 0$ , which implies that the ordinal profile  $r$  is not generic.

In the sequel we thus consider an equilibrium  $\tau$  such that  $\tau_{ab} > 0$ ,  $\tau_{ac} > 0$  and  $\tau_{bc} > 0$ . Hence, we can apply Lemma 1, and we note that, since  $\tau_a = \tau_b = \tau_c = 0$  under APL, we can write  $\delta_{ij}(\tau) = \tau_{ij} - \sqrt{\tau_{ik}\tau_{jk}}$ . We consider in turn all possible ordering of  $\tau_{ab}$ ,  $\tau_{ac}$  and  $\tau_{bc}$ .

**Case 1:**  $\tau_{ab} > \tau_{ac} > \tau_{bc}$ .

In that case,  $\delta_{ab}(\tau) > 0 > \delta_{bc}(\tau)$ . Thus,  $\mu_{ab} = -(\sqrt{\tau_{ac}} - \sqrt{\tau_{bc}})^2 > \mu_{bc} = \mu_{abc}$ .

Now, if  $\delta_{ac}(\tau) \leq 0$ , we have that  $\mu_{ab} > \mu_{ac} = \mu_{bc} = \mu_{abc}$ . Then, all voters preferring  $a$  to  $b$  cast a ballot  $ac$  (i.e. against  $b$ ), while all those preferring  $b$  to  $a$  cast a ballot  $bc$  (i.e. against  $a$ ). We obtain that  $\tau_{ab} = 0$ , a contradiction.

If  $\delta_{ac}(\tau) > 0$ , we obtain  $\mu_{ac} = (\sqrt{\tau_{ab}} - \sqrt{\tau_{bc}})^2 > (\sqrt{\tau_{ac}} - \sqrt{\tau_{bc}})^2 = \mu_{ab} > \mu_{bc}$ . Then,

we obtain as before that  $\tau_{ac} = 0$ , a contradiction.

**Case 1':**  $\tau_{ab} > \tau_{ac} = \tau_{bc}$ .

Here, we have that  $\delta_{ab}(\tau) > 0 > \delta_{ac}(\tau) = \delta_{bc}(\tau)$ . We obtain as before  $\mu_{ab} > \mu_{ac} = \mu_{bc} = \mu_{abc}$ , and then  $\tau_{ab} = 0$ , a contradiction.

**Case 2:**  $\tau_{ab} = \tau_{ac} > \tau_{bc}$ .

In that case, we obtain  $\mu_{ab} = \mu_{ac} > \mu_{bc}$  and  $\lim_{n \rightarrow \infty} \mathbb{P}[\widetilde{\text{piv}}_{ab} | n\tau] / \mathbb{P}[\widetilde{\text{piv}}_{ac} | n\tau] = 1$ .

We conclude that voters  $ab$  cast a ballot  $ab$ ,<sup>65</sup> voters  $ac$  cast a ballot  $ac$ , voters  $bc$  and  $cb$  cast a ballot  $bc$ . Moreover, voters  $ba$  cast a ballot  $ab$  if they attach a utility at least one half to  $a$ , and cast a ballot  $bc$  otherwise. Similarly, voters  $ca$  cast a ballot  $ac$  if they attach a utility at least one half to  $a$ , and cast a ballot  $bc$  otherwise.

We thus have  $\tau_{ab} = r_{ab} + r_{ba}(1 - F_{ba}(1/2))$  and  $\tau_{ac} = r_{ac} + r_{ca}(1 - F_{ca}(1/2))$ . As such equilibrium must respect the equation  $\tau_{ab} = \tau_{ac}$ , it can only be encountered for non-generic ordinal profiles  $r$ .

**Case 3:**  $\tau_{ab} = \tau_{ac} = \tau_{bc}$ .

In that case, all pivots are equally likely and all voters vote for their two favorite candidates: for all  $(i, j)$ , we have  $\tau_{ij} = r_{ij} + r_{ji}$ . Such an equilibrium can only be encountered for non-generic ordinal profiles  $r$ .  $\square$

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<sup>65</sup>Note that these voters always benefit strictly more from voting  $ab$  in the event  $\text{piv}_{ac}$  than they benefit from voting  $ac$  in the event  $\text{piv}_{ab}$ .

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## ONLINE APPENDIX

## APPENDIX B. CONVERGENCE OF THE UTILITY THRESHOLDS (ONLINE)

This online appendix is devoted to the proof of Theorem 1.

**Theorem 1.** *For any ordinal type  $o \in \mathcal{O}$ , for any profile  $\tau \in \Delta(\mathcal{M})$ , the sequence  $(u_o^n(\tau))_{n \geq 0}$  converges. We denote by  $u_o^\infty(\tau) \in [0, 1]$  its limit.*

While proving the theorem, we also provide explicit formulas for the asymptotic utility thresholds  $u_o^\infty(\tau)$ . The formulas provide the theoretical foundation for the Python package “Poisson-Approval”.

The proof is divided in three parts. First, we provide in Section B.1 asymptotic developments of basic events defined by the difference of two Poisson variables. Second, we show in Section B.2 that these developments can be directly applied to obtain asymptotic utility thresholds  $u_o^\infty(\tau)$  for profiles  $\tau$  such that (at least) two consecutive ballots are absent, that we refer to as *flower profiles*.<sup>66</sup> Third, focusing on non-flower profiles, we show in Section B.3 that asymptotic utility thresholds  $u_o^\infty(\tau)$  can be obtained from asymptotic developments of relevant pivot probabilities, which are themselves derived from asymptotic developments of probabilities of tie events.

The section concludes with an example of computation of an asymptotic utility threshold (Section B.4).

## B.1. Asymptotic Development of Some Basic Events

In this section,  $Z_1$  and  $Z_2$  denote two independent Poisson variables, with  $Z_i \sim \mathcal{P}(n\lambda_i)$  for each  $i \in \{1, 2\}$ . For the probabilities of the events defined below, we derive asymptotic developments of the form  $\exp(\mu n + \nu \log n + \xi + o(1))$  when  $n \rightarrow +\infty$ , with  $\mu, \nu, \xi \in \mathbb{R}$ .

**Lemma 4.** *For any  $k \in \mathbb{N}$ ,*

- (i) *If  $\lambda_1 = 0$* 
  - (a) *and  $k = 0$ , then  $\mathbb{P}[Z_1 = Z_2 + k] = \exp(-\lambda_2 n)$ .*
  - (b) *and  $k > 0$ , then  $\mathbb{P}[Z_1 = Z_2 + k] = 0$ .*
- (ii) *If  $\lambda_1 > 0$  and  $\lambda_2 = 0$ , then  $\mathbb{P}[Z_1 = Z_2 + k] = \exp(-\lambda_1 n + k \log n + k \log \lambda_1 - \log k!)$ .*
- (iii) *If  $\lambda_1 > 0$  and  $\lambda_2 > 0$ , then*

$$\mathbb{P}[Z_1 = Z_2 + k] = \exp\left(-\left(\sqrt{\lambda_1} - \sqrt{\lambda_2}\right)^2 n - \frac{1}{2} \log n - \frac{1}{2} \log\left(4\pi \lambda_2^{\frac{1}{2}+k} \lambda_1^{\frac{1}{2}-k}\right) + o(1)\right).$$

<sup>66</sup>With the graphical representation of our game in Figure 1 and Figure 2, flower profiles are such that relevant ballots belong to the same half-space, and are thus included in a stylized (lotus) flower.



*Proof.* Cases (i) and (ii) are direct applications of the definition of a Poisson distribution. Consider case (iii). As the difference between two independent Poisson distributions follows a Skellam distribution, we have:

$$\mathbb{P}[Z_1 = Z_2 + k] = e^{-(\lambda_1 + \lambda_2)n} \left( \frac{\lambda_1}{\lambda_2} \right)^{\frac{k}{2}} I_k \left( 2n \sqrt{\lambda_1 \lambda_2} \right),$$

where  $I_k$  denotes the modified Bessel function of the first kind of order  $k$  [Myerson, 2000]. Since  $2n \sqrt{\lambda_1 \lambda_2} \rightarrow +\infty$ , we can use the Hankel development:  $\log I_k(x) = x - \frac{1}{2} \log(2\pi x) + o(1)$  when  $x \rightarrow +\infty$ , hence the result.  $\square$

**Lemma 5.** *For any  $k \in \mathbb{N}$ ,*

(i) *If  $\lambda_1 = 0$*

(a) *and  $k = 0$ , then  $\mathbb{P}[Z_1 \geq Z_2 + k] = \exp(-\lambda_2 n)$ .*

(b) *and  $k > 0$ , then  $\mathbb{P}[Z_1 \geq Z_2 + k] = 0$ .*

(ii) *If  $\lambda_1 > \lambda_2 \geq 0$ , then  $\mathbb{P}[Z_1 \geq Z_2 + k] = \exp(o(1))$ .*

(iii) *If  $\lambda_1 = \lambda_2 > 0$ , then  $\mathbb{P}[Z_1 \geq Z_2 + k] = \exp(-\log 2 + o(1))$ .*

(iv) *If  $\lambda_2 > \lambda_1 > 0$ , then*

$$\mathbb{P}[Z_1 \geq Z_2 + k] = \exp \left( - \left( \sqrt{\lambda_1} - \sqrt{\lambda_2} \right)^2 n - \frac{1}{2} \log n - \frac{1}{2} \log \left( 4\pi \lambda_2^{\frac{1}{2}+k} \lambda_1^{\frac{1}{2}-k} \right) - \log \left( 1 - \sqrt{\frac{\lambda_1}{\lambda_2}} \right) + o(1) \right).$$

*Proof.* Case (i) is obtained as a direct application of the definition of a Poisson distribution.

