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Biased Opinion Dynamics: When the Devil Is in the Details

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Abstract

We investigate opinion dynamics in multi-agent networks when a bias toward one of two possible opinions exists; for example, reflecting a status quo vs a superior alternative.

Starting with all agents sharing an initial opinion representing the status quo, the system evolves in steps. In each step, one agent selected uniformly at random adopts the superior opinion with some probability α , and with probability $1 - \alpha$ it follows an underlying update rule to revise its opinion on the basis of those held by its neighbors. We analyze convergence of the resulting process under two well-known update rules, namely *majority* and *voter*.

The framework we propose exhibits a rich structure, with a non-obvious interplay between topology and underlying update rule. For example, for the voter rule we show that the speed of convergence bears no significant dependence on the underlying topology, whereas the picture changes completely under the majority rule, where network density negatively affects convergence.

We believe that the model we propose is at the same time simple, rich, and modular, affording mathematical characterization of the interplay between bias, underlying opinion dynamics, and social structure in a unified setting.

1 Introduction

Opinion formation in social groups has been the focus of extensive research. While many models considered in the literature confer the same *intrinsic* value to all opinions [CHK18], one might expect a group to quickly reach consensus on a clearly “superior” alternative, if present. Yet, phenomena such as *groupthink* may delay or even prevent such an outcome.

In this perspective, we investigate models of opinion formation in which a bias towards one of two possible opinions exists, for instance, reflecting intrinsic superiority of one alternative over the other.¹ In the remainder, we use labels 0 and 1 for the two opinions and we assume 1 is the *dominant* opinion, that is, the one towards which the agents have a bias. We investigate this question in a mathematically tractable setting, informally described as follows.

Assume some underlying opinion dynamics \mathcal{D} . Starting from an initial state in which all agents share opinion 0, the system evolves in rounds. In each round, one agent is selected uniformly at random. With some probability α , the agent adopts 1, while with probability $1 - \alpha$, the agent follows \mathcal{D} to revise its opinion on the basis of those held by its neighbors in an underlying network.

Although the general model we consider is simple and, under mild conditions on \mathcal{D} , the family of processes it describes always admits global adoption of opinion 1 as the only absorbing state, convergence to this absorbing state exhibits a rich variety of behaviors, which in non-obvious ways depends on the interplay between the network structure and the underlying opinion dynamics. The relatively simple, yet general, model we consider allows analytical investigation of the following question:

How does a particular combination of network structure and opinion dynamics affects convergence to global adoption of the dominant opinion? In particular, how conducive is a particular combination to rapid adoption?

Main findings. In general, the interplay between underlying network structure and opinion dynamics may elicit quite different collective behaviors.

In Section 3, we show that the expected time for consensus on the dominant opinion grows exponentially with the minimum degree under the *majority* update rule, in which agents update their opinion to the majority opinion in their neighborhoods [KR03]. Using asymptotic notation and denoting the number of agents in the network by n , we obtain that convergence time is super-polynomial in expectation whenever the minimum degree is $\omega(\log n)$. One might wonder, if the converse occurs, namely, if a logarithmic maximum degree affords (expected) polynomial convergence to the absorbing state. Even though we prove that this is indeed the case for specific topologies as cycles or restricted graph families, this does not seem to hold in general (see discussion in Section 5).

The results for majority are at odds with those we obtain in Section 4 for the *voter model*, where agents copy the opinion of a randomly selected neighbor [Lig12]. In this case, convergence to the absorbing state occurs within $\mathcal{O}(\frac{1}{\alpha}n \log n)$ rounds *with high probability*, regardless of the underlying network structure. We emphasize that convergence time remains $\mathcal{O}(n^{1+s} \log n)$ when $\alpha = \Theta(\frac{1}{n^s})$ for any $s > 0$.

Although results suggesting a negative impact of network density on convergence time have been proposed in the past, albeit for quite different models (e.g., [MS10]), the results above suggest that there might be more to the issue. In particular, the interplay between opinion dynamics and underlying network structure seems more complex than anticipated, with the former playing a key role in amplifying network effects.

¹Characterizing the notion of “superiority” is typically context-dependent and may be far from obvious. We remark that this aspect is outside the scope of this paper.

At a higher level, we provide a simple mathematical framework to investigate the interplay between opinion dynamics and underlying network structure in a unified setting, allowing comparison of different update rules with respect to a common framework. In this respect, we hope that our work moves in the direction of a shared framework to investigate opinion dynamics, as advocated in [CHK18].

1.1 Related Work

The problem we consider touches a number of areas where similar settings have been considered, with various motivations. The corresponding literature is vast and providing an exhaustive review is unfeasible here. In the paragraphs that follow, we discuss contributions that most closely relate to the topic of this paper.

Opinion diffusion and consensus. Opinion dynamics are widely used to investigate how group of agents modify their beliefs under the influence of other agents and possibly exogenous factors. A number of models have been proposed in the more or less recent past, mostly motivated by phenomena that arise in several areas, ranging from social sciences, to physics and biology. The reader is referred to [CHK18] and references therein for a recent, general overview of opinion dynamics in multi-agent systems. A first distinction is between settings in which the set of possible beliefs is continuous, e.g., the interval $[0, 1]$. This setting has been the focus of extensive research in social sciences and economics [DeG74, FJ90, FB17].

In this paper, we consider the case in which opinions are drawn from a discrete set, a setting that also received significant attention in the recent past. In particular, we focus on the *majority rule* and the *voter model*. Investigation of the majority update rule originates from the study of agreement phenomena in spin systems [KR03], while the voter model was motivated by the study of spatial conflict between species in biology and interacting stochastic processes/particle systems in probability theory and statistics [CS73, HL⁺75, Lig12]. These two models received renewed attention in the recent past, the focus mostly being on the time to achieve consensus and/or conditions under which consensus on one of the initial opinions is achieved with a minimum degree of confidence. The voter model is by now well understood. In particular, increasingly tight bounds on convergence time for general and specific topologies have been proposed over the recent past [HP99, CEOR13], while it is known that the probability of one particular opinion to prevail is proportional to the sum of the degrees of nodes holding that opinion at the onset of the process [DW83].

Consensus and network structure. Network structure has been known to play an important role in opinion diffusion and influence spreading for quite some time [Mor00], under a variety of models. For example, consensus under the voter model and dependence of its convergence on the underlying network topology have been thoroughly investigated [DW83, HP99, CEOR13]. For majority dynamics, [ACF⁺15] characterized topologies for which an initial majority can be subverted, showing that this is possible for all but a handful of topologies, including cliques and quasi-cliques. On the other hand, regardless of the network, there is always an initial opinion distribution, such that the final majority will reflect the initial one, while computing an initial opinion configuration that will subvert an initial majority is topology-dependent and NP-hard in general [AFG18].

A number of recent contributions investigated (among other aspects) the relationship between network structure and consensus in opinion formation games [FGV16, FV17], while extensions of the Friedkin-Johnsen model to evolving networks were investigated in [AFF19].

While expansion of the underlying graph typically accelerates convergence [CEOR12, KMTS19] in many opinion dynamics, some recent work explicitly points to potentially adverse effects of network structure on the spread of innovation, at least in scenarios where opinion update occurs

on the basis of private utilities that reflect both the degree of local consensus and intrinsic value of the competing opinions [MS10, You11].

While some of our findings are qualitatively consistent with previous work albeit under completely different models (in particular, [MS10]), our overall approach is very different, since it completely decouples the mechanism of opinion formation from modelling of the bias, affording a clear-cut mathematical characterization of the interplay between bias, underlying opinion dynamics and network structure.

Different forms of bias. Bias in opinion dynamics has been considered previously in the literature. We briefly review contributions that are at least loosely related to our framework. For the voter and majority update rules, [MMR16] introduces bias in the form of different, opinion-dependent firing rate frequencies of the Poisson clocks that trigger agents’ opinion updates, implicitly enforcing a bias toward the opinion with lower associated rate. While different, their model is similar to ours in spirit and some of their results for the voter model are consistent with ours. Yet, these results only apply in expectation and to very dense networks with degree $\Omega(n)$, whereas our results for the voter model hold for every undirected graph.

A somewhat related line of research addresses the presence of stubborn agents or zealots. Loosely speaking, stubborn agents have a bias toward some (initially or currently) held opinion, while zealots are agents that never deflect from some initial opinion. Restricting to the discrete-opinion setting, which is the focus of this paper,² the role of zealots and their ability to subvert an initial majority have been investigated for the voter model (see [Mob03] and follow-up work), while [ACF⁺17] investigates majority dynamics in the presence of stubborn agents that are biased toward the currently held opinion, providing a full characterization of conditions under which an initial majority can be subverted.

2 Notation and Preliminaries

Let $G = (V, E)$ be an undirected graph with $|V| = n$ nodes, each representing an agent. Without loss of generality, we assume that $V = [n] := \{1, \dots, n\}$. The system evolves in discrete time steps³ and, at any given time $t \in \mathbb{N}$, each node $v \in V$ holds an *opinion* $x_v^{(t)} \in \{0, 1\}$. We use the term opinion liberally here, in the sense that 0 and 1 in general represent competing alternatives, whose meaning is context-dependent and outside the scope of this paper. We denote by $\mathbf{x}^{(t)} = (x_1^{(t)}, \dots, x_n^{(t)})^\top$ the corresponding *state* of the system at time t . We assume that the initial state of the system is $\mathbf{x}^{(0)} = \mathbf{0} = (0, \dots, 0)^\top$; such assumption is discussed in Section 5. For each $v \in V$, we denote the neighborhood of v with $N_v := \{u \in V : \{u, v\} \in E\}$ and the degree of v with $d_v := |N_v|$. Finally, $\Delta := \min_{v \in V} d_v$ is the minimum degree of the nodes in G .