Case (ii): consider  $n$  large enough so that  $(\lambda_1 - \lambda_2)n - k > 0$ . Applying Chebyshev's inequality, we obtain:

$$\begin{aligned} \mathbb{P}[Z_1 < Z_2 + k] &\leq \mathbb{P} \left( |Z_1 - \lambda_1 n| \geq \frac{(\lambda_1 - \lambda_2)n - k}{2} \right) + \mathbb{P} \left( |Z_2 - \lambda_2 n| \geq \frac{(\lambda_1 - \lambda_2)n - k}{2} \right) \\ &\leq \frac{4n\lambda_1}{((\lambda_1 - \lambda_2)n - k)^2} + \frac{4n\lambda_2}{((\lambda_1 - \lambda_2)n - k)^2}, \end{aligned}$$

which tends to 0 since  $\lambda_1 > \lambda_2$ .

Case (iii): since  $\mathbb{P}[Z_1 = Z_2] = o(1)$  (Lemma 4), we have by symmetry of the variables that  $\mathbb{P}[Z_1 \geq Z_2] = \frac{1}{2} + o(1)$ . On the other hand, we have  $\mathbb{P}[Z_2 \leq Z_1 < Z_2 + k] = \sum_{k'=0}^{k-1} \mathbb{P}[Z_1 = Z_2 + k']$ . Using case (iii) of Lemma 4, we have  $\mathbb{P}[Z_1 = Z_2 + k'] = \frac{1}{\sqrt{4\pi\lambda_1 n}} (1 + o(1))$ , hence  $\mathbb{P}[Z_2 \leq Z_1 < Z_2 + k] = \frac{k}{\sqrt{4\pi\lambda_1 n}} (1 + o(1)) = o(1)$ . Finally, we deduce that  $\mathbb{P}[Z_1 \geq Z_2 + k] = \mathbb{P}[Z_1 \geq Z_2] - \mathbb{P}[Z_2 \leq Z_1 < Z_2 + k] = \frac{1}{2} + o(1)$ , hence the result.

Case (iv): we use the same technique as in the proof of Lemma 3 (towards the end of the proof). The event  $\{Z_1 > Z_2 + k\}$  can be written as  $\{Z_1 \geq Z_2 + k\} - 2$ , i.e. the event for which adding a unit to the variable  $Z_2$  creates an event in  $\{Z_1 \geq Z_2 + k\}$ . Applying the *Offset Theorem* [Myerson, 2000], we obtain that  $\frac{\mathbb{P}(Z_1 > Z_2 + k)}{\mathbb{P}(Z_1 \geq Z_2 + k)} \sim \phi_2$ , where  $\phi_2$  denotes the offset of 2 in the event  $\{Z_1 \geq Z_2 + k\}$ . As  $k$  is finite

and  $\lambda_2 > \lambda_1$ , the offset of 2 in  $\{Z_1 \geq Z_2 + k\}$  is the same as in  $\{Z_1 = Z_2\}$ , equal to  $\phi_2 = \sqrt{\frac{\lambda_1}{\lambda_2}}$ . Simple algebra yields  $\frac{\mathbb{P}(Z_1 \geq Z_2 + k)}{\mathbb{P}(Z_1 = Z_2 + k)} \sim 1/(1 - \sqrt{\frac{\lambda_1}{\lambda_2}})$ . We obtain the desired formula by using the asymptotic development of  $\mathbb{P}(Z_1 = Z_2 + k)$  from Lemma 4 (iii).  $\square$

### B.2. Flower profiles

We first derive asymptotic utility thresholds for *flower profiles*  $\tau$ , i.e. such that  $\tau_i + \tau_{ij} = 0$  for some  $i, j \in \mathcal{K}$ . Lemmas 4 and 5 allow us to compute the asymptotic developments of  $\mathbb{P}[\text{piv}_{ij}^o | n\tau]$ ,  $\mathbb{P}[\text{piv}_{jk}^o | n\tau]$ ,  $\mathbb{P}[\text{tie}_{abc}^{o,1} | n\tau]$ , and  $\mathbb{P}[\text{tie}_{abc}^{o,2} | n\tau]$  for any flower profile  $\tau$  and ordinal type  $o = ij$ .

Then, using expression (1) from Proposition 1\*, we obtain the asymptotic utility threshold:

$$u_o^\infty(\tau) = \lim_{n \rightarrow \infty} \frac{3\mathbb{P}[\text{piv}_{ij}^o | n\tau] + 2\mathbb{P}[\text{tie}_{abc}^{o,1} | n\tau] + \mathbb{P}[\text{tie}_{abc}^{o,2} | n\tau]}{3\mathbb{P}[\text{piv}_{ij}^o | n\tau] + 3\mathbb{P}[\text{piv}_{jk}^o | n\tau] + 4\mathbb{P}[\text{tie}_{abc}^{o,1} | n\tau] + 2\mathbb{P}[\text{tie}_{abc}^{o,2} | n\tau]}.$$

In particular, given the length of the asymptotic developments, we obtain that  $(u_o^n(\tau))_{n \geq 1}$  always converge.

### B.3. Non-flower profiles

We now focus on non-flower profiles  $\tau$ , for which  $\tau_i + \tau_{ij} > 0$  for any  $i, j \in \mathcal{K}$ . The section is divided in three parts. Section B.3.1 introduces the notion of pseudo-offsets and establishes some of their basic properties. This notion is used in Section B.3.2 to show that all relevant pivot probabilities can be written as equivalent to tie events. Section B.3.3 wraps up and provides formulas for the asymptotic utility thresholds, derived from the equivalents of pivot probabilities.

**B.3.1. Pseudo-offsets.** For each ballot  $m \in \mathcal{M}$ , we introduce the notion of *pseudo-offset* of ballot  $m$  at an event  $E \subseteq \mathcal{Z}$ , which extends the notion of offset to the case where  $\tau_m = 0$ .

If  $m = i$ , we denote by  $\psi_i^E$  the *pseudo-offset* associated to  $i$  at  $E$ , defined as follows:

$$\psi_i^E = \begin{cases} \phi_i, & \text{if } \tau_i > 0, \\ \phi_{ij}\phi_{ik} & \text{otherwise.} \end{cases}$$

where each  $\phi_m$  is the offset of ballot  $m$  at the event  $E$ . Similarly, if  $m = ij$ , we denote by  $\psi_{ij}^E$  the *pseudo-offset* associated to  $ij$  at  $E$ , defined as follows:

$$\psi_{ij}^E = \begin{cases} \phi_{ij} & \text{if } \tau_{ij} > 0, \\ \phi_i\phi_j & \text{otherwise.} \end{cases}$$

In the sequel, we simply write  $\psi_m$  for  $\psi_m^E$  when there is no ambiguity on the event  $E$ . When there is ambiguity, we write  $\psi_m^{[abc]}$  for  $\psi_m^E$  when  $E = \text{tie}_{abc}$  and  $\psi_m^{[ij]}$  for  $\psi_m^E$  when  $E = \widetilde{\text{piv}}_{ij}$  or  $E = \text{piv}_{ij}$  (the pseudo-offsets being the same in these two events).

The following lemma establishes basic properties of pseudo-offsets at pivotal and tie events.

**Lemma 6.** *For any non-flower profile  $\tau$ , for any event  $E \in \{\text{piv}_{ij}, \widetilde{\text{piv}}_{ij}, \text{tie}_{abc}\}$ :*

- (i) *The pseudo-offset of each ballot  $m$  at  $E$  is well-defined and positive:  $\psi_m > 0$ ,*
- (ii) *These pseudo-offsets satisfy for any  $i, j, k \in \mathcal{K}$ ,  $\psi_i \psi_{jk} = 1$  and  $\psi_{ij} = \psi_i \psi_j$ .*

*Proof.* Let  $\tau$  be a non-flower profile. We consider first the case for which  $E = \text{tie}_{abc}$  and then  $E \in \{\text{piv}_{ij}, \widetilde{\text{piv}}_{ij}\}$ . We prove the validity of (i) for the ballot  $m = ij$ . The proofs for all other ballots  $m$  are similar (since  $\tau$  is a non-flower profile), and are thus omitted.