Our framework assumes that agents exhibit a bias toward one of the opinions (e.g., reflecting intrinsic superiority of a technological innovation over the *status quo*), without loss of generality 1, which we henceforth call the *dominant opinion*. We model bias as a probability, with a parameter $\alpha \in (0, 1]$. All dynamics we consider are *Markovian*, that is, given the underlying graph G , the distribution of the state $\mathbf{x}^{(t)}$ at round t only depends on the state $\mathbf{x}^{(t-1)}$ at the end of the previous round. Moreover, they have $\mathbf{x} = \mathbf{1} = (1, \dots, 1)^\top$ as the only absorbing state. We use τ to denote the *absorption time*, which is the number of rounds for the process to reach the absorbing state $\mathbf{1}$. Finally, for a family of events $\{\mathcal{E}_n\}_{n \in \mathbb{N}}$ we say that \mathcal{E}_n occurs *with high probability* (*w.h.p.*, in short) if a constant $\gamma > 0$ exists such that $\mathbf{P}(\mathcal{E}_n) = 1 - \mathcal{O}(n^{-\gamma})$, for every sufficiently large n .

²For the continuous case, there is a vast literature; see the seminal paper [FJ90] and follow-up work.

³This is equivalent to the asynchronous model in which a node revises its opinion at the arrival of an independent Poisson clock with rate 1 [BGPS06].

3 Absorption Time for Majority Dynamics

In this section, we investigate the time to reach consensus on the dominant opinion under the majority update rule. More formally, we study the following random process: Starting from the initial state $\mathbf{x}^{(0)} = (0, \dots, 0)^\top$, in each round t a node $u \in [n]$ is chosen uniformly at random and u updates its value according to the rule

$$x_u^{(t)} = \begin{cases} 1 & \text{with probability } \alpha, \\ M_G(u, \mathbf{x}) & \text{with probability } 1 - \alpha, \end{cases}$$

where $\alpha \in (0, 1]$ is the bias toward the dominant opinion 1 and $M_G(u, \mathbf{x})$ is the value held in configuration $\mathbf{x}^{(t-1)} = \mathbf{x}$ by the majority of the neighbors of node u in graph G :

$$M_G(u, \mathbf{x}) = \begin{cases} 0 & \text{if } \sum_{v \in N_u} x_v < |N_u|/2, \\ 1 & \text{if } \sum_{v \in N_u} x_v > |N_u|/2, \end{cases}$$

and ties are broken uniformly at random, that is, if $\sum_{v \in N_u} x_v = |N_u|/2$ then $M_G(u, \mathbf{x}) = 0$ or 1 with probability $1/2$.

It is straightforward to see that for every positive α , the above Markov chain has $\mathbf{1}$ as the only absorbing state. However, the rate of convergence is strongly influenced by the underlying graph G . In Subsection 3.1 we prove a lower bound on the expected absorption time that depends exponentially on the minimum degree. This result implies super-polynomial expected absorption times for graphs whose minimum degree is $\omega(\log n)$. On the other hand, in Subsection 3.2 we prove that the absorption time is $\mathcal{O}(n \log n)$ on cycle graphs, and further graph families with sub-logarithmic maximum degree and polynomial (expected) absorption time are briefly discussed in Subsection 3.3.

3.1 Slow Convergence on High-Density Graphs

In this section we prove a general lower bound on the expected absorption time, which only depends on the minimum degree Δ . To this purpose, we use the following standard lemma on birth-and-death chains⁴ (see, e.g., [LP17, Section 17.3] for a proof).

Lemma 3.1. *Let $\{X_t\}_t$ be a birth-and-death chain with state space $\{0, 1, \dots, n\}$ such that for every $1 \leq k \leq n - 1$*

$$\begin{aligned} \mathbf{P}(X_{t+1} = k + 1 \mid X_t = k) &= p, \\ \mathbf{P}(X_{t+1} = k - 1 \mid X_t = k) &= q, \\ \mathbf{P}(X_{t+1} = k \mid X_t = k) &= r, \end{aligned}$$

with $p + q + r = 1$. For every $i \in \{0, 1, \dots, n\}$ let τ_i be the first time the chain hits state i , that is, $\tau_i = \inf\{t \mid X_t = i\}$. If $0 < p < 1/2$, the probability that starting from state k the chain hits state n before state 0 is

$$\mathbf{P}_k(\tau_n < \tau_0) = \frac{(q/p)^k - 1}{(q/p)^n - 1} \leq \left(\frac{p}{q}\right)^{n-k}.$$

It is not difficult to show that, for $\alpha \geq 1/2$, every graph with minimum degree $\Delta = \Omega(\log n)$ has $\mathcal{O}(n \log n)$ absorption time, w.h.p. Indeed, since every time a node updates its opinion the node chooses opinion 1 with probability at least α , as soon as all nodes update their opinion at least once (it happens within $\mathcal{O}(n \log n)$ time steps, w.h.p., by coupon collector argument) if $\alpha \geq 1/2$, every node u will have a majority of 1s in its neighborhood, w.h.p.

In the next theorem we prove that, as soon as α is smaller than $1/2$, the absorption time instead becomes exponential in the minimum degree.

⁴Birth-and-death chains are Markov processes for which, if in state k , a transition could only go to either state $k + 1$ or state $k - 1$.