Setting  $E = \text{tie}_{abc}$ , consider the pseudo-offset of  $m = ij$ . If  $\tau_{ij} > 0$ , the offset  $\phi_{ij}$  is well-defined and  $\psi_{ij} = \phi_{ij}$ . If not, we must have  $\tau_i > 0$  and  $\tau_j > 0$ . Thus,  $\phi_i$  and  $\phi_j$  are well-defined so that  $\psi_{ij} = \phi_i \phi_j$ . The *Dual Magnitude Theorem* [Myerson, 2002] implies that  $\mu[E] = \mu_{abc} = \min_{x, y \in \mathbb{R}} F(x, y)$  with:

$$F(x, y) = \tau_i e^{x+y} + \tau_j e^{-x} + \tau_k e^{-y} + \tau_{ij} e^y + \tau_{ik} e^x + \tau_{jk} e^{-x} e^{-y} - 1.$$

Let  $x^*$  and  $y^* \in [-\infty, +\infty]$  be respectively the optimal values of  $x$  and  $y$ . Hence, the offset-ratios of ballots  $i$ ,  $j$  and  $ij$  are equal to (if well-defined):  $\phi_i = e^{x^*+y^*}$ ,  $\phi_j = e^{-x^*}$  and  $\phi_{ij} = e^{y^*}$ . It follows that  $\phi_i \phi_j = e^{x^*+y^*} e^{-x^*} = e^{y^*} = \phi_{ij}$ . This, in turn, implies that  $\psi_{ij} = e^{y^*}$ , independently of whether  $\tau_i > 0$  or  $\tau_{ij} > 0$ . Thus, it suffices to show that  $y^* > -\infty$  to conclude the proof of (i).

Since  $\tau$  is non-flower, we have either  $\tau_k > 0$  or  $(\tau_{ik} > 0 \text{ and } \tau_{jk} > 0)$ . If  $\tau_k > 0$ , then  $F$  cannot be minimized for  $y = -\infty$ , hence  $y^* > -\infty$ . If  $\tau_{ik} > 0$  and  $\tau_{jk} > 0$ ,  $\tau_{ik} > 0$  implies that  $F$  cannot be minimized for  $x = +\infty$ , hence  $x^* < +\infty$ . Moreover,  $\tau_{jk} > 0$  implies that  $\tau_{jk} e^{-x^*} > 0$ . As a consequence,  $F$  cannot be minimized for  $y = -\infty$ . Therefore,  $y^* > -\infty$ , which proves that  $\psi_{ij} > 0$ , concluding the proof of (i) for the case  $E = \text{tie}_{abc}$ .

Consider now the case for which  $E \in \{\text{piv}_{ij}, \widetilde{\text{piv}}_{ij}\}$ . We have

$$\mu[\text{piv}_{ij}] = \mu[\widetilde{\text{piv}}_{ij}] = \mu_{ij} = \min_{x \in \mathbb{R}, y \in \mathbb{R}^+} F(x, y),$$

with the same function  $F$  as above. We note  $x^* \in [-\infty, +\infty]$  and  $y^* \in [0, +\infty]$  the optimal values of  $x$  and  $y$ . As before, we obtain  $\psi_{ij} = e^{y^*}$ , independently of whether  $\tau_i > 0$  or  $\tau_{ij} > 0$ . Since  $y^* \geq 0$ , we obtain  $\psi_{ij} \geq 1 > 0$ .

The formulas in (ii) simply derive from the following observations. With the

previous formulas, we always have in a non-flower profile  $\psi_i = e^{x^*+y^*}$  and  $\psi_{jk} = e^{-x^*-y^*}$  (where  $x^*$  and  $y^*$  are the optima from the minimization program associated to the magnitude of  $E$ ), so that  $\psi_i \psi_{jk} = 1$ . We also have  $\psi_{ij} = e^{y^*}$ ,  $\psi_i = e^{x^*+y^*}$  and  $\psi_j = e^{-y^*}$ , so that  $\psi_{ij} = \psi_i \psi_j$ , as required.  $\square$

The next lemma provides the key reason for the introduction of pseudo-offsets. It establishes an extension of the *Offset Theorem* [Myerson, 2000] to cases where some offsets  $\phi_m$  are not defined, applicable to any non-flower profile  $\tau$ .

**Lemma 7.** (*Pseudo-Offset Lemma*)

For any non-flower profile  $\tau$ , for any event  $E \in \{\text{piv}_{ij}, \widetilde{\text{piv}_{ij}}, \text{tie}_{abc}\}$ , for any ballot  $m \in \mathcal{M}$ , for any integer  $q$ ,

$$\lim_{n \rightarrow \infty} \frac{\mathbb{P}[E - qm \mid n\tau]}{\mathbb{P}[E \mid n\tau]} = (\psi_m^E)^q.$$

*Proof.* Take any event  $E \in \{\text{piv}_{ab}, \widetilde{\text{piv}_{ab}}, \text{tie}_{abc}\}$ , let  $q$  be an integer and consider first the ballot  $m = ij$ . If  $\tau_{ij} > 0$ , the offset of  $ij$  in  $E$  is well-defined, so that  $\psi_{ij}^E = \phi_{ij}$ , and we obtain the result by direct application of the *Offset Theorem* [Myerson, 2000].

Consider now the case where  $\tau_{ij} = 0$ . As  $\tau$  is non-flower, we must have  $\tau_i > 0$  and  $\tau_j > 0$ . Moreover, the set  $E - q(ij)$  coincides with the set  $E - q(i) - q(j)$ . Hence, the *Offset Theorem* implies that:

$$\lim_{n \rightarrow \infty} \frac{\mathbb{P}[E - q(ij) \mid n\tau]}{\mathbb{P}[E \mid n\tau]} = \lim_{n \rightarrow \infty} \frac{\mathbb{P}[E - q(i) - q(j) \mid n\tau]}{\mathbb{P}[E \mid n\tau]} = (\phi_i)^q (\phi_j)^q = (\psi_{ij}^E)^q,$$

where the last equality comes from  $\psi_{ij}^E = \phi_i \phi_j$ , as  $\tau_{ij} = 0$ .

Consider now the ballot  $m = i$ . If  $\tau_i > 0$ , the *Offset Theorem* directly implies the result. If  $\tau_i = 0$ , we must have both  $\tau_{ij} > 0$  and  $\tau_{ik} > 0$  since  $\tau$  is non-flower. Then, observe that  $E - q(i)$  coincides with the set  $E - q(ij) - q(ik)$ , so that

$$\lim_{n \rightarrow \infty} \frac{\mathbb{P}[E - q(i) \mid n\tau]}{\mathbb{P}[E \mid n\tau]} = \lim_{n \rightarrow \infty} \frac{\mathbb{P}[E - q(ij) - q(ik) \mid n\tau]}{\mathbb{P}[E \mid n\tau]} = (\phi_{ij})^q (\phi_{ik})^q = (\psi_i^E)^q.$$

$\square$

### B.3.2. *Equivalents of Pivot Probabilities.*

**Lemma 8.** For any non-flower profile  $\tau$  and any ordinal type  $o = ij$ , we have for  $n \rightarrow \infty$ :

$$\mathbb{P}[\text{tie}_{abc}^{o,1} \mid n\tau] \sim \psi_i^{[abc]} \mathbb{P}[\text{tie}_{abc} \mid n\tau], \quad \mathbb{P}[\text{tie}_{abc}^{o,2} \mid n\tau] \sim \psi_{ij}^{[abc]} \mathbb{P}[\text{tie}_{abc} \mid n\tau],$$

and

$$\mathbb{P}[\text{piv}_{ij}^o \mid n\tau] \sim (1 + \psi_{ik}^{[ij]}) \mathbb{P}[\widetilde{\text{piv}_{ij}} \mid n\tau], \quad \mathbb{P}[\text{piv}_{jk}^o \mid n\tau] \sim (\psi_i^{[jk]})^2 (1 + \psi_j^{[jk]}) \mathbb{P}[\widetilde{\text{piv}_{jk}} \mid n\tau].$$

*Proof.* By application of the *Pseudo-Offset Lemma* (Lemma 7), we have when  $n \rightarrow \infty$ :

$$\begin{aligned}\mathbb{P}[\text{tie}_{abc}^{o,1} | n\tau] &= \mathbb{P}[\text{tie}_{abc} - i | n\tau] \sim \psi_i \mathbb{P}[\text{tie}_{abc} | n\tau], \\ \mathbb{P}[\text{tie}_{abc}^{o,2} | n\tau] &= \mathbb{P}[\text{tie}_{abc} - ij | n\tau] \sim \psi_{ij} \mathbb{P}[\text{tie}_{abc} | n\tau],\end{aligned}$$

where the pseudo-offsets are defined at the event  $\text{tie}_{abc}$ .