Theorem 3.2. Let $G = (V, E)$ be an undirected graph with minimum degree Δ . Assume $\alpha \leq \frac{(1-\varepsilon)}{2}$, for an arbitrary constant $0 < \varepsilon < 1$. The expected absorption time for the biased opinion dynamics under the majority update rule is

$$\mathbf{E}[\tau] \geq \frac{e^{\frac{\varepsilon^2}{6}\Delta}}{6n}.$$

Proof. Let $S^{(t)}$ be the set of nodes with value 1 at time t . For each node $u \in V$, let $n_u^{(t)}$ be the fraction of its neighbors with value 1 at round t :

$$n_u^{(t)} = \frac{|N_u \cap S^{(t)}|}{|N_u|}.$$

Finally, let $\bar{\tau}$ be the first round in which $n_u^{(t)} \geq 1/2$ for at least one node $v \in V$, namely,

$$\bar{\tau} = \inf \left\{ t \in \mathbb{N} : n_u^{(t)} \geq 1/2, \text{ for some } u \in [n] \right\}.$$

Note that for each round $t \leq \bar{\tau}$ all nodes have a majority of neighbors sharing opinion 0, thus the selected agent at time t updates its state to 1 with probability α and to 0 with probability $1 - \alpha$. Moreover, clearly $\tau \geq \bar{\tau}$. We next prove that $\mathbf{E}[\bar{\tau}] \geq e^{\frac{\varepsilon^2}{6}\Delta}/(6n)$, which implies our thesis.

Observe that, for a node u with degree d_u that has k neighbors with value 1 in some round and for every $t \leq \bar{\tau}$, the probabilities $p_k(u)$ and $q_k(u)$ of increasing and decreasing, respectively, of one unit the number of its neighbors with value 1 are

$$p_k(u) = \frac{d_u - k}{n} \alpha, \text{ and } q_k(u) = \frac{k}{n} (1 - \alpha).$$

Hence, because $\alpha \leq (1 - \varepsilon)/2$, for every $k \geq d_u/(2 + \varepsilon)$ we have that

$$\frac{p_k(u)}{q_k(u)} = \frac{d_u - k}{k} \cdot \frac{\alpha}{1 - \alpha} \leq (1 + \varepsilon) \cdot \frac{1 - \varepsilon}{1 + \varepsilon} = 1 - \varepsilon.$$

Note that

$$\frac{d_u}{2} - \frac{d_u}{2 + \varepsilon} = d_u \frac{\varepsilon}{2(2 + \varepsilon)} \geq \frac{\varepsilon}{6} d_u.$$

From Lemma 3.1 it thus follows that, for each node u , as soon as the number of its neighbors with value 1 enters in the range $(d_u/(2 + \varepsilon), d_u/2)$, the probability that it will reach $d_u/2$ before going back to $d_u/(2 + \varepsilon)$ is at most

$$(1 - \varepsilon)^{\varepsilon d_u/6} \leq e^{-\varepsilon^2 d_u/6} \leq e^{-\frac{\varepsilon^2}{6}\Delta},$$

using $(1 - x)^x \leq e^{-x^2}$ for $x \in [0, 1]$. Hence, if we denote by Y_u the random variable indicating the number of trials before having at least $1/2$ of the neighbors of u at 1 we have that for every $t \geq 0$

$$\mathbf{P}(Y_u \geq t) \geq \left(1 - e^{-\frac{\varepsilon^2}{6}\Delta}\right)^t \geq e^{-(3t/2)e^{-\frac{\varepsilon^2}{6}\Delta}},$$

where in the last inequality we used that $1 - x \geq e^{-3x/2}$ for every $x \in [0, \frac{1}{2}]$. Thus,

$$\mathbf{P}(Y_u < t) \leq 1 - e^{-(3t/2)e^{-\frac{\varepsilon^2}{6}\Delta}} \leq \frac{3t}{2} e^{-\frac{\varepsilon^2}{6}\Delta},$$

using $1 - e^{-x} \leq x$ for every x . Finally, by using the union bound over all nodes, we have that

$$\mathbf{P}(\bar{\tau} < t) = \mathbf{P}(\exists u \in [n] : Y_u < t) \leq n \cdot \frac{3t}{2} e^{-\frac{\varepsilon^2}{6}\Delta}.$$

Thus, for $\bar{t} = e^{\frac{\varepsilon^2}{6}\Delta}/3n$ we have $\mathbf{P}(\bar{\tau} \leq \bar{t}) \leq 1/2$ and the thesis follows from Markov inequality:

$$\mathbf{E}[\bar{\tau}] \geq \bar{t} \mathbf{P}(\bar{\tau} \geq \bar{t}) \geq \frac{\bar{t}}{2}. \quad \square$$

3.2 Fast Convergence on the Cycle

In this section, we prove that the absorption time on an n -node cycle graph is $\mathcal{O}(\frac{1}{\alpha}n \log n)$, w.h.p. We make use of the following *structural* lemma.

Lemma 3.3 (Structural property of cycles). *Let C_n be the cycle on n nodes and let every node $v \in V$ have an associated state $x_v \in \{0, 1\}$. Let us call B_i and S_i the set of nodes in state i such that: every node $v \in B_i$ has both neighbors in the opposite state and every node $v \in S_i$ has one single neighbor in the opposite state. The following holds:*

$$|B_0| + \frac{|S_0|}{2} = |B_1| + \frac{|S_1|}{2}.$$

Proof. Given any possible binary coloring of C_n each node v belongs to one of the following categories:

- $v \in B_i$: node v is in state i and both its neighbors are in state $j \neq i$.
- $v \in R_i$: node v is in state i , its left neighbor is in state i , and its right neighbor is in state $j \neq i$.
- $v \in L_i$: node v is in state i , its right neighbor is in state i , and its left neighbor is in state $j \neq i$.
- $v \in Z_i$: node v is in state i and zero of its neighbors are in state $j \neq i$, i.e., both are in state i .

We also call $S_i = R_i \cup L_i$. Figure 1 illustrates the eight (counting symmetries) possible categories. Let us consider a clockwise walk through C_n that returns to its starting point. Keeping into

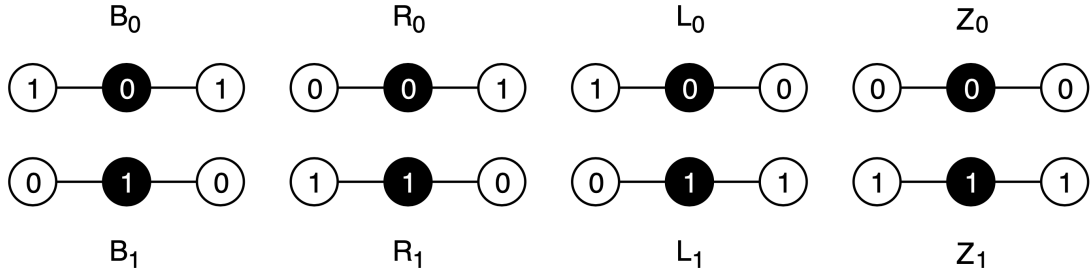


Figure 1: Categories of a node v in C_n ; node v is black while its left and right neighbors are white.

account the categories of the nodes previously described it is possible to generate a graph H_C that describes all possible binary configurations of a C_n graph, for every $n \in \mathbb{N}$. We call H_C the *Cycle Binary Configuration Graph* (Figure 2). The nodes of H_C represent the possible categories of the nodes of C_n while the edges the possible neighbors in C_n , considering a clockwise walk. For example, there is no edge from B_0 to R_0 since the neighbors of B_0 are both in state 1, while a node in R_0 is in state 0.

Let us pick any node v in C_n and let us walk through clockwise until we return to v . Let us pick the node of H_C corresponding to the category v belongs to and follow the clockwise walk that we do on C_n also on H_C , by moving on the corresponding states. It follows that after n steps the walk on C_n will be back to v and the walk on H_C will be back to the node representing the category of v . Note that this implies that the walk on H_C is a cycle and, more in general, that every cycle of length n on H_C represent a possible binary configuration of the nodes of a corresponding cycle graph C_n .

Note that every possible cycle in H_C is a combination of simple cycles (that go through each node at most once) on H_C . We prove that the structural property of the lemma holds for

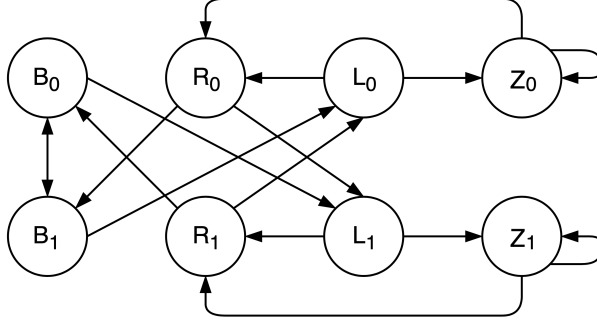


Figure 2: The *Cycle Binary Configuration Graph* H_C .

every simple cycle on H_C . By commutativity and associativity of addition, the property directly transfer also to composition of simple graphs. In order to reduce the number of simple cycles (which are 17; they are easy to find on a computer given the small size of the graph H_C —the problem is $\#P$ -hard [AB09]), we avoid cycles that pass through Z_i since $|Z_i|$ does not appear in the lemma; in fact, every cycle passing through Z_i does $L_i \rightarrow Z_i \rightarrow R_i$ and the only other outgoing edge of L_i is $L_i \rightarrow R_i$. In other words, excluding simple cycles passing through node Z_i does not have any effect on the following calculations. By also taking advantage of symmetries in i and j , all the remaining simple cycles are the following four, for which the equality of the lemma is true:

- $(B_i \rightarrow B_j)$: $|B_i|$ cancels out with $|B_j|$.
- $(B_i \rightarrow L_j \rightarrow R_j)$: $|B_i|$ cancels out with $\frac{|R_j|+|L_j|}{2}$.
- $(R_i \rightarrow L_j \rightarrow R_j \rightarrow L_i)$: $\frac{|R_i|+|L_i|}{2}$ cancels out with $\frac{|R_j|+|L_j|}{2}$.
- $(B_i \rightarrow B_j \rightarrow L_i \rightarrow R_i \rightarrow L_j \rightarrow R_j)$: $|B_i|$ cancels out with $|B_j|$; $\frac{|R_i|+|L_i|}{2}$ cancels out with $\frac{|R_j|+|L_j|}{2}$. \square

Theorem 3.4 (Cycles). *Let $G = C_n$ be the cycle on n nodes. Under the majority update rule, we have $\tau = \mathcal{O}\left(\frac{1}{\alpha}n \log n\right)$, with high probability.*