Recall that  $\widetilde{\text{piv}}_{ij} = \text{piv}_{ij} \cup \text{tie}_{abc}$ . Then, using the notation  $\psi_m$  for the pseudo-offset of  $m$  at  $\text{piv}_{ij}$ , we obtain:

$$\mathbb{P}[\widetilde{\text{piv}}_{ij} | n\tau] = \mathbb{P}[\text{piv}_{ij} - ij | n\tau] \sim \psi_{ij} \mathbb{P}[\text{piv}_{ij} | n\tau].$$

It follows that:

$$\begin{aligned}\mathbb{P}[\text{piv}_{ij}^o | n\tau] &= \mathbb{P}[\text{piv}_{ij} - i | n\tau] + \mathbb{P}[\text{piv}_{ij} - ij | n\tau] \sim \mathbb{P}[\text{piv}_{ij} | n\tau](\psi_i + \psi_{ij}) \\ &\sim \mathbb{P}[\widetilde{\text{piv}}_{ij} | n\tau] \frac{\psi_i + \psi_{ij}}{\psi_{ij}} \\ &\sim \mathbb{P}[\widetilde{\text{piv}}_{ij} | n\tau](1 + \psi_{ik}),\end{aligned}$$

where we use the identities  $\psi_i/\psi_{ij} = \psi_i\psi_k = \psi_{ik}$  (Lemma 6). Similarly, using now the notation  $\psi_m$  for the pseudo-offset of  $m$  at  $\text{piv}_{jk}$ , we have

$$\mathbb{P}[\text{piv}_{jk}^o | n\tau] \sim \mathbb{P}[\text{piv}_{jk} | n\tau](\psi_i + \psi_{ij}) \sim \mathbb{P}[\widetilde{\text{piv}}_{jk} | n\tau] \frac{\psi_i + \psi_{ij}}{\psi_{jk}} = \mathbb{P}[\widetilde{\text{piv}}_{jk} | n\tau](\psi_i)^2(1 + \psi_j),$$

where we use the identities  $1/\psi_{jk} = \psi_i$  and  $\psi_{ij} = \psi_i\psi_j$  (Lemma 6).  $\square$

The following result goes beyond Lemma 1 by providing precise estimates of relevant pivot probabilities, rather than magnitudes. In each case, pivot probabilities are proportional to some tie event, whose asymptotic development can then be easily computed.

**Lemma 9.** *For any non-flower profile  $\tau$ , noting  $\psi_k$  for  $\psi_k^{[abc]}$ , we have:*

- (i) *If  $\delta_{ij}(\tau) > 0$ , then  $\psi_k > 1$ . We have  $\mathbb{P}[\widetilde{\text{piv}}_{ij} | n\tau] \sim \mathbb{P}[\text{tie}_{ij} | n\tau]$  and  $\frac{\mathbb{P}[\text{tie}_{abc}|n\tau]}{\mathbb{P}[\text{piv}_{ij}|n\tau]} \rightarrow 0$ .*
- (ii) *If  $\delta_{ij}(\tau) = 0$ , then  $\psi_k = 1$ . We have  $\mathbb{P}[\widetilde{\text{piv}}_{ij} | n\tau] \sim \frac{1}{2}\mathbb{P}[\text{tie}_{ij} | n\tau]$  and  $\frac{\mathbb{P}[\text{tie}_{abc}|n\tau]}{\mathbb{P}[\text{piv}_{ij}|n\tau]} \rightarrow 0$ .*
- (iii) *If  $\delta_{ij}(\tau) < 0$ , then  $0 < \psi_k < 1$ . We have  $\mathbb{P}[\widetilde{\text{piv}}_{ij} | n\tau] \sim \frac{1}{1-\psi_k}\mathbb{P}[\text{tie}_{abc} | n\tau]$ .*

*Proof. Case (i):  $\delta_{ij}(\tau) > 0$ .*

The *Dual Magnitude Theorem* [Myerson, 2002] implies that  $\mu_{abc} = \min_{x,y \in \mathbb{R}} F(x,y)$  with:

$$F(x,y) = \tau_i e^{x+y} + \tau_j e^{-x} + \tau_k e^{-y} + \tau_{ij} e^y + \tau_{ik} e^x + \tau_{jk} e^{-x} e^{-y} - 1.$$

Let  $x^*$  and  $y^* \in [-\infty, +\infty]$  be respectively the optimal values of  $x$  and  $y$  in  $\mu_{abc}$ .

The offset-ratios of ballots  $k$ ,  $ik$  and  $ij$  are equal to:

$$\phi_k = e^{-y^*}, \quad \phi_{ik} = e^{x^*} \quad \text{and} \quad \phi_{ij} = e^{-x^*} e^{-y^*}.$$

It follows that  $\psi_k = e^{-y^*}$ , independently of whether  $\tau_k > 0$  or not.

As  $\delta_{ij}(\tau) > 0$ , Lemma 1 implies that  $\mu_{ij} > \mu_{abc}$ . Since  $\mu_{ij} = \min_{x \in \mathbb{R}, y \geq 0} F(x, y)$ , it follows that  $y^* < 0$ . Therefore,  $\psi_k = e^{-y^*} > 1$ , as wanted.

The probability of the event  $\text{tie}_{ij}$  may be written as:

$$\mathbb{P}[\text{tie}_{ij} \mid n\tau] = \mathbb{P}[s_i = s_j \geq s_k \mid n\tau] + \mathbb{P}[s_i = s_j < s_k \mid n\tau] = \mathbb{P}[\widetilde{\text{piv}}_{ij} \mid n\tau] + \mathbb{P}[s_i = s_j < s_k \mid n\tau].$$

Applying the *Dual Magnitude Theorem*, we have that  $\mu[\text{tie}_{ij}] = \min_{x \in \mathbb{R}} F(x, 0)$  and  $\mu[\{s_i = s_j < s_k\}] = \min_{x \in \mathbb{R}, y \leq 0} F(x, y)$ . As  $y^* < 0$ , this last magnitude is equal to  $\mu_{abc}$  and is strictly lower than  $\mu[\text{tie}_{ij}]$ . Therefore,  $\frac{\mathbb{P}[s_i = s_j < s_k \mid n\tau]}{\mathbb{P}[\text{tie}_{ij} \mid n\tau]} \rightarrow 0$ , and we thus obtain  $\mathbb{P}[\text{tie}_{ij} \mid n\tau] \sim \mathbb{P}[\widetilde{\text{piv}}_{ij} \mid n\tau]$  as wanted.

Finally, as  $\mu_{ij} > \mu_{abc}$ , we have that  $\frac{\mathbb{P}[\text{tie}_{abc} \mid n\tau]}{\mathbb{P}[\text{piv}_{ij} \mid n\tau]} \rightarrow 0$ .

**Case (ii):**  $\delta_{ij}(\tau) = 0$ .

Following the proof of Lemma 1,  $\delta_{ij}(\tau) = 0$  corresponds to the case where  $y^* = 0$ , so that  $\psi_k = 1$ . To show that the event  $\text{tie}_{abc}$  is negligible w.r.t.  $\widetilde{\text{piv}}_{ij}$ , we apply the *Pseudo-offset Lemma* (Lemma 7). As  $\mathbb{P}[\widetilde{\text{piv}}_{ij} \mid n\tau] = \mathbb{P}[s_i = s_j \geq s_k \mid n\tau]$ , for any fixed integer  $Q$ , we have:

$$\begin{aligned} \mathbb{P}[\widetilde{\text{piv}}_{ij} \mid n\tau] &\geq \sum_{q=0}^Q \mathbb{P}[s_i = s_j = s_k + q \mid n\tau] \\ &\geq \left( \sum_{q=0}^Q (\psi_k)^q \right) \mathbb{P}[\text{tie}_{abc} \mid n\tau] (1 + o(1)) \geq Q \mathbb{P}[\text{tie}_{abc} \mid n\tau] (1 + o(1)). \end{aligned}$$

We thus obtain  $\frac{\mathbb{P}[\text{tie}_{abc} \mid n\tau]}{\mathbb{P}[\widetilde{\text{piv}}_{ij} \mid n\tau]} \rightarrow 0$ .