Proof. Denote by V_i the set of nodes with state i . Given a configuration $\mathbf{x} \in \{0, 1\}^n$ of C_n , let $B_i = \{v \in V_i : \forall u \in N_v, x_u \neq i\}$ and $S_i = \{v \in V_i : \exists u, w \in N_v, x_u \neq x_w\}$ (see Lemma 3.3). Let X_t be the random variable indicating the number of nodes in state 1 at round t and observe that for every k , we have:

$$\mathbf{P}(X_t = h \mid X_{t-1} = k) = \begin{cases} q_k & \text{if } h = k - 1, \\ r_k & \text{if } h = k, \\ p_k & \text{if } h = k + 1, \end{cases}$$

where $q_k = (1 - \alpha) \left(\frac{|B_1|}{n} + \frac{1}{2} \frac{|S_1|}{n}\right)$, $p_k = \alpha \frac{n-k}{n} + (1 - \alpha) \left(\frac{|B_0|}{n} + \frac{1}{2} \frac{|S_0|}{n}\right)$, and $r_k = 1 - q_k - p_k$. Therefore, the expected value of X_t , conditioned to $X_{t-1} = k$, is

$$\begin{aligned} \mathbf{E}[X_t \mid X_{t-1} = k] &= (k-1)q_k + kr_k + (k+1)p_k = k - q_k + p_k \\ &= k + \alpha \frac{n-k}{n} + \frac{1-\alpha}{n} \left(|B_0| + \frac{|S_0|}{2} - |B_1| - \frac{|S_1|}{2}\right) \\ &\stackrel{(a)}{=} k + \alpha \frac{n-k}{n}, \end{aligned}$$

where in derivation (a) we use Lemma 3.3. We therefore have:

$$\begin{aligned}
\mathbf{E}[X_t] &= \sum_{k=0}^n \mathbf{E}[X_t \mid X_{t-1} = k] \mathbf{P}(X_{t-1} = k) \\
&= \sum_{k=0}^n \left(\alpha + \left(1 - \frac{\alpha}{n}\right) k \right) \mathbf{P}(X_{t-1} = k) \\
&= \alpha \sum_{k=0}^n \mathbf{P}(X_{t-1} = k) + \left(1 - \frac{\alpha}{n}\right) \sum_{k=0}^n k \mathbf{P}(X_{t-1} = k) \\
&= \alpha + \left(1 - \frac{\alpha}{n}\right) \mathbf{E}[X_{t-1}].
\end{aligned}$$

Solving this recursion with $\mathbf{E}[X_0] = 0$ we get

$$\mathbf{E}[X_t] = \alpha \sum_{i=0}^{t-1} \left(1 - \frac{\alpha}{n}\right)^i = \alpha \frac{1 - (1 - \alpha/n)^t}{\alpha/n}.$$

The expected number $n - X_t$ of nodes in state 0 at round t is thus

$$\mathbf{E}[n - X_t] = n \left(1 - \frac{\alpha}{n}\right)^t,$$

that is smaller than $\frac{1}{n}$ for $t \geq \frac{2}{\alpha} n \log n$. Hence,

$$\mathbf{P}\left(\tau > \frac{2}{\alpha} n \log n\right) = \mathbf{P}\left(n - X_{\frac{2}{\alpha} n \log n} \geq 1\right) \stackrel{(b)}{\leq} \mathbf{E}\left[n - X_{\frac{2}{\alpha} n \log n}\right] \leq 1/n,$$

where in (b) we use the Markov inequality. □

3.3 Further Low-Density Graph Families

It is not difficult to show that convergence times are also polynomial in the cases of trees of degree $\mathcal{O}(\log n)$ and disconnected cliques of size $\mathcal{O}(\log n)$. These results are summarized as the following theorem.

Theorem 3.5 (Trees and disconnected cliques). *Assume $G = (V, E)$ is a tree of degree $\mathcal{O}(\log n)$ (resp. a set of disconnected cliques, each of size $\mathcal{O}(\log n)$). Then, for every constant $\alpha \in (0, 1]$, the expected absorption time is polynomial.*

4 Absorption Time for the Voter Model

As mentioned in the introduction, the voter model has received considerable attention as an opinion dynamics in the more and less recent past [Lig12]. It may be regarded as a “linearized” form of the majority update rule, in the sense that, upon selection, a node pulls each of the two available opinions with probability proportional to the opinion’s support within the node’s neighborhood. Despite such apparent similarity, the two update rules result in quite different behaviors of the biased opinion dynamics. Namely, for the voter model, absorption times to the dominant opinion are polynomial with high probability as long as $1/\alpha$ is polynomial, regardless of the underlying topology. These results are clearly at odds with those of Section 3.

The biased voter model can formally be defined as follows: Starting from some initial state $\mathbf{x}^{(0)}$, at each round t a node $u \in [n]$ is chosen uniformly at random and its opinion is updated as

$$x_u^{(t)} = \begin{cases} 1 & \text{with probability } \alpha, \\ V_G(u, \mathbf{x}) & \text{with probability } 1 - \alpha, \end{cases}$$

where $\alpha \in (0, 1]$ is a parameter measuring the bias toward the better opinion 1 and $V_G(u, \mathbf{x})$ is the value held in configuration $\mathbf{x}^{(t-1)} = \mathbf{x}$ by a node sampled uniformly at random from the neighborhood of node u . We assume $\mathbf{x}^{(0)} = \mathbf{0}$ for simplicity, though we remark that Theorem 4.1 below holds for any $\mathbf{x}^{(0)} \in \{0, 1\}^n$.