As  $\mathbb{P}[\widetilde{\text{piv}}_{ij} \mid n\tau] = \mathbb{P}[s_i = s_j \geq s_k \mid n\tau]$ , we may write:

$$\begin{aligned} \mathbb{P}[\widetilde{\text{piv}}_{ij} \mid n\tau] &= \mathbb{P}[\text{tie}_{ij} \mid n\tau] \times \mathbb{P}[s_i \geq s_k \mid \text{tie}_{ij}, n\tau] \\ &= \mathbb{P}[\text{tie}_{ij} \mid n\tau] \times \mathbb{P}[Z_i - Z_{jk} \geq Z_k - Z_{ij} \mid Z_i - Z_{jk} = Z_j - Z_{ik}, n\tau] \\ &= \mathbb{P}[\text{tie}_{ij} \mid n\tau] \times \mathbb{P}[X^n \geq Y^n \mid n\tau], \end{aligned}$$

where the (independent) variables  $X^n$  and  $Y^n$  are defined by:

- $X^n = (Z_i - Z_{jk} \mid Z_i - Z_{jk} = Z_j - Z_{ik})$ ,
- $Y^n = Z_k - Z_{ij}$ .

Since  $(Z_m)_{m \in \mathcal{M}}$  are independent Poisson variables, we may apply Proposition 1 from Durand and de Panafieu [2021]. If we note  $E_X = \tau_i \sqrt{\frac{\tau_j + \tau_{jk}}{\tau_i + \tau_{ik}}} - \tau_{jk} \sqrt{\frac{\tau_i + \tau_{ik}}{\tau_j + \tau_{jk}}}$ , we obtain that the variable  $\frac{X^n - nE_X}{\sqrt{n}}$  is asymptotically gaussian and centered, unless  $\tau_i = \tau_{jk}$  or  $\tau_j = \tau_{jk}$  or  $\tau_j = \tau_{ik}$  or  $\tau_i = \tau_{ik}$ , in which case it follows a Dirac measure

centered in 0.

Let us note  $E_Y = \tau_k - \tau_{ij}$ . The variable  $Y^n$  can be seen as the sum of  $n$  independent random variables following the Skellam distribution of parameters  $\tau_k$  and  $\tau_{ij}$ . If  $\tau_k + \tau_{ij} > 0$ , by application of the central limit theorem, we obtain that the variable  $\frac{Y^n - nE_Y}{\sqrt{n}}$  is asymptotically gaussian and centered. If  $\tau_k + \tau_{ij} = 0$ ,  $\frac{Y^n - nE_Y}{\sqrt{n}}$  simply follows a Dirac measure centered in 0.

Note that we have by assumption  $0 = \delta_{ij}(\tau) = E_X - E_Y$ , hence  $E_X = E_Y$ . We obtain:

$$\mathbb{P}[X^n \geq Y^n \mid n\tau] = \mathbb{P}\left[\frac{X^n - nE_X}{\sqrt{n}} \geq \frac{Y^n - nE_Y}{\sqrt{n}} \mid n\tau\right].$$

As  $\tau$  is a non-flower profile, the variables  $\frac{X^n - nE_X}{\sqrt{n}}$  and  $\frac{Y^n - nE_Y}{\sqrt{n}}$  cannot simultaneously follow the Dirac measure centered in 0 (the conditions are incompatible). Therefore, one variable is asymptotically gaussian and centered, while the other variable either is asymptotically gaussian and centered or follows the Dirac measure centered in 0. As a result, the probability that one variable is higher or equal to the other tends to one half. We thus obtain:

$$\mathbb{P}[\widetilde{\text{piv}}_{ij} \mid n\tau] = \mathbb{P}[\text{tie}_{ij} \mid n\tau] \times \mathbb{P}[X^n \geq Y^n \mid n\tau] \sim \frac{1}{2} \mathbb{P}[\text{tie}_{ij} \mid n\tau].$$

**Case (iii):**  $\delta_{ij}(\tau) < 0$ .

Following the same logic as in case (i), we obtain that  $y^* > 0$  and  $\psi_k < 1$ . Moreover, we know from Lemma 6 that  $\psi_k > 0$ . As in the proof of Lemma 3 (towards the end), we have  $y^* > 0$ , so that the pseudo-offset of ballot  $k$  is the same in events  $\text{tie}_{abc}$  and  $\widetilde{\text{piv}}_{ij}$ . Following that proof, we may apply the *Pseudo-offset Lemma* (Lemma 7) by observing that  $\text{piv}_{ij} = \widetilde{\text{piv}}_{ij} - k$ , from which we finally obtain:

$$\frac{\mathbb{P}[\text{tie}_{abc} \mid n\tau]}{\mathbb{P}[\widetilde{\text{piv}}_{ij} \mid n\tau]} \sim 1 - \psi_k.$$

□

**B.3.3. Asymptotic utility thresholds.** We study the decision problem for a voter with ordinal type  $o = ab$  so that the relevant pivot events involve pairs  $ab$  and  $bc$ . We consider three cases:

- If  $\delta_{ab}(\tau) \geq 0$  and  $\delta_{bc}(\tau) \geq 0$ , then Lemma 8 implies that:

$$\mathbb{P}[\text{piv}_{ab}^o \mid n\tau] \sim (1 + \psi_{ac}^{[ab]}) \mathbb{P}[\widetilde{\text{piv}}_{ab} \mid n\tau].$$

Moreover, since  $\delta_{ab}(\tau) \geq 0$ , Lemma 9 implies that:

$$\mathbb{P}[\widetilde{\text{piv}}_{ab} \mid n\tau] \sim \frac{1 + \mathbb{1}_{\{\delta_{ab}(\tau) > 0\}}}{2} \mathbb{P}[\text{tie}_{ab} \mid n\tau].$$

Thus,  $\mathbb{P}[\text{piv}_{ab}^o \mid n\tau]$  is equivalent (up to a constant) to  $\mathbb{P}[\text{tie}_{ab} \mid n\tau]$ . Similarly,

since  $\delta_{bc}(\tau) \geq 0$ , we obtain:

$$\mathbb{P}[\text{piv}_{bc}^o \mid n\tau] \sim (\psi_a^{[bc]})^2(1 + \psi_b^{[bc]}) \frac{1 + \mathbb{1}_{\{\delta_{bc}(\tau) > 0\}}}{2} \mathbb{P}[\text{tie}_{bc} \mid n\tau].$$

Since  $\lim_{n \rightarrow \infty} \frac{\mathbb{P}[\text{tie}_{abc} \mid n\tau]}{\mathbb{P}[\text{piv}_{ab} \mid n\tau]} = 0$  by Lemma 9, Lemma 8 implies that  $\mathbb{P}[\text{tie}_{abc}^{o,1} \mid n\tau]$  and  $\mathbb{P}[\text{tie}_{abc}^{o,2} \mid n\tau]$  are also negligible w.r.t.  $\mathbb{P}[\text{piv}_{ab} \mid n\tau]$  when  $n \rightarrow \infty$ . Hence, applying expression (1) from Proposition 1\*, we obtain:

$$u_o^n(\tau) \sim \frac{1}{1 + \frac{(\psi_a^{[bc]})^2(1 + \psi_b^{[bc]})(1 + \mathbb{1}_{\{\delta_{bc}(\tau) > 0\}})}{(1 + \psi_{ac}^{[ab]})(1 + \mathbb{1}_{\{\delta_{ab}(\tau) > 0\}})} \times \frac{\mathbb{P}[\text{tie}_{bc} \mid n\tau]}{\mathbb{P}[\text{tie}_{ab} \mid n\tau]}}. \quad (3)$$

Finally, we can compute the limit  $u_o^\infty(\tau)$  thanks to the asymptotic developments of  $\mathbb{P}[\text{tie}_{ab} \mid n\tau]$  and  $\mathbb{P}[\text{tie}_{bc} \mid n\tau]$ , obtained from Lemma 4.<sup>67</sup>

- If  $\delta_{ab}(\tau) \geq 0 > \delta_{bc}(\tau)$  or  $\delta_{bc}(\tau) \geq 0 > \delta_{ab}(\tau)$ . Assume first that  $\delta_{ab}(\tau) \geq 0$  and  $\delta_{bc}(\tau) < 0$ . Then, combining Lemma 8 and Lemma 9, we obtain that  $\mathbb{P}[\text{piv}_{bc}^o \mid n\tau]$ ,  $\mathbb{P}[\text{tie}_{abc}^{o,1} \mid n\tau]$  and  $\mathbb{P}[\text{tie}_{abc}^{o,2} \mid n\tau]$  are all equivalent (up to a constant) to  $\mathbb{P}[\text{tie}_{abc} \mid n\tau]$ , and thus negligible with respect to  $\mathbb{P}[\text{piv}_{ab}^o \mid n\tau] \sim (1 + \psi_{ac}^{[ab]})\mathbb{P}[\text{piv}_{ab} \mid n\tau]$ . We thus have  $u_o^\infty(\tau) = 1$ , by application of (1).

If on the other hand  $\delta_{bc}(\tau) \geq 0 > \delta_{ab}(\tau)$ , then all relevant pivots become negligible with respect to  $\mathbb{P}[\text{piv}_{bc}^o \mid n\tau]$ , and we obtain  $u_o^\infty(\tau) = 0$ .