As the proof of Theorem 4.1 highlights, the biased opinion dynamics under the voter update rule can be succinctly described by a *nonhomogeneous* Markov chain [Sen06]. Although non-trivial to study in general, we are able to provide tight bounds in probability for the simplified setting we consider.

Theorem 4.1. *Let $G = (V, E)$ be an arbitrary graph. The biased opinion dynamics with voter as update rule reaches state $\mathbf{1}$ within $\tau = \mathcal{O}(\frac{1}{\alpha} n \log n)$ steps, with high probability.*

Proof. For every node $v \in V$, the expected state of v at time $t + 1$, conditioned on $\mathbf{x}^{(t)} = \mathbf{x}$ is

$$\begin{aligned} \mathbf{E} \left[x_v^{(t+1)} \mid \mathbf{x}^{(t)} = \mathbf{x} \right] &= \frac{1}{n} \left[\alpha + \frac{(1-\alpha)}{d_v} \sum_{u \in N_v} x_u \right] + \left(1 - \frac{1}{n} \right) x_v \\ &= \frac{\alpha}{n} + \frac{1}{n} \left[(1-\alpha)(P\mathbf{x})_v + (n-1)(I\mathbf{x})_v \right], \end{aligned}$$

where $P = D^{-1}A$ is the transition matrix of the simple random walk on G (with D the diagonal degree matrix and A the adjacency matrix of the graph) and I is the identity matrix. Considering all nodes we can write the vector form of the previous equation as follows:

$$\mathbf{E} \left[\mathbf{x}^{(t)} \mid \mathbf{x}^{(t-1)} = \mathbf{x} \right] = \frac{\alpha}{n} \mathbf{1} + \frac{1}{n} \left[(1-\alpha)P + (n-1)I \right] \mathbf{x}.$$

This immediately implies the following equation, relating expected states at times $t-1$ and t (with $\mathbf{E} [\mathbf{x}^{(0)}] = \mathbf{x}$):

$$\mathbf{E} \left[\mathbf{x}^{(t)} \right] = \frac{\alpha}{n} \mathbf{1} + \frac{1}{n} \left[(1-\alpha)P + (n-1)I \right] \mathbf{E} \left[\mathbf{x}^{(t-1)} \right].$$

Now, consider $\mathbf{1} - \mathbf{x}^{(t)}$, the difference between the absorbing state vector $\mathbf{1}$ and the state vector at a generic time t . Obviously, $(\mathbf{1} - \mathbf{x}^{(t)})_v \geq 0$ deterministically, for every v and for every t . As for the expectation of this difference, we have:

$$\mathbf{E} \left[\mathbf{1} - \mathbf{x}^{(t)} \right] = \frac{1}{n} \left[(1-\alpha)P + (n-1)I \right] \mathbf{E} \left[\mathbf{1} - \mathbf{x}^{(t-1)} \right], \quad (1)$$

where the equality follows by collecting and rearranging terms, after observing that both matrices P and I have eigenvalue 1 with associated eigenvector $\mathbf{1}$. Moreover, we have

$$\frac{1}{n} \left[(1-\alpha)P + (n-1)I \right] = \left(1 - \frac{\alpha}{n} \right) \hat{P},$$

with $\hat{P} := \frac{n-1}{n-\alpha} \left[\left(\frac{1-\alpha}{n-1} \right) P + I \right]$ a stochastic matrix. This follows immediately by observing that both P and I are stochastic, so that all rows of $(1-\alpha)P + (n-1)I$ identically sum to $n-\alpha$. By solving the recursion in Eq. (1) we obtain

$$\mathbf{E} \left[\mathbf{1} - \mathbf{x}^{(t)} \right] = \left(1 - \frac{\alpha}{n} \right)^t \hat{P}^t \left[\mathbf{1} - \mathbf{x}^{(0)} \right] \stackrel{(a)}{=} \left(1 - \frac{\alpha}{n} \right)^t \mathbf{1} - \left(1 - \frac{\alpha}{n} \right)^t \hat{P}^t \mathbf{x}^{(0)},$$

where in (a) we use the fact that \hat{P}^t is a stochastic matrix, thus with main eigenvalue 1 and associated eigenvector $\mathbf{1}$. Next, observe that for every v , we have $\left(\hat{P}^t \mathbf{x}^{(0)} \right)_v \geq 0$, so we also have $\mathbf{E} \left[1 - x_v^{(t)} \right] \leq \left(1 - \frac{\alpha}{n} \right)^t$.

Therefore, for every time $t \geq \frac{2}{\alpha} n \log n$ we have

$$\mathbf{E} \left[1 - x_v^{(t)} \right] \leq \frac{1}{n^2}$$

for every $v \in V$. Because the $x_v^{(t)}$'s are binary random variables

$$\mathbf{P} \left(x_v^{(t)} = 0 \right) = \mathbf{P} \left(1 - x_v^{(t)} = 1 \right) \leq \mathbf{P} \left(1 - x_v^{(t)} \geq 1 \right) \leq \mathbf{E} \left[1 - x_v^{(t)} \right] \leq \frac{1}{n^2}$$

where in the second-to-last inequality we used the Markov inequality. Hence, in $\mathcal{O}(\frac{1}{\alpha} n \log n)$ rounds the process converges to the absorbing state $\mathbf{1}$, with high probability. \square

Note that Theorem 4.1 implies that the convergence time is still $\mathcal{O}(n^{1+s} \log n)$ when $\alpha = \Theta(\frac{1}{n^s})$ for any $s > 0$, hence polynomial as long as s is constant.

5 Discussion and Outlook

In this paper, we considered biased opinion dynamics under two popular update rules, namely majority [KR03] and the voter model [Lig12]. Although related, these two models exhibit substantial differences in our setting. Whereas the voter model enforces a drift toward the majority opinion within a neighborhood, in the sense that this is adopted with probability proportional to the size of its support, majority is a nonlinear update rule, a feature that seems to play a crucial role in the scenario we consider. This is reflected in the absorption time of the resulting biased opinion dynamics, which is $\mathcal{O}(\frac{1}{\alpha} n \log n)$ for the voter model, regardless of the underlying topology, whereas it exhibits a far richer behavior under the majority rule, being super-polynomial (possibly exponential) in dense graphs. It may be worth mentioning that in the case of two opinions, the majority rule is actually equivalent to the (unweighted) median rule, recently proposed as a credible alternative to the weighted averaging of the DeGroot's and Friedkin-Johnsen's models [MBCD19].

A modular model. Both scenarios we studied are instantiations of a general model that is completely specified by a triple $(\mathbf{z}, \alpha, \mathcal{D})$, with \mathbf{z} an initial opinion distribution, $\alpha \in (0, 1]$ a probability measuring the magnitude of the bias toward the dominant opinion, and \mathcal{D} an *update rule* that specifies some underlying opinion dynamics. In more detail, a biased opinion dynamics can be succinctly described as follows.

The system starts in some state $\mathbf{x}^{(0)} = \mathbf{z}$, corresponding to the initial opinion distribution; for $t > 0$, let $\mathbf{x}^{(t-1)} = \mathbf{x}$ be the state at the end of step $t - 1$. In step t , a node v is picked uniformly at random from V and its state is updated as follows:

$$x_v^{(t)} = \begin{cases} 1 & \text{with probability } \alpha, \\ \mathcal{D}_G(v, \mathbf{x}) & \text{with probability } 1 - \alpha, \end{cases}$$

where $\mathcal{D}_G : V \times \{0, 1\}^n \rightarrow \{0, 1\}$ is the update rule.⁵ When the update rule is probabilistic (as in the voter model), $\mathcal{D}_G(v, \mathbf{x})$ is a random variable, conditioned to the value \mathbf{x} of the state at the end of step $t - 1$.

Remark. It is simple to see that $\mathbf{1}$ is the only absorbing state of the resulting dynamics, whenever $\alpha \neq 0$ and \mathcal{D} does not allow update of an agent's opinion to one that is not held by at least one of the agent's neighbors, which is the case for many update rules in the discrete-opinion setting.

⁵The subscript G highlights the fact that result of the application of a given update rule \mathcal{D} in general depends on both the current state and the underlying graph G . The above definition can be easily adjusted to reflect the presence of weights on the edges.

We further remark that the initial condition $\mathbf{x}^{(0)} = \mathbf{0}$ considered in this paper is not intrinsic to the model, it rather reflects scenarios (e.g., technology adoption) where a new, superior alternative to the status quo is introduced, but its adoption is possibly slowed by inertia of the system. Although the reasons behind system's inertia are not the focus of this paper, inertia itself is expressed here as a *social pressure* in the form of some update rule \mathcal{D}_G . Another reason for choosing a fixed initial state ($\mathbf{0}$ in our case) is being able to compare the behavior of the biased opinion dynamics under different update rules on a common basis.

Finally, it is worth mentioning that Theorem 4.1 and the upper bounds given in Section 3.3 hold regardless of the initial opinion distribution.

Outlook. This paper leaves a number of open questions. A first one concerns general upper bounds on convergence times under the majority update rule. Even though the topology-specific upper bounds given in Section 3 might suggest general upper bounds that depend on the maximum degree, thus mirroring the result of Theorem 3.2, this turns out to not be the case, with preliminary experimental results suggesting a more complicated dependence on degree distribution. In particular, convergence time is fast for reasonably large values of $\alpha < 1/2$ (e.g., $\alpha \geq 0.1$), but it presents a sharp transition as α becomes sufficiently small (e.g., this happens around 0.01 for the Petersen graph). The dependence of this threshold on n is not completely clear.

A further question is whether expected absorption time is always $\mathcal{O}(n \log n)$ when $\alpha \geq 1/2$, irrespective of the underlying dynamics and topology. This is clearly true for the voter model from Theorem 4.1 and it also holds for majority, whenever the underlying network has minimum degree $\Omega(\log n)$ (see comment after Lemma 3.1 for an idea of the proof argument for dense graphs).

We finally remark that our results and most results in related work apply to the case of two competing opinions. An obvious direction for further research is extending our results to the case of multiple opinions.

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