- If  $\delta_{ab}(\tau), \delta_{bc}(\tau) < 0$ . Then, we have  $\psi_a, \psi_c < 1$  (Lemma 9). As the pseudo-offsets are the same in the events  $\text{tie}_{abc}$ ,  $\text{piv}_{ab}$  and  $\text{piv}_{bc}$ , we may write, by application of Lemma 8 and Lemma 9:

$$\mathbb{P}[\text{piv}_{ab}^o \mid n\tau] \sim \frac{1 + \psi_{ac}}{1 - \psi_c} \mathbb{P}[\text{tie}_{abc} \mid n\tau], \quad \mathbb{P}[\text{piv}_{bc}^o \mid n\tau] \sim \frac{(\psi_a)^2(1 + \psi_b)}{1 - \psi_a} \mathbb{P}[\text{tie}_{abc} \mid n\tau].$$

Combining with the equivalents of tie events in Lemma 8, we obtain by application of (1).<sup>68</sup>

$$u_o^\infty(\tau) = \frac{3 \frac{1 + \psi_{ac}}{1 - \psi_c} + 2\psi_a + \psi_{ab}}{3 \frac{1 + \psi_{ac}}{1 - \psi_c} + 3 \frac{\psi_a^2(1 + \psi_b)}{1 - \psi_a} + 4\psi_a + 2\psi_{ab}}. \quad (4)$$

Finally, we have shown that for each profile  $\tau \in \Delta(\mathcal{M})$  and for each ordinal type  $o \in \mathcal{O}$ , the sequence  $(u_o^n(\tau))_{n \geq 1}$  converges, and we have provided a formula for computing  $u_o^\infty(\tau)$  in each case. This concludes the proof of Theorem 1.

<sup>67</sup>The pseudo-offsets  $\psi_a^{[bc]}$ ,  $\psi_b^{[bc]}$  and  $\psi_{ac}^{[ab]}$  coincide with the corresponding pseudo-offsets in the tie events  $\text{tie}_{bc}$  and  $\text{tie}_{ab}$  (respectively). These quantities can be computed analytically, and the Python package “Poisson-Approval” thus uses their exact formulas.

<sup>68</sup>In the Python package “Poisson-Approval”, the pseudo-offsets are analytically computed whenever possible. Otherwise, the pseudo-offsets are obtained by a numeric optimization of the program defined by the *Dual Magnitude Theorem* [Myerson, 2002].



#### B.4. A (difficult) example

In this section, we provide an example of computation of the asymptotic utility threshold.

Consider the following profile:  $\tau_a = 3/20$ ,  $\tau_b = 9/20$ ,  $\tau_{ac} = 1/20$  and  $\tau_{bc} = 7/20$ . We have  $\mu_{ab} = \mu_{bc} = -1/5$  and  $\mu_{ac} = \mu_{abc} = \frac{\sqrt{21}-7}{10} \approx -0.242 < -1/5$ . We thus have  $\delta_{ab}(\tau) > 0$  and  $\delta_{bc}(\tau) > 0$  (Lemma 1).

We consider the decision problem of a voter with ordinal type  $o = ab$ . Numerically, we obtain the relevant pseudo-offsets:  $\psi_{ac}^{[ab]} = 2$  in the event  $\widetilde{\text{piv}_{ab}}$ , while  $\psi_a^{[bc]} = 1$  and  $\psi_b^{[bc]} = 1/3$  in the event  $\widetilde{\text{piv}_{bc}}$ . By application of (3), we obtain:

$$u_o^n(\tau) \sim \frac{1}{1 + \frac{4}{9} \frac{\mathbb{P}[\text{tie}_{bc} \mid n\tau]}{\mathbb{P}[\text{tie}_{ab} \mid n\tau]}}.$$

Then, we may write  $\mathbb{P}[\text{tie}_{ab} \mid n\tau] = \mathbb{P}[Z_a + Z_{ab} = Z_b + Z_{bc}]$ , where  $Z_a + Z_{ac} \sim \mathcal{P}(\frac{n}{5})$  and  $Z_b + Z_{bc} \sim \mathcal{P}(\frac{4n}{5})$  are independent. Applying Lemma 4 (iii), we obtain:

$$\begin{aligned} \mathbb{P}[\text{tie}_{ab} \mid n\tau] &= \exp \left( - \left( \sqrt{\frac{n}{5}} - \sqrt{\frac{4n}{5}} \right)^2 - \frac{1}{2} \log(n) - \frac{1}{2} \log \left( 4\pi \sqrt{\frac{n \times 4n}{5 \times 5}} \right) + o(1) \right) \\ &= e^{-\frac{n}{5} - \frac{1}{2} \log(n) - \frac{1}{2} \log(\frac{8\pi}{5}) + o(1)}. \end{aligned}$$

We obtain similarly that  $\mathbb{P}[\text{tie}_{bc} \mid n\tau] = e^{-\frac{n}{5} - \frac{1}{2} \log(n) - \frac{1}{2} \log(\frac{3\pi}{5}) + o(1)}$ . To conclude, we obtain:

$$u_o^n(\tau) \sim \frac{1}{1 + \frac{4}{9} \times \frac{e^{-\frac{n}{5} - \frac{1}{2} \log(n) - \frac{1}{2} \log(\frac{3\pi}{5}) + o(1)}}{e^{-\frac{n}{5} - \frac{1}{2} \log(n) - \frac{1}{2} \log(\frac{8\pi}{5}) + o(1)}}} \sim \frac{1}{1 + \frac{4}{9} \times e^{\frac{1}{2} \log(\frac{8}{3}) + o(1)}}.$$

Simple algebra yields  $u_o^\infty(\tau) = \frac{9\sqrt{3}}{9\sqrt{3} + 8\sqrt{2}}$ .

Note that, in this example, using magnitudes and the *Offset theorem* (or equivalently, the *Pseudo-Offset Lemma*) alone would not be sufficient to obtain  $u_o^\infty(\tau)$ . With these tools, one obtains that both events  $\text{piv}_{ab}^o$  and  $\text{piv}_{bc}^o$  are infinitely more likely than  $\text{tie}_{abc}$ , but it remains *a priori* difficult to compare the probabilities of these two events. Yet, the methods are extremely useful to relate  $u_o^\infty(\tau)$  to the probabilities of tie events, whose asymptotic developments can then be computed.

#### APPENDIX C. NUMERICAL APPENDIX (ONLINE)

This (online) appendix is devoted to robustness checks for the numerical results obtained under the adaptive procedure. It also contains some examples and figures that complement the analysis.

C.1. *Robustness to the parameters of the adaptive procedure*

In this section, we consider alternative choices for the parameters of the adaptive procedure. In Table 4, we report the convergence rate (computed for a maximum of  $P = 1,000$  periods) and the frequency with which the Condorcet winner is elected when it exists for several values of  $\alpha^p$ , the parameter governing voters' belief updating, while keeping  $\beta^p = \frac{1}{\log(p+1)}$ . The first row displays  $\alpha^p = 1$ , the case for which voters only take the latest poll into account. The third row corresponds to  $\alpha^p = \frac{1}{\log(p+1)}$  as in the article. The last row displays  $\alpha^p = \frac{1}{p}$  as in classical fictitious play.

$\alpha^p$	Convergence rate			Condorcet Consistency		
	AV	PL	APL	AV	PL	APL
1	93.9%	100.0%	0.0%	99.94%	66.2%	54.7%
0.5	95.0%	100.0%	0.0%	99.98%	67.2%	52.8%
$\frac{1}{\log(p+1)}$	95.2%	100.0%	0.0%	99.96%	66.1%	49.5%
$\frac{1}{\sqrt{p}}$	94.7%	100.0%	0.0%	100.0%	66.0%	46.2%
$\frac{1}{p}$	0.0%	0.0%	0.0%	99.95%	66.5%	44.7%

TABLE 4. Robustness to the belief updating parameter  $\alpha^p$  ( $P = 1,000$ ).

We observe that the convergence rate of the procedure for each voting rule is robust to different choices of  $\alpha^p$ , but in the case  $\alpha^p = \frac{1}{p}$ , for which it becomes null for all rules. This is not surprising: the adjustment of beliefs is then too slow for the procedure to meet our stringent convergence test before a number of  $P = 1,000$  periods. Yet, we observe that for all choices of the parameter  $\alpha^p$ , including the one with no convergence, the frequency with which the Condorcet winner is elected under each voting rule appears consistent. While this frequency slightly decreases for APL from the first to the lowest rows of the table, the election of the Condorcet winner always remains more likely under AV than under any other rule.

In Table 5, we report the convergence rate (computed for a maximum of  $P = 1,000$  periods) and the frequency with which the Condorcet winner is elected when it exists for several values of  $\beta^p$ , the share of updating voters at period  $p$ , while keeping  $\alpha^p = \frac{1}{\log(p+1)}$ . The first row ( $\beta^p = 1$ ) corresponds to the case for which all voters play a best-reply at each period.

$\beta^p$	Convergence rate			Condorcet Consistency		
	AV	PL	APL	AV	PL	APL
1	93.9%	100.0%	0.0%	99.8%	66.7%	10.3%
0.5	94.6%	100.0%	0.0%	99.96%	67.0%	26.8%
$\frac{1}{\log(p+1)}$	95.2%	100.0%	0.0%	99.96%	66.1%	49.5%
$\frac{1}{\sqrt{p}}$	95.0%	100.0%	0.0%	99.98%	67.0%	57.1%
$\frac{1}{p}$	5.6%	0.0%	0.0%	99.97%	65.7%	60.3%

TABLE 5. Robustness to the per-period share of updating voters  $\beta^p$  ( $P = 1,000$ ).

The convergence rates under AV and PL are both high and consistent, but in the case  $\beta^p = \frac{1}{p}$ , for which they significantly drop. The Condorcet winner becomes less likely to be selected under APL as the per-period share of updating voter increases, but in any case, it is under AV that she is most likely to be elected.

### C.2. Robustness to the distribution of preference intensities

In this section, we consider the robustness of our results to the distributions of preference intensities. This is important: we have seen in Proposition 3 that if the distributions of utilities satisfy CSCW, i.e. if they are not biased against the Condorcet winner, then no other candidate than the Condorcet winner can be elected at a cardinal equilibrium under AV. In the article, simulations are conducted with  $\rho_o \sim \mathcal{U}((0,1))$  for all  $o$ , so that CSCW is satisfied (the distribution is symmetric). We thus consider two alternative utility distributions:  $\rho_o \sim \mathcal{U}([0.09,0.11])$  for all  $o$ , so that utilities are concentrated around 0.1 (CSCW is then violated); and the polar case  $\rho_o \sim \mathcal{U}([0.89,0.91])$  for all  $o$ , so that utilities are concentrated around 0.9 (CSCW is then satisfied). We report on Table 6 the frequency with which the Condorcet winner is elected when it exists, and the average utilitarian welfare loss, for each set of distributions.

$\rho_o$	Condorcet Consistency			Average Welfare Loss		
	AV	PL	APL	AV	PL	APL
$\mathcal{U}((0,1))$	99.96%	66.1%	49.5%	0.007	0.060	0.099
$\mathcal{U}([0.09,0.11])$	98.5%	66.5%	49.3%	0.011	0.086	0.115
$\mathcal{U}([0.89,0.91])$	98.5%	66.0%	49.0%	0.033	0.062	0.113

TABLE 6. Robustness to the distribution of preference intensities.

We observe that our results are mostly robust, as AV always dominates the two other rules on both criteria, although it becomes slightly less efficient for each criterion in absolute terms. In particular, our results remain valid in the second row of the table, for which CSCW is violated.

### C.3. Robustness to the initial poll

We now consider the robustness of our results to the distribution from which the initial poll  $\tau^0$  is drawn in the adaptive procedure. While we assume that  $\tau^0$  is drawn uniformly on  $\Delta(\mathcal{M})$  in the article, we consider here two alternative specifications. In the first one, we consider the region of ballot profiles  $\tau$  that are obtained when voters use undominated strategies, and we draw  $\tau^0$  uniformly on this region. In the second one, we assume that  $\tau^0$  coincides with the ballot profile obtained when all voters are (model 1-) expressive. We report on Table 7 the frequency with which the Condorcet winner is elected when it exists, and the average utilitarian welfare loss, for each distribution of the initial poll  $\tau^0$ .

Distribution of $\tau^0$	Condorcet Consistency			Average Welfare Loss		
	AV	PL	APL	AV	PL	APL
uniform	99.96%	66.1%	49.5%	0.007	0.060	0.099
uniform undominated	99.997%	81.7%	48.9%	0.007	0.031	0.099
(model 1-) expressive	99.999%	96.8%	48.9%	0.007	0.009	0.099

TABLE 7. Robustness to the initial poll.

We observe that the results for AV and APL are robust to the draw of the initial poll. The main difference appears for PL, which improves going from the first to the second row, and from the second to the third one, both in terms of Condorcet consistency and average welfare. Yet, even in the hypothetical case for which the initial poll is expressive, AV still slightly dominates PL.

### C.4. APL on divided preferences

**C.4.1. Illustration.** We report on Figure 9 the winning frequencies of each candidate under APL, as a function of the ordinal preference profile  $r$  taken on the domain of divided preferences, as specified in Section 6.2.3.

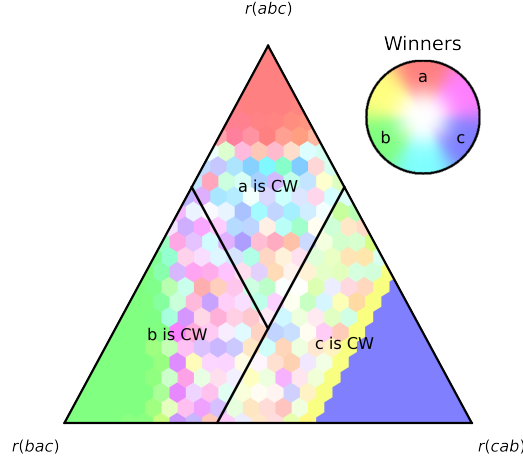


FIGURE 9. Candidates' long-run winning frequencies under APL with divided preferences and a fixed share  $r_{cb} = 20\%$  of voters.

We observe that the election pattern under APL is much less regular than under AV or PL, in line with the instability of APL (Proposition 5). When one candidate is a Condorcet winner with many supporters, she is elected for sure. But otherwise, the elected candidate does not seem much related to voters' preferences. Note for instance the yellow region on the right of the figure. In this region,  $c$  is a (rather strong) Condorcet winner, but APL only selects  $a$  or  $b$ . Note in particular that a Condorcet loser may well be elected under APL, while this never arises under AV or PL.

**C.4.2. The Bad Apple example.** Myerson [2002] introduces an example of divided preferences with  $r_{ab} = r_{ba} = 50\%$ , while  $\rho_{ab} = \rho_{ba}$  is the Dirac measure concentrated on  $2/3$ . The third candidate,  $c$ , is interpreted as the *bad apple*, disliked by all voters. Myerson proves that a *large equilibrium*  $\tau^*$  exists for this profile under APL, it is such that  $\tau_{ab}^* = \tau_{ac}^* = \tau_{bc}^* = 1/3$ . This large equilibrium is supported by a sequence of profiles  $(\tau^n)_{n \geq 1}$ , where  $\tau^n$  is an equilibrium for an electorate of expected size  $n$ . Myerson shows that, along this sequence, the worst candidate  $c$  is elected with a small but positive probability, estimated at 4.4% for  $n = 9,000,000$ .

We run the adaptive procedure at this profile under APL. For each of the assumptions on the distribution of the initial poll  $\tau^0$  discussed in Section C.3, we estimate that the worst candidate  $c$  gets elected with a large frequency of around 70% (between 68.6% and 71.7%). In the long run, we observe that the perceived profile  $\hat{\tau}^p$  converges to  $\tau^*$ . Thus, the large equilibrium  $\tau^*$  has relevant predictive power for the adaptive procedure, in terms of long-run *average behavior*. Yet, the actual profile  $\tau^p$  often deviates from  $\tau^*$ , even in the long run, as we observe frequent and recurrent jumps along the trajectory. This electoral instability under

APL is captured by the absence of *asymptotic equilibrium* established in Proposition 5.

### C.5. Welfare with and without a Condorcet winner

In this section, we disentangle the welfare comparisons for profiles with and without a Condorcet winner (note that Figure 4 aggregates all profiles). We report on Figure 10 the empirical cumulative distributions of utilitarian welfare losses under each voting rules, conditioning on the existence of a Condorcet winner in the left panel, and on the non-existence of a Condorcet winner in the right panel.

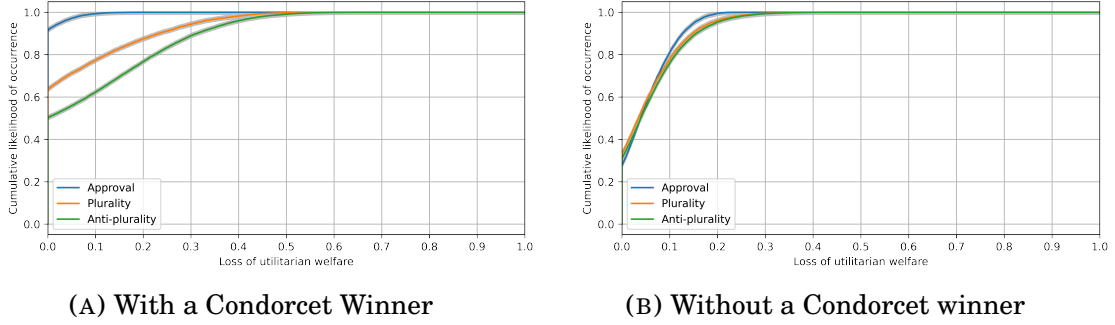


FIGURE 10. Cumulative distributions of utilitarian welfare losses.

### C.6. Welfare with (model 1-) expressive voters

To complement Section 6.4, we report statistics on welfare losses when some voters are (model 1-) expressive. We assume that half of the electorate follows this behavioral rule, while remaining voters are strategic. We report on Figure 11 the empirical cumulative distribution of utilitarian welfare losses when half of the electorate is (model 1-) expressive.

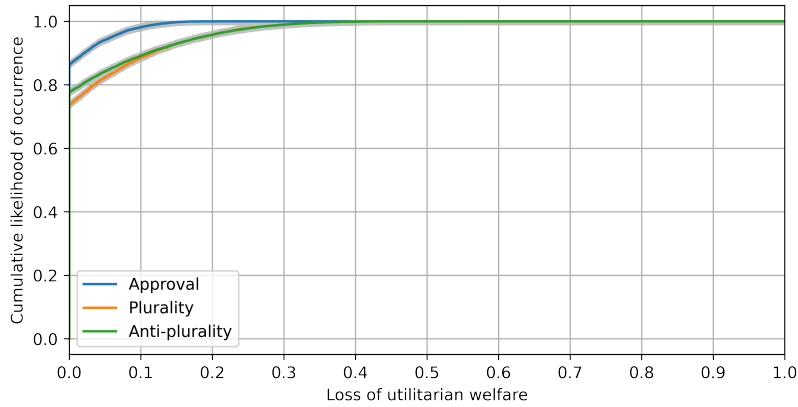


FIGURE 11. Cumulative distributions of utilitarian welfare losses with 50% of (model 1-) expressive voters.

We report on Figure 12 the empirical cumulative distributions of utilitarian welfare losses when half of the electorate is (model 1-) expressive, computed for  $W_{PL}$  in the left-panel and for  $W_{APL}$  in the right panel.

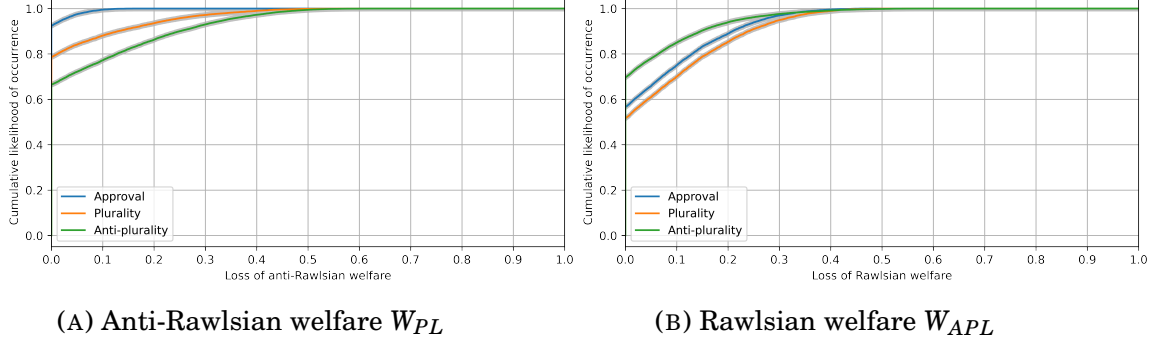


FIGURE 12. Cumulative distributions of welfare losses with 50% of (model 1-) expressive voters.

We find that, for both utilitarian and anti-Rawlsian welfare measures, AV remains more efficient than the other rules in terms of first-order stochastic dominance. However for Rawlsian welfare, APL becomes more efficient than the other rules.

### C.7. Distribution of asymptotic utility thresholds under AV

We draw on Figure 13 the empirical cumulative distribution of the asymptotic utility thresholds under AV. The figure aggregates (over 10,000 draws) the cumulative distributions obtained for each draw of  $(r, \tau^0)$ , where for each type  $o$ , the asymptotically threshold  $u_o^\infty$  is assigned a weight  $r_o$ .

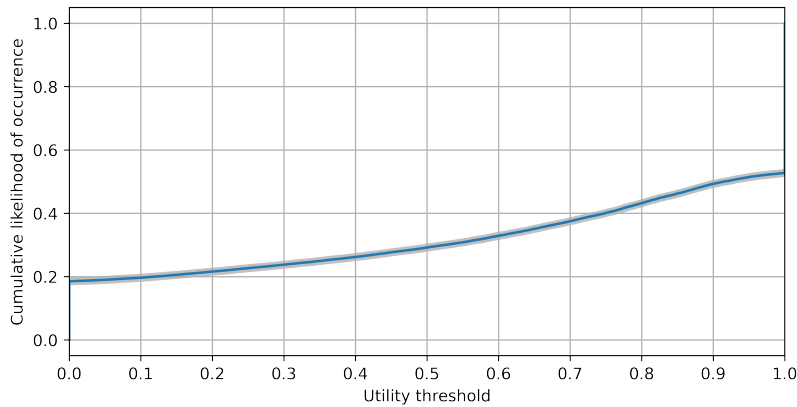


FIGURE 13. Cumulative distribution of asymptotic utility thresholds under AV.

### C.8. An example where the challenger is approved by a majority under AV

We describe one example of a preference profile for which the adaptive procedure sometimes reaches an election outcome such that both the winner (ranked first) and the challenger (ranked second) obtain a majority of approvals. The ordinal profile  $r$  is defined by  $r_{ab} = 33\%$ ,  $r_{ac} = 1\%$ ,  $r_{ba} = 8\%$ ,  $r_{bc} = 8\%$ ,  $r_{ca} = 2\%$  and  $r_{cb} = 48\%$ . The distribution  $\rho$  is such that  $\rho_o \sim \mathcal{U}((0,1))$  for all  $o \in \mathcal{O}$ . Note that  $c$  is the Condorcet winner in this example.

We ran the adaptive procedure for multiple draws of  $\tau^0$  from the uniform distribution on  $\Delta(\mathcal{M})$ . For some draws, the procedure converged to the ordinal equilibrium  $\tau$  such that  $\tau_a = 33\%$ ,  $\tau_{ac} = 3\%$ ,  $\tau_b = 16\%$  and  $\tau_{bc} = 48\%$ . For this particular profile, the non-Condorcet winner  $b$  is elected and the scores are given by  $\gamma_a = 36\%$ ,  $\gamma_b = 64\%$  and  $\gamma_c = 51\%$ . Hence, the challenger  $c$  is approved by a majority of voters. Finally, observe that this example corresponds to one of the very rare cases (estimated at  $100 - 99.96 = 0.04\%$  in Table 3) for which the profile  $\rho$  and the initial poll  $\tau^0$  are such that Condorcet winner is not elected in the long-run outcome of the procedure under AV.

### C.9. Confidence Intervals

Within the article, we do not specify confidence intervals in the tables for the sake of readability. As all estimates are computed for 10,000 draws, we report here the 95% confidence interval associated to all possible point estimates of a frequency for this number of draws. That is, we report on Figure 14 the 95% confidence interval for the parameter  $f \in (0,1)$ , for each possible realization  $\theta \in \{0, \dots, 10000\}$  of a variable drawn from the binomial distribution with parameters 10,000 and  $f$ .

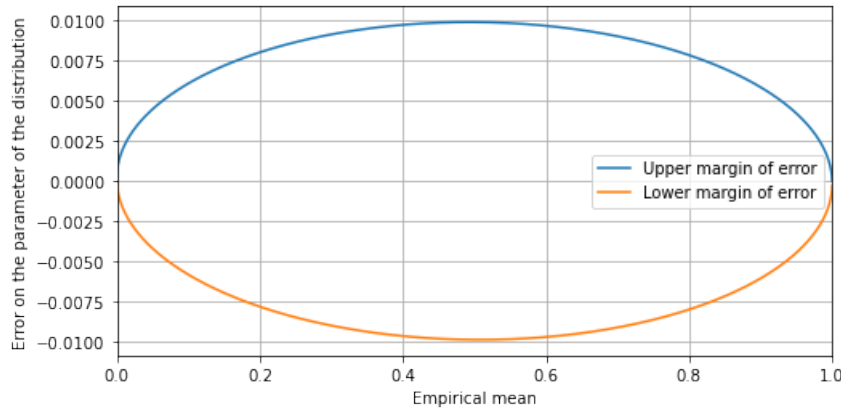


FIGURE 14. 95% confidence interval for 10,000 draws.

We observe that the boundaries of the 95% confidence interval are always



within one percentage point of the point estimate for the frequency  $f$ . The confidence interval becomes asymmetric and narrower for very low or very high estimated frequencies.